Electromyographic evaluation of muscle firing patterns in the ridden horse during jumping as an objective method of informing current jump training programmes

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ABSTRACT

The sport of show jumping (SJ) places great physical demands on the equine athlete. Despite this, selection and training strategies for the equine jumping athlete are largely based on anecdotal methods. SJ horses are generally selected at a young age based on quality of movement and jump technique. Numerous studies have provided information on the biomechanical demands of jumping. However, research has not sufficiently investigated how quality jump technique and performance may be improved through training in the SJ horse.

The horse's ability to execute the physical demands required for SJ is greatly influenced by muscular adaptation to training. Scientifically evidenced training programmes incorporate exercises, which mimic the duration, intensity, neuromuscular activity and movement patterns that are experienced during competition. However, a lack of understanding on how equine muscles facilitate the jumping effort represents a major gap in knowledge. Therefore, the aim of this thesis was to explore muscle firing patterns, which facilitate "quality" movement during different phases of the equine jump and to determine whether these support traditional training methods in the jumping horse.

Surface electromyography (sEMG) and three-dimensional (3D) kinematic data were collected synchronously from a group of elite and non-elite jumping horses during canter and jump trials over a 1.0m fence. sEMG data were collected from the Superficial Gluteal, Biceps Femoris (vertebral head), Triceps Brachii (long head), Trapezius (cervical head), and Splenius. Lack of standardised methods within equine sEMG research represents a major gap in knowledge. Therefore, four original studies were conducted to develop optimal methods for the acquisition and analysis of sEMG data collected from equine subjects during jumping. These methods were employed in the main study of the thesis.

An original questionnaire was designed to define "quality" movement and "traditional" training methods in the jumping horse, based on the opinions and preferences of highly qualified equestrians. Questionnaire results revealed obvious preferences for specific movement traits, which were used to inform kinematic data analysis. The incorporation of questionnaire findings ensured that research had practical application within the equine industry.

Kinematic data analysis in the main study of the thesis revealed that "quality" movement traits between elite and non-elite athletes were largely non-significant. These findings suggested that movement alone may not be an accurate method for differentiating between good and poor jump technique and performance. However, sEMG data revealed differences in neuromuscular strategies between groups, which had a direct influence on jump technique. Elite horses exhibited the greatest capacity for generation of muscular force and power, particularly in the hindlimb during jump take-off. This finding was evidenced by greater: integrated EMG (iEMG), average rectified value, and peak amplitude data. As a result, "quality" jump technique was facilitated through greater vertical displacement and velocity of the centre of mass (CM) during jump take-off and suspension phases.

These findings provide objective evidence for equestrians to place greater emphasis on strength (anaerobic training), as questionnaire findings revealed a trend for largely aerobic training programmes in the jumping horse. Findings also suggest that equestrians prioritise movement traits, which are indicative of muscular strength when selecting equine jumping athletes. This study has demonstrated the benefits of sEMG for the development of scientifically evidenced training and selection processes in the equine SJ athlete.

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List of Abbreviations

2D – two-dimensional

3D – three-dimensional

A1 – approach stride 1

ANOVA – analysis of variance

ARV – average rectified value

BS – British Showjumping

CM – centre of mass

CSA – cross-sectional area

DDFT – deep digital flexor tendon

DIPJ - distal interphalangeal joint

DOF – degrees of freedom

EMG - electromyography

FEI - Fédération Equestre Internationale (International Equestrian Federation)

FL – forelimb

GE – gait events

GNEF – German National Equestrian Federation

GRF – ground reaction force

GTS – German Training Scale

HL – hindlimb

HNP – head and neck position

HR – heart rate

IED – inter-electrode distance

iEMG – integrated electromyography

ISH – Irish Sports Horse

IT – interval training

IZ – innervation zone

KWPN – Studbook of the Royal Dutch Sport Horse

LA – blood lactate

LCS – laboratory coordinate system

LdF – leading forelimb

LdH – leading hindlimb

LPF – low-pass filter

LSD – long, slow distance

LSR – lateral styloid process of the radius

M1 – move-off stride 1

MCPJ – metacarpophalangeal joint

MTPJ – metatarsophalangeal joint

MTU – muscle-tendon unit

MU – motor unit

MUAP – motor unit action potential

NC – novice competition

NH – National Hunt

PA – peak amplitude

PCSA – physiological cross-sectional area

PDNB – palmar digital nerve block

PT – plyometric training

QTM – Qualisys Track Manager

ROM – range of motion

SCS – segment coordinate system

SDFT – superficial digital flexor tendon

sEMG – surface electromyography

SENIAM – Surface Electromyography for the Non-Invasive Assessment of Muscles

SET – standard exercise test

SJ – showjumping

SNR – signal-to-noise ratio

SSC – strength-shortening cycle

TB – Thoroughbred

TI – suspensory ligament

TrF – trailing forelimb

TrH – trailing hindlimb

V3D – Visual 3D

WB – Warmblood

Glossary of terms and units

cm – centimetre

bpm – beats per minute

Hz - hertz

μV – microvolt

m – metre

mm – millimetre

ms – millisecond

mV - millivolt

s – second

V_{LA4} – velocity at which blood lactate concentration of 4 mmol-l^{-1} is reached

V_{200} – velocity at which a heart rate of 200 beats per minute is reached

Z_{CM} – vertical displacement of centre of mass

$\dot{Z}_{CM}$ – vertical velocity of centre of mass

$\ddot{Z}_{CM}$ – vertical acceleration of centre of mass

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Chapter 1. Introduction

Equestrian Jumping is one of three equestrian Olympic sports and is considered to be the most popular equestrian discipline recognized by the Fédération Equestre Internationale (FEI) (Fédération Equestre Internationale, 2015a). Of seven equestrian disciplines represented by the FEI, showjumping (SJ) has consistently represented the greatest number of FEI events per year since 1994 (Fédération Equestre Internationale, 2004, 2013). Jumping horses represent a large portion of the sport horse population, where in the UK alone, British Showjumping reported over 400,000 starters per year (British Showjumping, 2015). At the highest levels, SJ horses are expected to jump 10 – 13 obstacles, which can reach heights of up to 1.70 m and widths of 2.00 m, all whilst competing against the clock (Fédération Equestre Internationale, 2015b). Due the high physical demands placed on equine jumping athletes, several years of technical training and physiological conditioning are required for a jumping horse to reach its full potential, which equates to significant financial investments, resources and time (Cassiat et al., 2004; Bobbert et al., 2005; Santamaria et al., 2002 2005). Despite the physical demands and popularity of SJ, the selection of individuals and training strategies for the equine jumping athlete are largely based on traditional, anecdotal methods (Smith et al., 1999).

A horse's jumping ability and performance potential is commonly determined at a young age based on qualitative movement traits outlined by various studbooks (Ducro et al., 2007; Santamaria et al., 2004a, b; Thorén Hellsten et al., 2006). Horses that display quality movement traits, are therefore more likely to be accepted for entry into the studbook or selected as jumping prospects. As a result, various biomechanical studies have examined the equine jumping technique in an effort to quantitatively understand the characteristics which denote a "good jumper" and whether specific movement traits can be used to predict performance later in life (Barrey et al., 1993; Barrey and Galloux, 1997; Powers and Harrison, 2000; Cassiat et al., 2004; Bobbert et al., 2005; Powers, 2005; Santamaria et al., 2004a, b, 2005; Lewczuk et al., 2013). However, these studies have not offered conclusive findings, suggesting that movement traits alone are not an accurate indicator of future performance.

Biomechanical examinations of the equine jump technique have provided a greater understanding of the demands and movement patterns of jumping horses. However, the availability and applicability of this research to equine industry professionals is limited (Barrey, 1999) and is considered to be of relatively little value unless it can be applied to practical training sessions (Powers and Harrison, 1999). Furthermore, the subjective assessment of quality jump technique is not limited to studbook guidelines and equestrians are likely to exhibit personal preferences and opinions when assessing a prospective jumping athlete (Lewczuk et al., 2013). Kinematic studies that have evaluated quality jump technique have however neglected to consider these differences of opinion. The incorporation of a wider range of opinions when assessing quality jump technique into scientific studies would enhance knowledge transfer, as their integration is likely to produce findings which are more relevant to the equine industry professional (Winfield, 2010).

Quality of jump technique has been linked to: inherent talent, training or a combination of both (Santamaria et al., 2005). In racing, trainer and training method are factors highly associated with the likelihood of winning a race or prize money (More, 2009; Verheyen et al., 2009; Ely et al., 2010) However, research has not sufficiently investigated how jump technique and performance may be improved through training in the SJ horse. To the authors knowledge, only two studies have investigated the effect of early jump training on the quality of jump technique later in life, reporting that early training did not have a permanent effect on kinematic variables (Santamaria et al., 2005, 2006). Jumping horses are highly susceptible to repetitive strain and overload injuries associated with jumping (Meershoek et al., 2001a, b; Murray et al., 2006) and generally begin jump training later in life at around three or four years of age (Santamaria et al., 2005, 2006). Improved jump technique may be linked to decreased risk of repetitive strain injury (Meershoek et al., 2001a), as ground reaction force (GRF) data have revealed that trained horses experience less limb loading than their inexperienced counterparts (Schamhardt et al., 1993). Previous research has investigated training regimens used on SJ yards, reporting a variety of techniques amongst trainers (Lönnell et al., 2010, 2013; Sommer et al., 2015). However, no studies have investigated which training methods are the most effective in reducing the risks of musculoskeletal injuries and optimising performance and technique in the equine jumping athlete. Further research is therefore required to inform current anecdotal training regimes and to build upon current training and selection methods, which are relevant to the equine industry professional.

Sport- specific training is used in human athletes, where drills are designed to mimic the duration and intensity of technical skills required for competition (Müller et al., 2000; Keteyian and Schairer, 2010; Bompa and Buzzichelli, 2015; Bompa and Carrera, 2015). Although this is often the basis of anecdotal training in horses, the development of human sport science has surpassed that of the equine athlete and the need for objective discipline-specific training in equestrian sport is an area requiring further research (Lekeux et al., 1991; Barrey and Valette, 1993; Clayton, 1996; Lönnell et al., 2014). Even with advances in fields such as Equitation Science, which utilise research-based evidence to inform or support equine training and welfare (McGreevy, 2007), trainers continue to employ techniques, which are not evidence based (Smith et al., 1999; Ely et al., 2010). If the training and conditioning of equine athletes is to follow a similar path to human sport, equestrians must be willing to advance anecdotal training by incorporating scientifically-evidenced methods into training regimes. Unfortunately, a strong link between researchers and the equine industry professional has not been developed, which has been highlighted as a major reason for the lack of scientific advances in current equestrian management and training methods (van Weeren, 2008; Winfield, 2010). It is therefore necessary to bridge the gap between equestrians and researchers by conducting research, which considers the opinions and tacit knowledge of industry professionals. This will ensure that research offers relevant and objective ways of informing current anecdotal training and management practices.

Although previous research has provided information on the biomechanical demands of jumping, a comprehensive understanding of equine locomotion requires an examination of muscle activity, which represents the active component of the locomotor system (Robert et al., 1999). Furthermore, the horse's ability to execute the diversity of physical activities required for show jumping are greatly influenced by muscular adaptations to training demands (Rivero and Letelier, 2000). Muscle training is also critical for increasing or maintaining athletic performance and reducing the prevalence of exercise induced injuries in sport horses (Rivero, 2007). Unfortunately, there is a lack of scientific research evaluating optimal training methods for developing the strength and power necessary for improving dynamic performance in equine athletes (Rivero, 2009). Extensive research has focused on muscular adaptation to exercise, however the influence of specific training parameters, such as optimal intensity and duration, have not been sufficiently explored in the jumping horse (Rivero, 2007; Rivero et al., 2007 Sommer et al., 2015). Research has also neglected to observe how equine muscles behave during jumping, and a lack of understanding on how muscles facilitate optimal movement patterns for jumping represents a major gap in knowledge.

Surface electromyography (sEMG) is a commonly used tool in human physiology and provides the only non-invasive, quantitative means of estimating the degree of muscle activation by recording potentials from electrodes placed on selected superficial muscles (Winter and Yack, 1987; Duchêne and Goubel, 1993; Hewson et al., 2003; Zsoldos et al., 2010a; Valentin and Zsoldos, 2016). sEMG allows researchers to obtain integrated knowledge about equine movement through the assessment of muscle activation patterns in relation to cyclic limb movements (van Wessum et al., 1999). Several researchers have used sEMG as a non-invasive method to assess muscle activation patterns when evaluating equine gait, locomotion and lameness (Colborne et al., 2001; Peham et al., 2001a; Crook et al., 2010; Robert et al., 1999, 2000, 2001a, b, 2002; Hodson-Tole, 2006; Zsoldos et al., 2010a, b; Harrison et al., 2012). The popularity of equine sEMG research is increasing, however to the author's knowledge only one study has investigated and validated a method for equine sEMG signal processing (Peham et al., 2001b). This represents a major gap in knowledge and research is required to investigate and develop methods for accurate sEMG detection, acquisition and analysis in equine subjects (Valentin and Zsoldos, 2016)

The ability to quantitatively measure muscle activity using sEMG has allowed equine researchers to further understand how the horse adjusts to exercise and exertion. Modifications in muscular activity related to variations in speed and incline have lead researchers to suggest where this information may be applied to the objectively-based training of horses (Robert et al., 2000, 2001a; 2002; Hodson-Tole, 2006; Crook et al., 2010; Kienapfel, 2015). However, to the author's knowledge, only two studies have used sEMG to study muscle activity during jumping in the horse (Giovagnoli et al., 1998; St. George and Williams, 2013). Unfortunately, both studies utilized a small sample size and as a result conclusive findings could not be drawn from either study. Furthermore, no studies have utilised sEMG to investigate how muscles facilitate desirable movement and performance in the jumping horse.

Biomechanics research has provided information relating to differences horses with good and poor jump technique (Barrey 1993; Schamhardt et al., 1993; Barrey and Galloux, 1997; Barrey and Langlois, 2000; Powers and Harrison, 2000; Cassiat et al., 2004; Bobbert et al., 2005; Powers, 2005). However, no studies have investigated whether differences in muscle activity patterns occur in elite and non-elite equine jumping athletes. This information may provide objective information on whether muscle activity patterns in non-elite horses can be improved through appropriate training exercises, which mimic muscle activity patterns observed in elite athletes. sEMG research is therefore required to understand how muscles adapt to the distinctive physiological and biomechanical demands of jumping in order to objectively inform and improve of current anecdotal jump training methods and decrease the risk of injury in equine jumping athletes. A better understanding of the functional activity of muscles recruited for jumping would provide essential information for trainers, who invest several years of technical training and physiological conditioning into jumping horses (Cassiat et al., 2004; Bobbert et al., 2005).

1.1 Aims and objectives

The overall aim of the study is to explore muscle firing patterns, which facilitate "quality" movement during different phases of the equine jump and to determine whether these support traditional training methods in the jumping horse. The development of optimal methods for the acquisition and analysis of sEMG and kinematic data, which incorporate the opinions and preferences of equine industry professionals, forms a major component of the thesis. The objectives for the main study of the thesis are:

- To define "quality" movement based on perceptions of industry experts, described using a questionnaire.
- To characterise "traditional" training methods based on perceptions of industry experts, described using a questionnaire.
- To quantify fundamental movement and muscle firing patterns during canter and during jumping using kinematics and surface electromyography in elite and non-elite horses.
- To explore whether "quality" movement, as defined by the questionnaire, can be defined quantitatively from movement and muscle firing patterns in elite and non-elite horses.
- To determine whether "traditional" training methods, identified by the questionnaire, facilitate preferred movement and muscle firing patterns that would support the development of "quality" movement in non-elite horses.

Chapter 2. Literature Review

2.1 Background: The Sport

Equestrian jumping originates from the British Parliament's introduction of the Enclosures Act in England during the eighteenth century (British Showjumping, 2016; International Olympic Committee, 2015a), which created legal property boundaries for "common" land in the countryside (UK Parliament, 2016). The subsequent erection of fences and boundaries introduced obstacles for foxhunters, who were previously able to gallop across open fields. These changes made jumping ability a desired and necessary trait for foxhunters (British Showjumping, 2016). In the 19th century, major cavalry schools in Italy, France and Vienna taught riders to sit with a deep seat and long stirrups over fences (British Showjumping, 2016). This jumping position became the norm, until the famous Italian equestrian, Captain Fiederico Caprilli, revolutionized the jumping position by introducing the "forward seat" at the 1901 International Horse Show in Turin (Clayton, 1994a; van Weeren, 2013). The forward seat revealed the true extent of jumping ability in horses as it allowed greater freedom of movement for the horse, resulting in improved balance. These realisations lead to the first SJ competitions, with the forward seat now widely adopted as the general technique of modern equestrians (International Olympic Committee, 2015a).

The first officially organised jumping competitions were included in the program for the Royal Dublin Society's show in 1864 and were comprised of a high jump, wide jump and stone wall competition (Clayton, 1994a; van Weeren, 2013). Following this, the sport gained popularity across England and Europe, with the 1900 World Exhibition in Paris hosting the first international jumping competition (Clayton, 1994a). 1907 marked the first international SJ competition in England, as part of Olympia horse show. From here, the sport of SJ underwent a number of rule changes, as early rules were largely arbitrary and differed across countries (British Showjumping, 2016). In 1921 the Fédération Equestre Internationale (FEI) was formed, which aided in the establishment of universal rules for international competition (British Showjumping, 2016). Modern SJ in its current format was first featured in the Olympics in 1912 and was largely dominated by military competitors (International Olympic Committee, 2015b). However, as machines began to replace military horses, civilians and women became more prevalent in competition (International Olympic Committee, 2015b). Today, SJ is one of few Olympic sports where men and women compete equally (Clayton, 1994a; International Olympic Committee, 2015b; van Weeren, 2013; Fédération Equestre Internationale, 2015a).

SJ has developed significantly since its introduction in the early 1900's, and is now described as the FEI's most popular discipline (Fédération Equestre Internationale, 2015a) with an extensive worldwide following. The modern-day sport has undergone significant changes in the level of difficulty, with increased technicality of courses, more challenging and fragile fence designs, and stricter time limits (Brand, 2013; Horse & Hound, 2014). These changes are especially apparent in comparison to the first Olympic SJ course, which consisted of 15 obstacles with a maximum height of 1.40 m and spreads of 4 m (Clayton, 1994a). Current obstacle dimensions are much greater with a maximum height of 1.70 m and widths of 2.00 m for spread fences, 2.20 m for triple bars and 4.50 m for water jumps (Fédération Equestre Internationale, 2015b). However, height restrictions do not apply to Six-Bar, Puissance, and Power and Skill competitions, with the current record for equestrian high jump held by Captain Alberto Larraguibel Morales and his horse, Huaso, for clearing 2.47 m in 1949 (Guinness World Records, 2016).

The standard of elite horses has also markedly improved, with European Warmbloods (WB) dominating top-level competition, where Thoroughbreds (TB) and Irish horses were once predominant (Brand, 2013; Horse & Hound, 2014). Although these breeds are still seen in competition, top European WB horses are highly sought after and have been purchased for reported sums of a €7 – 11 million (Brand, 2013; Parisi, 2013; Sorge, 2013). The number of top-level competitions has also increased markedly in recent years, with competitions spread across many different countries. Modern international competitions now offer greater prize money. For example: the Rolex Grand Slam series offers the winner of three grand prix events (CHIO Achen, CSIO Spruce Meadows and CHI Geneva) an additional €1 million in addition to the €3.1 million accumulated from winning each individual event (Rolex, 2016). The introduction of competition series such as the "Longines Global Champions Tour" and the "Furusiyya FEI Nations Cup™ Jumping Series", which function on a "global format", have made international travel necessary for modern elite horses. The evolution of SJ is indisputable and, as a result, the physical and mental demands placed on equine jumping athletes are greater than ever before.

2.2 Physical and physiological demands of modern showjumping

The assessment of exercise related parameters such as: heart rate (HR), blood lactate (LA) and packed cell volume can provide valuable information related to the anaerobic and aerobic demands of a particular discipline. This information is important, as it can provide a basis to inform and improve: performance evaluation, training and management programmes for equine athletes (Art et al., 1990a; Lekeux et al., 1991). Extensive studies have been conducted to investigate the physiological effects of specific exercise on galloping, trotting and endurance race horses (Art et al., 1990a; Sommer et al., 2015). This information has led to scientifically informed training methods, where exercises are based on the energy demands of the specific discipline (Evans, 1994). However, few studies have investigated these parameters in the SJ horse, which is relatively surprising considering its status as a recognized Olympic discipline since 1912. The majority of existing physiological studies for the SJ horse are dated (Art et al., 1990a, b; Lekeux et al., 1991; Barrey and Valette, 1993), but have provided invaluable information regarding the metabolic demands of jumping. Furthermore, the majority of these studies have reported similar findings, warranting their consideration when reviewing the physiological demands of SJ.

A minimum speed of 300-400 m/min is required for the majority of SJ competitions and may increase in speed classes or during a jump off round (Clayton, 1994a). Time motion analysis of SJ competitions revealed average speeds of 399-445.2 m/min, with jumping efforts occurring every 4.3 – 5.6 seconds across three different competition levels (Clayton, 1996a). These speeds are relatively slow compared to other disciplines. However, studies investigating physiological parameters during SJ competitions have revealed high energetic demand despite the relatively slow speeds travelled by the SJ horse. During warm up for high level competition, average HR of approximately 96.5 bpm have been observed (Lekeux et al., 1991), with increases of >120 bpm observed when a warm up fence was jumped (Barrey and Valette, 1993), indicating moderate exercise intensity (Clayton, 1994a). However, HR in the range of 179.4 ± 3.9 – 189.2 ± 3.5 bpm have been recorded during competition over a 1.40 m course of fences (Lekeux et al., 1991). These findings are similar to other studies that have reported peak HR of 191.4 ± 3.8 bpm (Art et al., 1990a) and 205.5 ± 0.5 bpm (Barrey and Valette, 1993) during high-level competition with fence heights ranging from 1.45-1.50 m. Unsurprisingly, Barrey and Valette (1993) observed an apparent correlation between increased HR and fence height, suggesting that this parameter is influenced by competition level.

A working HR that exceeds 150-160 bpm is generally associated with reaching the lactate threshold (Persson, 1983) where blood lactate (LA) concentrations can exceed 4 mmol/L indicating anaerobic energy production (Rivero and Piercy, 2008). The high HR observed during SJ competition therefore reveals an anaerobic energy requirement for jumping. This is in accordance with studies reporting substantial increases in LA concentration following SJ competition, with average post competition LA values ranging between 9.01 ± 0.9 mmol/L (Art et al., 1990a) and 4.57 ± 1.93 mmol/L in horses competing at various levels (1.25 - 1.50 m) (Art et al., 1990a; Lekeux et al., 1991; Barrey and Valette, 1993). Lekeux et al. (1991) suggest that workloads in excess of 600 m/min would be required to observe the changes in LA and HR reported for SJ horse's post-competition, as moderate exercise of 350 m/min has proven to be insufficient for evoking these changes in LA.

Therefore, the observed increases in HR and LA exceed the expected values for speeds observed during SJ competition, indicating that anaerobic metabolism makes a significant contribution to the energy required during jumping (Art et al., 1990a; Lekeux et al., 1991, Clayton et al., 1994a).

The energy requirements for SJ are therefore supplied by a combination of aerobic and anaerobic metabolism, with aerobic metabolism related to cantering at a moderate speed and anaerobic metabolism largely related to the production of energy required for jump take-off (Art et al., 1990a; Barrey and Valette, 1993). Anaerobic metabolism required for jumping has been linked to higher oxygen demands of muscles during force production at take-off and for forward acceleration at landing (Bobbert and Santamaria, 2005). These findings are in accordance with Sloet et al. (2006), who found significant increases in HR and LA concentrations in riding school horses that completed a course of small fences (0.8 – 1.0 m) compared to the same course at canter without fences. Both tests were performed at an average speed of, 350 m/min, which further validates that the jumping effort is largely responsible for the increased workload observed in the jumping horse at relatively moderate speeds (Sloet et al., 2006).

Clayton (1996a) states that conditioning programmes should ideally be tailored to the specific contribution of aerobic and anaerobic pathways required for energy production in specific disciplines. An understanding of energetic demands is therefore essential information for the development of appropriate conditioning programmes for the equine athlete (Clayton, 1991, 1994a, 1996a; Evans, 1994).

2.3 Training the Equine Jumping Athlete

2.3.1 The current state of training

The proven contribution of both anaerobic and aerobic metabolism in SJ has lead researchers to make suggestions for scientifically evidenced jump training programs (Barrey and Valette, 1993; Clayton, 1996a). With this information available, equestrians have the opportunity to follow the path of human sport science, which has seen advances in training methods and performance through the application of scientific training principles (Derman and Noakes, 1994). Unfortunately, equestrian sport is notoriously bound by tradition, with most equestrians employing anecdotal training methods that have been passed down through generations without scientific validation (Derman and Noakes, 1994; Powers and Harrison, 2000). The sport-specific conditioning of human athletes includes exercises which mimic the duration and intensity of skills required during competition (Clayton, 1996a; Müller et al., 2000; Keteyian and Schairer, 2010; Bompa and

Buzzichelli, 2015; Bompa and Carrera, 2015). However, the frequency, duration, intensity and types of exercises employed for the training of showjumpers has not been sufficiently documented in scientific research (Sommer et al., 2015). This is in contrast to an extensive library of books written by experienced equestrians, documenting their personal experiences and anecdotal training methods.

Training is defined as a programme of exercise, which aims to: improve or maintain the horse's physical performance, improve motor skill and neuromuscular co-ordination, delay the onset of fatigue and decrease the risk of musculoskeletal injury (Rose and Evans, 1990; Marlin and Nankervis, 2002; Rogers et al., 2007; Blood and Studdert, 1990 cited by Clayton and van Weeren, 2013). A programme must also strive to maintain the horse's willingness and enthusiasm for exercise (Rose and Evans, 1990; Marlin and Nankervis, 2002; Rogers et al., 2007). A structured training programme for the equine athlete should aim to improve performance through the induction of beneficial physiologic changes (Rivero, 2007), which provoke adaptation of relevant body systems and enable the horse to perform athletic tasks (Evans, 1994). Conventional anecdotal training programmes for the jumping horse generally include basic dressage, coordination and strength training, but the importance of conditioning work to improve aerobic capacity and anaerobic power is generally overlooked (Barrey and Valette, 1993). This is outlined in recent research, which has attempted to document the training regimes of SJ trainers (Lönnell et al., 2010, 2014; Munk et al., 2010; Egenvall et al., 2013; Sommer et al., 2015).

Lönnel et al. (2014) investigated the training regimes of 31 professional SJ trainers from yards across four European countries over 6 months, reporting substantial variation in training exercises and workload between trainers. Ridden work represented the major component of training regimes, with flatwork representing 41% of the total proportion of time exercised, followed by: hacking (19%), competition (14%), jumping (10%), lunging (6%), fitness work (6%) and hill work (0.3%) (Lönnell et al., 2014). A preliminary study by Lönnell et al. (2010) reported similar findings from 17 professional SJ trainers, which revealed an emphasis on flatwork and hacking, with less time spent on jumping and fitness exercises. A study comparing training practices of amateur and professional SJ riders revealed that the average percent of days that employed flatwork were similar between groups and represented between 50-60% of training days (Sommer et al., 2015). This finding is similar to those reported by Lönnell et al. (2010, 2014); however professional trainers were found to dedicate a higher percentage of training days to jumping exercises than amateur riders (Sommer et al., 2015).

These studies have provided some insight into the training strategies used by professional trainers and have attempted to document the intensity, duration and frequency of specific exercises. These parameters are used to define the volume of work within a training programme (Clayton, 1991; Marlin and Nankervis, 2002), which represents an essential consideration for the development of scientifically evidenced programmes. The volume of work defines the systematic exposure to gradual increases in stress on the physiological systems, which provoke adaptive changes to training (Roger et al., 2007). Studies by Lönnell et al. (2010, 2014) and Sommer et al. (2015) provided trainers with a diary to track the intensity, duration and frequency of daily training practices. However, the inherent subjectivity of this documentation method suggests that quantitative measurements reported for exercise intensity and duration must be considered with caution. Intensity was subjectively judged by trainers using an arbitrary visual analogue scale of 0 (low) -1 (high), which was reported as a percent value that was averaged for rider, country and overall total (Lönnell et al., 2014). Subjective exercise intensities ranging from 5%, during hacking at walk, to 85% at fitness gallop work were reported by Lönnell et al. (2010). Interestingly, Lönnell et al. (2014) reported subjective intensities ranging from 8-64% for hacking, 15-82% for jumping and 33-80% for flatwork exercises. Only Lönnell et al., (2010) presented quantitative intensity data, reporting speeds of 350-800m/min during canter and gallop work, however the method used to quantify speed was not explicitly described. The high variability in subjectively judged exercise intensities, coupled with highly ambiguous percent values, makes it difficult to interpret and apply this data to the design of scientifically evidenced training programmes.

Frequency and duration data for specific exercises have been presented as minimum-maximum ranges, with Lönnell et al. (2010) reporting 1.5-7 sessions per week for flatwork, 0-6 for hacking and 0-2 for jumping/ fitness work. Similar findings were reported by Lönnell et al. (2014), apart from fitness work, where 0-4.6 sessions per week were reported. Low variability for mean overall duration of exercise sessions was found between riders, with the majority reporting durations of approximately 40 minutes (Lönnell et al., 2010, 2014). This is in accordance with Sommer et al. (2015), who reported exercise durations between 30 and 60 minutes for professional and amateur SJ riders. However, min-max ranges for the duration of individual exercise activities were found to vary considerably, with ranges of 16-63min and 15-64min reported for jumping and fitness work, respectively (Lönnell et al., 2014). Rider variation was further described by Lönnell et al. (2014) who observed one rider as hacking 47% of the overall time exercised and 5 riders as hacking <5% of time exercised. Again, these findings reveal considerable variation between riders and an overall prioritisation of flatwork over jumping exercises.

Although these studies have provided some valuable scientific evidence for the type of training and management strategies employed by equine industry professionals, further research is required to quantitatively measure the duration, intensity and frequency of specific exercises. Previous research has replicated the speed and duration of exercise sessions in TB racehorses to determine which training strategies are most likely to result in increased performance and decreased risk of musculoskeletal injury (Estberg et al., 1995, 1998; Boston and Nunamaker, 2000; Verheyen et al., 2006, 2009; Ely et al., 2010). However, this type of research will not be possible for the SJ horse until further quantitative data on exercise intensity, duration and frequency are obtained.

2.3.2 The development of objective jump training methods

Recent research has investigated the effects of training on specific physiological parameters in the equine jumping athlete. Standard exercise tests (SET) have been used to investigate the effects of different interval training methods (Munk et al., 2010) and individual training methods of professional and amateur riders (Sommer et al., 2015) on physiological parameters in the SJ horse. SETs are commonly used to evaluate physiologic response to training in racehorses, and can be performed on treadmills or in the field (Bitschnau et al., 2010; Munk et al., 2010, 2013). HR and LA are commonly investigated, as both parameters provide a reliable method for determining fitness levels in the horse (Bitschnau et al., 2010). Munk et al. (2010, 2013) investigated the effect of three different interval training (IT) methods on performance using three different SETs, which measured HR, LA and the number of obstacles knocked down. IT methods were in the form of outdoor gallop work, indoor sprint exercise, and consecutive gymnastic jumping efforts (totalling 150 jumps per session). SETs were conducted on an outdoor track (SET_{V4}), indoors over an elliptical track of fences (SET_{JUMP}) and over a jump course of 11 obstacles (SET_{COURSE}), where fence heights were set according to age and the height each horse could comfortably jump. Each IT method was found to improve different fitness parameters, with outdoor gallop work and consecutive jumping efforts resulting in significant increases in V_{LA4} (Munk et al., 2013). Interestingly, the indoor sprint IT did not significantly alter V_{LA4}, but resulted in a significant decrease in V_{200}. The authors were unable to provide an explanation for this finding. In general, higher V_{LA4} values are indicative of fitter horses and have been linked to increased performance (Evans et al., 1993; Couroucé et al., 1997; Eaton et al., 1999; Linder, 2000; Couroucé-Malblanc and Hodgson, 2013). Therefore, findings from this study indicate that IT methods, which consist of gallop work and consecutive jumping efforts, may result in increased aerobic capacity and fitness in the jumping horse. Number of fence knock downs were not improved by any of the three IT methods (Munk et al., 2013). Level of fatigue was found to decrease following conditioning using all IT methods, while improved jump technique was only observed following gallop IT work (Munk et al., 2013). However, jump technique and level of fatigue were subjectively judged and must therefore be considered with caution.

In a similar study, Sommer et al. (2015) examined the effect of exercises employed by professional and amateur riders on V_{LA4} and HR in SJ horses. Three SETs, consisting of 5 incremental speed intervals, were performed over a 5-month study period and HR and LA were measured following each test. Professional and amateur riders recorded training protocols between SETs, detailing type, duration, and intensity of specific exercises. Results revealed an emphasis on flatwork, in accordance with Lönnell et al. (2010, 2014). However, training programmes differed between professional and amateur riders, with professional horses generally exercising less often, with shorter duration and higher intensity exercise sessions than amateur horses. The relationship between V_{LA4} and training programmes revealed that increased: competitive activity, percentage of jumping days and duration of jumping exercise resulted in increased V_{LA4} in professional horses. Both amateur and professional horses showed increased V_{LA4} when: the general mean duration of all exercises were increased, when flatwork exercise duration increased and when the number of days at pasture increased (Sommers et al., 2015). These findings suggest that increased duration of both flatwork and jumping exercise may improve fitness in SJ horses.

Studies using SETs have provided preliminary information regarding physiological adaptations to different training exercises in the SJ horse. Findings from these studies also indicate that V_{LA4} provides an objective method for evaluating training efficacy and tracking fitness improvements in individual horses. However, these studies have conducted SETs under field conditions, which are generally difficult to standardise due to environmental variables that can influence test results (Marlin and Nankervis, 2002). The reported relationships between physiological adaptation and specific exercises must therefore be considered with caution, as standardisation between tests cannot be confirmed. Furthermore, studies investigating the training methods of equestrians have used a relatively small sample size. For example, the comparison of professional and amateur training methods made by Sommers et al. (2015) only employed one professional trainer, which is certainly not representative of the entire population. Further research is therefore required to quantify and evaluate the physiologic responses to training methods, as reported by equine trainers under standardised conditions.

2.3.3 Recommendations for objective training methods in the SJ horse

Although scientific research has provided suggestions for training the SJ horse, to the author's knowledge, Clayton (1991, 1994a) is the only researcher to explicitly describe scientifically evidenced training programmes, which are based on the energetic requirements of the SJ discipline. In any equine athlete, cardiovascular conditioning, strength training and suppling exercises represent the main components of any training programme (Clayton, 1991), with some authors describing alternate phases that are dependent on discipline. For instance, conventional training of the TB racehorse is designed to facilitate increased aerobic capacity and is generally characterised by an endurance phase, aerobic-anaerobic phase and an anaerobic phase (Rivero, 2007). However, this programme is unlikely to induce physiological adaptations that would meet the physical demands of the SJ horse, which relies on a combination of anaerobic and aerobic metabolism. Training and conditioning represent the major components of the horse's physical training and it is important to note the difference between terms. Conditioning induces physiological changes, whilst training, which is commonly referred to as "schooling", develops neuromuscular coordination that facilitates technical skill (Clayton, 1991, 1994a).

2.3.3(i) Cardiovascular (aerobic) conditioning

The cardiovascular phase of a training programme improves the ability of the cardiovascular, respiratory and muscular systems to produce energy through metabolic pathways, which are appropriate for the specific discipline (Clayton, 1991, 1994a). In horses, the cardiovascular and muscular systems adapt rapidly to exercise, with changes in these systems observed after a few weeks (Eaton et al., 1999; Knight et al., 1991). However, the principal focus of this literature review will be on muscular adaptations to specific training phases. Equine skeletal muscles are highly adaptable to training (Snow and Valberg, 1994; Rivero, 2007) and comprise up to 55% of body weight in the TB and approximately 45% in other breeds (Snow and Valberg, 1994). Therefore, muscular adaptation to training has a considerable influence on strength (power generation), stamina (fatigue resistance) and speed (velocity of shortening), all of which are important traits of the SJ horse (Rivero, 2007). Extensive research has examined equine muscle fibre ultrastructure, heterogeneity, and the structural and functional adaptations to training, which are extensively described in a principal review by Snow and Valberg (1994). Overall, these studies have answered questions related to what can be modified in equine muscle by training. However, further research is required to determine optimal methods for obtaining these modifications and how they can be tailored to suit the physical demands of specific equestrian disciplines (Rivero, 2007).

Initial muscular adaptation to training occurs via an increase in aerobic metabolism, as the main energy production required for exercise at low to moderate intensities comes from aerobic pathways (Rivero et al., 2007). Depending on the stimulus applied, the adaptive response of muscle can take the form of muscle fibre (myofibre) hypertrophy or remodelling (Snow and Valberg, 1994; Serrano et al., 2000; Rivero et al., 2007). Hypertrophy, also referred to as the quantitative response, describes adaptation where myofibres increase in size, or cross-sectional area (CSA), but retain their basal biochemical and structural properties (Serrano et al., 2000; Rivero et al., 2007). Remodelling, also referred to as the qualitative response, describes adaptation where myofibres acquire different structural and metabolic properties, but retain their basal CSA. The reader is referred to Snow and Valberg (1994) for a comprehensive review of muscle fibre types present in equine skeletal muscle. Briefly, equine skeletal muscle is comprised of three main fibre types: type I (slow-oxidative), type IIA (fast-oxidative glycolytic) and type IIB (fast glycolytic), which is sometimes referred to as IIX, depending on the author (Snow and Valberg, 1994; Rivero, 2007). Type I and type II fibres are also referred to as slow twitch and fast twitch fibres, respectively, with slow twitch capable of working aerobically over longer periods of time and fast twitch capable of high power output and contraction velocity (Snow and Valberg, 1994; Rivero and Piercy, 2008).

Cardiovascular conditioning comprises long slow-distance (LSD) work or low intensity aerobic exercises, which are followed by progressive IT in the strength training phase (Clayton, 1991). The LSD phase is fairly generic for all horses, regardless of their specific discipline. It is essential for young horses to ensure appropriate adaptive responses of musculoskeletal tissue prior to more strenuous strength training work (Barneveld and van Weeren, 1999; Smith et al., 1999). In horses, long-term endurance training, consisting of LSD exercises, has been found to induce significant remodelling, involving a transition from fast-to-slow muscle fibre types (Serrano et al., 2000). Early (3-month) and long-term (8-month) endurance exercise was found to induce adaptive remodelling responses, with prolonged training duration increasing the magnitude of fast-to-slow muscle fibre transition (Serrano et al., 2000). Serrano et al. (2000) reported hypertrophy in type IIA fibres, however this was minimal. Although there is some degree of contention related to remodelling adaptations of equine muscle in relation to training, conflicting findings between studies are largely related to methodological differences (Tyler et al., 1998; Serrano et al., 2000). Furthermore, findings reported by Serrano et al (2000) are in accordance with previous studies that have reported significant increases in type IIA:IIB fibre ratio following endurance and high intensity training, indicating an increase in oxidative muscle fibres (Henkel et al., 1983; Tyler et al., 1998). Trained Standardbred trotters have also been found to exhibit an increased IIA:IIB fibre ratio, when compared to their inactive counterparts (Essén-Gustavsson and Lindholm, 1985).

These studies are of particular relevance to training the SJ horse, as findings indicate that prolonged endurance training induces decreased velocity of muscle shortening (Tyler et al., 1998; Serrano et al., 2000), which may decrease the horse's ability to produce the muscular forces required to lift and accelerate the horse at jump take-off. These findings highlight the importance of striking a balance between aerobic and anaerobic training in the SJ horse, and suggest that prolonged cardiovascular training may be detrimental to developing the anaerobic capacity required for jumping and sprinting.

As a general rule, Clayton (1991) suggest a gradual progression to a fitness level where the SJ horse can work for approximately 50 minutes at an average speed of 6 - 8 km/h, including 2 - 3 minutes of canter work. The LSD phase can range between 3 - 12 months, with the rate of progression dependent on the age, basal fitness level, breed and history of a specific horse (Clayton, 1991, 1994a; Rogers et al., 2007). LSD exercise should consist of walk, trot and slow canter with progressive increases in intensity or duration, but always keeping exercise within the aerobic zone below 140 bpm (Clayton, 1991). Following LSD, the training programme should focus on increased exercise intensity using IT training. IT training should incorporate progressive increases in canter work between 350-400m/min in accordance with competition speeds reported in previous literature (Clayton, 1994a; 1996a). A 1:1 work rest ratio is recommended for initial IT sessions, but may increase between 1:2 and 1:6, depending on the intensity of canter work (i.e. increased HR) (Clayton, 1991). To the author's knowledge, no studies have explicitly investigated the physiological adaptations induced by the training recommendations put forth by Clayton (1991, 1994a). However, Clayton (1991, 1994a) recommend IT training that incorporates sprint work and gymnastic jumping, which have been shown to increase V_{LA4} (Munk et al., 2013), justifying their use for increasing aerobic capacity in the SJ horse. The initial cardiovascular stage described by Clayton (1991, 1994a) to improve aerobic capacity is also in accordance with suggestions from previous physiological (Art et al., 1990a; Barrey and Valette, 1993) and temporal (Clayton, 1996a) studies on the SJ horse.

2.3.3(ii) Strength (anaerobic) training

Initial training practices should aim to proportionately optimise muscular strength, stamina and speed, which is generally achieved using cardiovascular conditioning (Rivero, 2007). Following this phase, exercise training should be oriented towards development and maintenance of muscular traits that are directly related to the physiological demands of a particular discipline (Rivero, 2007). The strength training phase is particularly relevant to the jumping horse and should be designed to develop the explosive power of the muscles (Clayton, 1994a). The maximum force that can be produced by skeletal muscle is related to its physiological cross-sectional area (PCSA) and fibre type composition (Rivero and Letelier, 2000; Rietbroek et al., 2007; Rivero et al., 2007). Power production is the product of the force generated and shortening velocity of muscle (Alexander, 2002; Kearns et al., 2002). A muscle's potential to produce force and velocity is a function of the biochemical characteristics of muscle fibres and the muscle fibre arrangement within the whole muscle (Alexander, 2002; Kearns et al., 2002). The ultrastructure and architectural arrangement of muscle fibres within a muscle will therefore heavily influence athletic performance in the equine SJ athlete (Kearns et al., 2002).

Previous studies have reported a relatively balanced proportion of muscle fibre types in the hindlimb (HL) muscles of sports horses, including SJ horses (Rivero and Letelier, 2000; Rivero et al., 2001). This is in contrast to muscles of TB racehorses that are characterised by a very high percentage of fast-twitch fibres (particularly IIB), and endurance horses, which exhibit a high percentage of type II and IIA fibres (Snow and Guy, 1980; Rivero et al., 1989; Rivero and Letelier, 2000). SJ horses were also found to exhibit relatively large CSA of type II fibres, which is advantageous for force production during jumping (Rivero and Letelier, 2000). As previously described, increased muscle fibre CSA results in increased peak force capacity, as total force output is proportional to the CSA of the muscle fibre mass recruited. Strength training in the SJ athlete should therefore aim to induce hypertrophy of type II fibres, as well as recruitment and increased contraction velocity of type II fibres (Rivero, 2009). Research has shown that increased aerobic capacity is the most common muscular adaptation to training in horses, however improvements in strength (via myofibre hypertrophy) and speed (via enhanced anaerobic capacity) are more difficult to achieve (Rivero, 2009).

The horse is adapted to produce force in an economical manner, with muscles located proximally on the skeleton and their tendon located distally to reduce the weight of the lower limb (Snow and Valberg, 1994, Wilson et al., 2001; McGuigan and Wilson, 2003). The lighter lower limb behaves as a pendulum to maximise efficiency by decreasing the energy required to overcome inertia during swing phase (Snow and Valberg, 1994, Wilson, 2001; McGuigan and Wilson, 2003). The total force exerted across a muscle is therefore the sum of: active forces generated by active contractile proteins of muscle and passive forces provided by elastic tissues of the muscle-tendon unit (Roberts et al., 1997; Biewener, 1998; Alexander, 2002; Rivero, 2009). In horses, locomotor efficiency is associated with the strength-shortening cycle (SSC) of the muscle-tendon unit. In humans, SSC is often used to describe plyometric training (PT), which describes exercises that involve high-intensity eccentric contractions, followed immediately by a rapid concentric contraction (Malisoux et al., 2006). Human research has revealed that PT is effective for increasing explosive leg power, as measured by vertical jump height (i.e. Adams et al., 1992; Matavulj et al., 2001; Markovic, 2007; De Villarreal et al., 2010), which is thought to be the result of increased motor unit (MU) recruitment and an increased ability to store kinetic energy within the elastic components of muscle (Bosco, 1982 cited by Adams et al., 1992). PT exercises generally include various body-weight jumping-type exercises, such as countermovement jumps (Markovic, 2007), and have been described as inducing a more rapid transition from eccentric to concentric contraction, resulting in increased force production and dynamic strength (Adams et al., 1992). SSC is inherent in most equine gaits, as each stride cycle consists of eccentric lengthening of the muscle-tendon unit, where passive structures absorb elastic energy, followed by concentric shortening, where energy is released to aid acceleration and reduce muscular work (Rivero, 2009; McGuigan and Wilson, 2003). This has been postulated as a reason for the difficulties associated with strength training in equine athletes compared with other athletic species (Rivero, 2009).

The equine jump inherently incorporates SSC exercise (Rivero, 2009) and has been found to induce significant hypertrophy of type IIA muscle fibres in HL muscle (Islas et al., 2000; Rivero and Letelier, 2000). Following an intensive 6-month jump training programme, Rivero and Letelier (2000) reported: a significant increase in IIA fibre CSA, a decrease in IIA fibres, an increase in hybrid IIA/B fibres and no changes to IIB fibre percentage. Rivero and Letelier (2000) postulated that these changes were likely to be even more pronounced in untrained, young horses. However, Rietbroek et al. (2007) found no significant alterations in fibre type composition and CSA in horses exposed to jump training from the age of 0.5 – 3 years of age, reporting that muscle adaptations were the result of development and were not training induced. Contradictory findings are likely the result of differences between training regimes, as Rietbroek et al. (2007) employed a less intense programme of free jumping 2 days/ week and 20-minutes on a mechanical walker 3 days/ week. During free jumping sessions, horses jumped a 3-fence combination 6 times, with heights ranging from 40-90cm, depending on age (Rietbroek et al., 2007). This is in contrast to Rivero and Letelier (2000), who describe a 6-month training programme comprised of 30 minutes ridden exercise at walk, trot and gallop at approximately 40-65% of maximal aerobic capacity, followed by 60 minutes of jump training over fences ranging from 80-100cm, 6 days/ per week. This programme also included afternoon exercise of 60 minutes of unridden flatwork or free jumping over 100 – 110cm fences, which alternated every second day.

It is important to note that each strength training session causes some minor ultrastructural damage to muscle tissue, which is regarded as having an excellent ability to repair itself (Clayton, 1994a; Rivero and Letelier, 2000). The damage-induced muscle fibre degeneration and regeneration cascade is typically the result of metabolically demanding exercise and is necessary for inducing beneficial muscular adaptation and progressive increases in performance (Kim et al., 2005). Fibre damage is generally caused by excessive strain in contracting fibres and is not due to the absolute force produced by the muscle (Seene and Kassik, 2013) and is more pronounced following eccentric exercise (Faulkner et al., 1993; McHugh et al., 1999). The muscle fibre damage-regeneration cycle has been shown to provide a protective effect for reducing the risk of musculoskeletal injury in horses (Kim et al., 2005). However, if sufficient time for repair is not facilitated damage may accumulate, predisposing the horse to injury (Clayton, 1994). This highlights the importance of systematic recovery periods within a training programme to encourage regular regeneration of muscle tissue (Seene and Kassik, 2013). Therefore, results from the study by Rivero and Letelier (2000) should be considered with caution, as the training programme was likely too intensive for practical application to training the SJ horse.

Strength training exercises for the SJ horse must aim to recruit type II muscle fibres and should mimic the range and speed of joint motion experienced during jumping, specifically flexion and extension of HL joints at take-off (Clayton, 1991; 1994a). Clayton (1991, 1994a) recommends high intensity strength training used in conjunction with a small number of repetitions for the SJ horse. Suggested exercises include: gymnastic jumping, slope training and step gradients, which can be classified as SSC exercises (Clayton, 1991). The recommended frequency of strength training is 2 - 3 times per week, allowing time for rest and minor tissue repair between sessions (Clayton, 1991; 1994a). Horses in competition will require fewer sessions, as a competition will act as a strength training session in itself. In accordance with Munk et al (2010), Clayton (1991, 1994a) recommends IT training using gymnastic jumping, where increases in jump height facilitate increased intensity. Jump training is beneficial for strengthening bone and tendinous structures in a sport specific manner (Clayton, 1991, 1994a), however the injury risks associated with jump training must be considered when designing the training programme and are described in detail in Section 2.3.4.

There is a lack of research investigating appropriate training methods for the development of strength and power in equine athletes (Rivero, 2009). However, strength training suggestions put forth by Clayton (1991; 1994a) are in accordance with Rivero et al (2007) who state that high intensity training is comparable to strength training in human athletes. These similarities are due to increases in CSA that have been reported in previous equine studies (Tyler et al., 1998; Rivero et al., 2007). Interestingly, Sommer et al. (2015) revealed that the intensity of exercise and fitness level of horses, as subjectively judged by amateur and professional SJ riders, did not increase with training. This finding indicates that training programmes employed by both groups were not designed to induce increases in performance through progressive increases in exercise intensity (Sommer et al., 2015). This highlights lack of knowledge transfer between researchers and equestrian practitioners.

Although training recommendations put forth by Clayton (1991; 1994a) are based on scientific principles of exercise physiology, no studies have explicitly validated their efficacy for inducing physiologic adaptation and performance in the SJ horse. However, many of the suggestions are in accordance with previous physiological studies of SJ horses, which have been highlighted throughout this section. Furthermore, findings from studies discussed in Section 2.3.1 from Lonnell et al (2010, 2014) reveal that these suggestions may also be in accordance with training strategies employed by SJ trainers, as flatwork was reported as the largest proportion of training programmes and may be indicative of cardiovascular conditioning. However, the minimal incorporation of progressive increases in exercise intensity reported by professional and amateur trainers (Lonnell et al., 2010, 2014; Sommer et al., 2015) suggests that inadequate emphasis is placed on anaerobic strength training. This section has emphasised the importance of muscular adaptation to strength training in the SJ horse and highlights the need for further research, which examines muscular adaptations and activity patterns as a method for informing current anecdotal jump training programmes.

2.3.4 Injury risks for the SJ horse in training

Successful performance in equestrian sport requires regular training; however frequent training at a high intensity is a known risk factor for overtraining and overload injuries (Bruin et al., 1994; Tyler-McGowan et al., 1999; McGowan et al., 2002; Munk et al., 2010). As previously discussed in Section 2.3.3(ii), these injuries generally occur due to an insufficient balance within the degeneration and regeneration cascade in the musculoskeletal system (Bruin et al., 1994; Tyler-McGowan et al., 1999; Clayton, 1994a). Jump training is a known risk factor for musculoskeletal injury in the equine athlete, which is largely attributed to the large GRF forces experienced by the forelimb (FL) at landing (Schamhardt et al., 1993a; Meershoek et al., 2001a; Murray et al 2006). Williams et al. (2001) and Bailey et al. (1998) determined that the overall rate of clinical conditions was greater in jump races compared to flat racing, with National Hunt (NH) racing generating twice the number of incidents as flat racing in Britain (Williams et al., 2001). Racing fractures in NH racing have also been associated with jumping, with 78% of non-fall fractures occurring at a hurdle (Parkin et al., 2006). A similar trend has been reported in sports horses, with Warmblood (WB) SJ horses exhibiting a shorter competitive life than their dressage counterparts (Ducro et al., 2009).

The SJ horse is predisposed to injuries to the suspensory ligament (TI), distal deep digital flexor tendon (DDFT) and superficial digital flexor tendon (SDFT) in the FL (Dyson, 2000; Williams et al., 2001; Murray et al., 2006). Horses in other jumping disciplines, such as NH, are also predisposed to TI injuries, as well as injuries to the thoracolumbar region and distal interphalangeal joint (DIPJ) (Pinchbeck et al., 2004; Murray et al., 2006). It is generally assumed that injuries to the TI, DDFT and SDFT are caused by repetitive strain and extreme forces experienced by the FL during landing (Meershoek et al., 2001a). Tendon loading during landing is influenced by jump height, with near-maximal tendon forces displayed over heights of 1.20m in non-elite horses. It has also been postulated that tendon loading is likely to be influenced by training level and ability of individual equine athletes (Meershoek et al., 2001a). This theory is based on findings by Shamhardt et al (1993a), who found that experienced horses generated similar GRF amplitude and force impulse over a 1.30m fence to an inexperienced horse executing an 0.80 m fence. However, this was not supported by Dyson et al. (2006) who reported a significant increase in risk of DDFT and TI in the FL of elite horses compared their non-elite counterparts. Dyson et al. (2006) related increased risk of injury in elite horses to the fact that they are generally older and at greater risk of degenerative changes, and execute larger fences heights during competition.

Meershoek et al (2001a) also suggest that increased tendon loading is more likely to be observed during fatigue and may be compensated for by increased muscle activation to minimize additional load on passive structures (Meershoek et al., 2001a). In human athletes, it has been suggested that weakness in the supporting musculature of joints may predispose development of abnormal movement patterns during fatigue, which increases loading of tendons and ligaments (Hunt, 2003). Compensatory muscular strategies have also been described in horses during fatigue, which are thought to increase risk of musculoskeletal injury (Clayton, 1994a). The muscular compensatory strategies of horses during fatigue have not been sufficiently explored, however it is recommended that strength training be terminated at initial signs of fatigue to avoid injury (Clayton, 1994a). These findings highlight the importance of muscular conditioning for decreasing the risk of musculoskeletal injuries in SJ horses.

Human research has revealed an association between level of strength and flexibility and rate of musculoskeletal injury in athletic populations (Knapik et al., 1991; Orchard et al., 1997; Tyler et al., 2002; Hunt, 2003). Orchard et al. (1997) concluded that the strength ratio of the agonist to antagonist muscle groups was the most effective predictor of musculoskeletal strain in football players. This study is in accordance with Tyler et al. (2002), who found that hockey players with muscular weakness in adductor muscles were more likely to experience adductor strain during the competitive season. Muscular weakness has also been identified as a significant factor in human overuse injuries and it has been proposed that greater emphasis on strength and conditioning issues may reduce the rate of muscle strain and overuse injury (Hunt, 2003).

The importance of strength training in equine SJ athletes has been discussed in Section 2.3.3(ii). However, there is a scarcity of scientific research evaluating optimal training methods for developing strength whilst decreasing the risk of injury in equine athletes (Rivero, 2009). Injury rates in equine athletes have been shown to vary significantly by trainer, suggesting that variations in training regimes influence injury risk (Ely et al., 2009). Interestingly, Egenvall et al. (2013) reported that variation of exercises comprising SJ training programmes was found to act as a protective-factor against days lost to injury. These areas highlight the need for further investigation into the relationship between muscle activation as a means of developing informed training programs, which may improve performance and decrease risk of injury.

2.4 Common selection methods for the modern equine jumping athlete

2.4.1 European studbook selection process

Equine studbooks and breed registries are responsible for the selection of horses, which will maintain a high standard of breed characteristics and bloodlines within the specific breed. SJ is a major breeding objective for sport horse breeding, with the overall goal being success in competition across all levels (Thorén Hellsten et al., 2006). The majority of modern elite SJ horses are WB (Dyson et al., 2000) and the selection processes for these horses will therefore form the focus of this section.

European WB studbooks employ slightly different strategies for the selection of jumping horses, some with a focus more on annual competition performance and others placing more emphasis on conformation and specific movement traits of young horses. The general timescale for the selection process of jumping horses across European WB studbooks is illustrated in Figure 2.1. The selection of the French Saddle horse (Selle Francais) is solely evaluated based on annual performance in competition (Barrey and Langlois, 2000; Santamaria et al., 2004a). Belgian, Finnish and Norwegian WB studbooks follow a similar, competition-based structure (Bruns et al., 2001, cited by Thorén Hellsten et al., 2006) where horses undergo the first selection process after they have competed in a series of age-specific classes or special competition series, such as the “Cycle Classique”, which is employed by the Selle Francais studbook (Barrey and Langlois, 2000; Thorén Hellsten et al., 2006). However, this evaluation method exhibits disadvantages, as it is limited to the evaluation of older horses, which have already undergone sufficient training in order to compete in young horse competitions. This is especially relevant in SJ horses, which are generally not sufficiently conditioned or trained for competition until approximately 6 years of age (Santamaria et al., 2006). By this time, breeders and trainers have already invested significant time and finances into the preparation of these horses (Santamaria et al., 2004b). Furthermore, performance recognition at more advanced levels has also been associated with an increase in the length of generation interval, which slows genetic improvement (Thorén Hellsten et al., 2006; Whitaker, 2006)

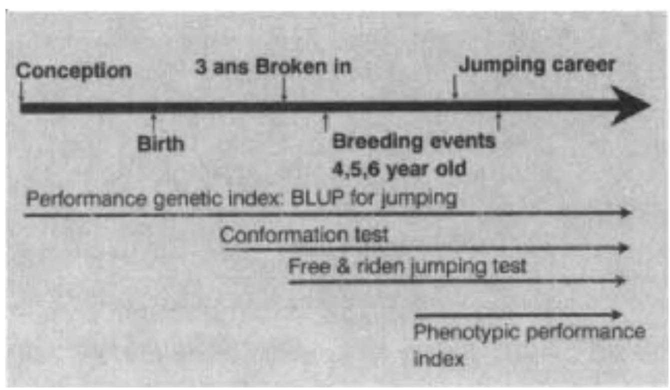


Figure 2.1 General timescale for the selection process of jumping horses across European warmblood studbooks (Barrey and Langlois, 2000).

Other studbooks, including the majority of German WB breeds, are selected based on the evaluation of several traits outlined by the studbook, which is conducted during performance testing at the age of 3 and 4 for stallions and mares. Performance testing is conducted using field or station testing format. Station tests are employed in most countries where stallions aged between 3 and 4 are trained at station, typically a state-owned stud, for 70-100 days, which ensures that all horses are trained in a standardised environment (Koenen and Aldridge, 2002; Thorén Hellsten et al., 2006). However, the duration of station tests can vary significantly, for example Great Britain conducts station testing over an 8-day period for both sexes (Koenen and Aldridge, 2002; Thorén Hellsten et al., 2006). Station tests for mares are held by certain breeding organisations and typically last 14-50 days (Thorén Hellsten et al., 2006). The field-testing format is employed by many breed organisations, but consists of only one day of testing for both sexes (Thorén Hellsten et al., 2006). A summary of the young horse testing procedures employed by major European countries producing sport horses is provided by Thorén Hellsen et al. (2006) and Koenen and Aldridge (2002).

Performance testing is conducted by external judges and riders/ trainers who subjectively evaluate horses based on specific traits, including: rideabilty, free jumping, ridden jumping, walk, trot, gallop and cross country manner (Barry and Langlois, 2000; Santamaria et al., 2004a). If approved, horses are genetically evaluated based on competition performance records following performance testing.

2.4.2. The subjective evaluation of "quality" movement for selection

Performance testing of young sport horses in Europe is essential for selecting horses that will fulfil the breeding goals of the studbook (Koenen et al., 2004; Becker et al., 2012). High performance levels of WB horses in modern competition provide evidence for the effectiveness the selection and breeding processes employed by European breed organisations (Back et al., 1994). However, although the traits evaluated in performance tests are generally well established and accepted amongst the equestrian industry, the evaluation process is inherently subjective (Thorén Hellsen et al., 2006).

Studies have shown that visual evaluation performed by studbook judges shows moderate to strong correlation with successful performance later in life (Ducro et al., 2007a, b; Wallin et al., 2003; Thorén Hellsen et al., 2006). However, previous studies have reported poor to moderate reliability and agreement scores for the subjective judgement of equine movement in competition (Hawson et al., 2010; Stachurska 2006; Stachurska and Bartyzel, 2011) and in lameness examinations (Keegan et al., 1998; Keegan et al., 2010; Hewston et al., 2006). These studies should therefore be considered when reviewing the subjective selection of horses, as similar deficiencies in inter-assessor reliability may be present in the selection processes of studbook judges.

Visual evaluation of movement is not only dependent on the subjective criteria of each judge, but also on the limitations of the human eye for registering subtle alterations in movement and jump technique (Holmström et al. 1994a; Schamhardt et al. 1993b; Dyson, 2011). Qualitative evaluation of gait by the human eye relies on the brain to draw on previous experiences to process visual information and to form an opinion on motion (Clayton and Schamhardt, 2013). Subjective evaluation of lameness through observation of the horse in motion is a standard of practice for veterinarians (Fuller et al., 2006; Keegan et al., 1998, 2010; Dyson, 2011). However, studies evaluating subjective lameness scoring between experienced equine veterinarians have reported “moderate” reliability (Hewston et al., 2006), with inter-assessor agreement between evaluators being “marginally acceptable” (Keegan et al., 2010) or “just above acceptable limits” (Fuller et al., 2006).

A notable study by Keegan et al (1998) investigated correlation between subjectively assessed change in clinical lameness score and objectively measured changes in kinematic variables following palmar digital nerve block (PDNB) administration. Video recordings of horses trotting on a treadmill were shown to veterinarians of varying experience for subjective lameness evaluation. Poor between-observer agreement for change in lameness score following PDNB administration was found and did not permit definitive correlations to be drawn between change in kinematic variables and subjective lameness score (Keegan et al., 1998). However, symmetry of vertical displacement of poll and time of maximum vertical hoof displacement during swing were found to be correlated with subjective change in lameness score following PDNB (Keegan et al., 1998). These findings suggest that quantifiable gait characteristics could be applied in practice to increase objectivity in lameness evaluation. Methodological limitations in the study by Keegan et al (1998) were highlighted as factors that may have influenced poor between-observer agreement and included: lack of audio in videotapes, variations in experience level between veterinarians, and lack of observer experience and knowledge of treadmill-induced gait alterations (Butchner et al., 1994). Thus, a later study allowed veterinarians to perform full lameness evaluations in horses moving over-ground and reported slight improvement in between-observer agreement scores compared to those from Keegan et al. (1998). However, the low between-observer agreement scores reported by both studies for evaluating mild lameness were disappointing (Keegan et al., 1998, 2010). These findings prompted Keegan et al. (2010) to state that current subjective evaluation practices are not acceptable for cases of mild lameness and the development of objective methods for lameness detection are warranted.

Keegan et al. (1998, 2010) attribute differences in agreement for subjective lameness scoring to limitations in temporal and spatial visual acuity between evaluators. Estimated temporal resolution of the human eye has been reported between 4-25Hz and is dependent on task, object size, stimulus, and luminance level (Hess and Plant, 1985; Verstraten et al., 2000; Näsänen et al., 2006). Keegan et al. (2010) suggest that the human eye just achieves the sampling rate required to evaluate equine movement at trotting speeds of 4m/s. However, the human eye is unlikely to meet the temporal resolution required to detect subtle movement asymmetries at faster speeds (Keegan et al., 2010). The lack of reliability and agreement for the subjective scoring of lameness justifies the incorporation of objective methods (i.e. inertial sensors, kinematic motion analysis systems) into equine lameness exams, which would benefit equine practitioners (Keegen et al., 1998, 2010).

A similar trend for inter-assessor agreement has been observed in the subjective scoring methods for movement and aesthetics awarded by dressage judges (Stachurska 2006; Stachurska and Bartyzel, 2011; Hawson et al., 2010). Research has revealed disagreement and limited reliability between judges scoring at international dressage competitions (Stachurska 2006), including Grand Prix classes at two Olympic games (Hawson et al., 2010; Stachurska and Bartyzel, 2011). These findings further highlight the advantages of implementing objective motion analysis technology into the evaluation of equine movement (Peham et al., 2001). The accuracy of subjective scoring in dressage is especially relevant from a breeding perspective, as performance will have a significant influence on determining the breeding value of a dressage horse. This is especially relevant in breeding organisations whose selection processes rely solely on annual competition performance (i.e. Selle Francais). However, few studies have validated subjective movement scoring against quantitative movement analysis technology.

2.4.3 Implementation of objective movement analysis into the subjective selection process

Researchers have provided recommendations for the improvement of performance testing criteria including: placing more weight on rider/ trainer scores (Deitl et al., 2005), the inclusion of additional traits linked to balance (Becker et al., 2012) and generating standardised estimated breeding values across studbooks (Koenen and Aldridge, 2002). Objective kinematic motion analysis technology has also been described as a useful tool for providing additional quantitative information for the subjective evaluation of movement (Santamaria et al., 2006; Clayton and Schamhardt, 2013). An early study by Langlois (1990 cited by Holmström et al., 1993) reported poor correlation between SJ competition results and expert evaluation of free jump technique, stating that judgments could more effectively characterise movement traits using an objective "photographic method". Most authors stress that kinematic measurement techniques should supplement existing subjective evaluation methods and should not fully replace the opinions of experienced human judges (Barrey and Langlois, 2000; Santamaria et al., 2006). However, despite these suggestions, little research has been conducted to evaluate how kinematic variables correlate with subjectively judged traits, which dictate the quality of movement.

Back et al. (1994) identified objective kinematic gait variables, which correlated with Dutch Warmblood judging criteria at the trot. Linear and temporal kinematics and sagittal plane joint angle data were collected from horses trotting on treadmill using active photodiode markers. Quantitative data were correlated with trot quality, as subjectively scored by a judge, which was based on stride length, strength and suppleness criteria outlined by the studbook (KWPN) (Back et al., 1994). Measured kinematic variables were found to be highly correlated with subjective gait score of the judge, with FL stride duration, scapula rotation and maximum fetlock extension being independently responsible for variation in the subjective scores (Back et al., 1994). These three kinematic variables were also significantly correlated with subjective variables: stride length, strength and suppleness, respectively, providing objective criteria for the quantification of subjective equestrian terminology (Back et al., 1994).

Holmström et al. (1994) conducted a similar investigation to evaluate the relationship between gait scores and kinematic variables for Swedish horses grouped as “good” and “poor” at the trot. Holmström et al. (1994) reported increased stride duration, increased FL swing phase retraction, and greater tarsal and metatarsophalangeal joint (MTPJ) extension as kinematic variables, which were indicative of horses judged as exhibiting “good” quality trot. These findings are in accordance with Back et al. (1994). To the author’s knowledge, no studies have investigated the relationship between kinematic measurements and subjective variables used to evaluate quality movement during canter. This represents a gap in knowledge for evaluation of movement in the jumping horse, as canter represents the gait employed during competition (Clayton 1991; 1996a) and has been described as the most important gait for a SJ horse (Palmaan, 1978). Furthermore, research has determined that canter is the only trait evaluated during performance testing, which is highly correlated with future performance in both dressage and SJ (Wallin et al., 2003). Further research is therefore required to investigate whether desired movement traits in canter can be quantitatively measured using motion analysis technology to inform current subjective evaluation methods.

To the author’s knowledge, only one study has evaluated agreement between subjective performance testing scores for jumping and quantitative measurements of movement traits using motion analysis technology (Lewczuk, 2013). In this study, WB stallions (*n*=32) that had completed 100 days at station, were filmed during free jumping trials at performance evaluation. Videographic data were digitised and linear kinematic variables were calculated based on free jumping traits described in subjective evaluation criteria. Linear kinematics were analysed in relation to judges scores for each trait. Inter-rater repeatability of judges was found to be within acceptable limits, while agreement between judges was only within acceptable limits for certain traits, implying that judges may interpret trait definitions differently (Lewczuk, 2013). Correlations between subjective scoring values and kinematic parameters varied between low and middle-high, but highlighted that judges display a preference for distance of landing, elevation of the body and FL lifting traits (Lewczuk, 2013). However, the methods employed for this study may have affected the validity of results and findings must therefore be considered with caution. For example, data analysis was limited to investigating linear kinematics, which does not provide a thorough depiction of the movement traits for free jumping criteria outlined in the study (i.e. FL joint flexion during jump suspension). Furthermore, horses were described as executing fences ranging from 0.90-1.20 m in height, but the authors do not specify whether jump height was included as a factor in their statistical analysis. Jump height has been found to influence kinetic and kinematic variables (Clayton and Barlow, 1989; Schamhardt et al., 1993; Bobbert and Santamaria, 2005; Powers, 2005; Lewczuk et al., 2007), suggesting that non-standardized fence heights may have affected direct comparisons of kinematic and judged scores between horses. Further research in this area is required to determine the reliability of judge's scores on actual jump technique in the equine athlete.

Barrey and Langlois (2000) state "a trait, which is evaluated qualitatively by an expert, is less heritable than the same trait measured quantitatively". This statement was used to describe the advantages of incorporating quantitative gait analysis into subjective movement evaluation for improved scoring efficacy, which may facilitate early evaluation of jumping ability (Barrey and Langlois, 2000). These authors also state that gait analysis technology should act in addition to subjective scoring, as traits such as rideabilty and character can only be evaluated by experienced expert judges. However, the lack of research examining the application of objective motion analysis technology for subjective evaluation of quality movement during canter and jump, represents a major gap in knowledge for the SJ horse and is an area requiring further investigation.

2.4.4 Selection methods employed by equestrians

As previously stated, the traits that are subjectively evaluated in performance testing are widely accepted within the equestrian industry as being clear and unambiguous. However, equestrians are not restricted to predefined criteria when evaluating prospective equine athletes, and will incorporate on their own preferences during the selection process. It is likely that the traits outlined by studbooks will influence the anecdotal selection process of the general equestrian. However, to the author's knowledge no study has explicitly investigated the personal preferences of experienced equestrians when evaluating quality movement. The definition of "quality" movement is subjective and may differ between experts (Back et al., 1994; Clayton and van Weeren, 2013) and many influential equestrian authors have described what comprises quality movement in the jumping horse, based on their preferences and experiences. For example: Palmaan (1978) emphasises a “loose, free movement” which is ground covering and shows “great mobility”. A “quality” canter is anecdotally described as a “light, bouncing” stride with natural balance (Palmaan, 1978).

Although movement has a significant influence on the selection process of future performance horses, several factors are also known to influence performance in the jumping horse (Williams, 2013). The jumping ability of a horse is a complex trait, which is multi-factorial in nature (Barrey and Langlois, 2000). Various characteristics, including: inherent talent, conformation, reactivity and willingness are generally accepted contributors to the jumping ability of an individual horse. As a result, research has investigated the effects of personality (Visser et al., 2003) and conformation (de Godoi et al., 2016) in relation to jumping ability and performance in SJ. To the authors knowledge, no studies have incorporated the preferred traits and selection criteria employed by equestrians outside of breeding organizations. This represents an important gap in knowledge, as integration of this information may help to increase the external validity of equine biomechanics studies.

2.5 Practical application of objective training and selection methods for the showjumping horse

The preceding sections have demonstrated the subjective nature of training, evaluation of quality movement and selection methods for the equine jumping athlete. Equine researchers have emphasised the need for collaboration between scientists and industry professionals to progress equestrian training and management practices towards a more scientifically-evidenced state, as has been done in human athletics (Rivero, 2007; van Weeren, 2008; Winfield 2010). In comparison to race times achieved by human athletes, the racehorse has not exhibited marked improvements in recent decades (Gaffey and Cunningham, 1988; Rose and Evans, 1990; Smith et al., 1999). This has been attributed to training methods that have not been scientifically developed to maximize performance (Gaffey and Cunningham, 1988; Rose and Evans, 1990; Smith et al., 1999). Deeply rooted traditionalism in equestrian training has also been described in sport horse disciplines like dressage (van Weeren, 2008), further highlighting the need to bridge the intrinsic gap between equine researchers and industry professionals. As described in Section 2.3.3, extensive literature has examined and described physiological adaptations to exercise in the equine athlete, with some researchers using this information to offer suggestions for sport-specific training programmes. Despite this, scientific approaches to training are not widely adopted amongst current equestrians, which has been attributed to: lack of knowledge transfer, minimal scientific background, difficulties associated with interpreting scientific research and low external validity of conditioning programmes (Rogers et al, 2007; Rivero, 2007, Winfield, 2010).

The inherently subjective nature of equine movement evaluation and selection processes has lead researchers to propose integration of quantitative movement analysis into current practice. Objective gait analysis has increased understanding of equine locomotion, especially where limitations of the human eye impede observation of subtleties in movement (Barrey, 1999; van Weeren, 2008). Still, gait analysis technology has not been widely adopted in practice, which has been associated with the high cost of obtaining equipment, the tedious nature of data collection and analysis, and the unique skill set required for use (van Weeren, 2008). Biomechanics research has evaluated the equine jump technique, which is described in Section 2.6. These studies have been conducted to understand the movement required to execute the jump, but also to refine subjective selection processes by defining biomechanical traits that may be used to predict performance (i.e. Barrey and Galloux, 1997; Powers and Harrison, 2000; Bobbert et al., 2005; Powers, 2005; Santamaria et al., 2004a, b, 2005, 2006). Muscular adaptation to training has been directly linked to the movements executed during exercise (Rivero and Letelier, 2000), highlighting how a combined knowledge of biomechanics and muscular adaptation to training may help inform current anecdotal training methods. However, for science to be applied in equestrian practice, research must be relevant to the industry professional. Researchers must therefore put forth a collaborative effort to incorporate the tacit knowledge, opinions and preferences of equestrians into research (Winfield, 2010). Communication with equestrians via questionnaires and focus groups may be appropriate for gathering information, which may be used to tailor research to questions that are relevant in industry practice.

2.6 Biomechanics of the equine jump technique

Biomechanical consideration of the equine jump technique is essential for a comprehensive understanding of the physical and physiological demands placed on the sports horse. This is especially relevant in the SJ horse, as mechanical laws govern the trajectory of the horse's centre of mass (CM) and trunk rotation during jump suspension, which are known to determine the success of the jumping effort (Clayton, 1994a, Barrey and Galloux, 1997). Investigation of the equine jump technique dates back to the work of Eadweard Muybridge, who revolutionized equine gait analysis using photography in the 19th century. Muybridge's photographic documentation of locomotion in animals and human transformed modern gait analysis and his 1887 publication, Animal Locomotion, included plates of the equine jumping effort (Figure 2.2). Since then, many researchers have recognised the role of biomechanics for understanding specific variables that may indicate the effectiveness and performance potential of horses for jumping (Bogert et al., 1994; Cassiat et al., 2004; Santamaria et al., 2002, 2004a, b, 2005, 2006; Bobbert et al., 2005). This is a particular area of interest for equine biomechanists and numerous studies have been conducted to kinematically and kinetically evaluate the equine jump technique.

Figure 2.2 Eadward Muybridge's photographic examination of the equine jumping effort. Plate 640 "Daisy" jumping a hurdle, saddled (1887). (Adapted from: Muybridge, 1979).

2.6.1 Kinematic measurement technique

Early biomechanics research focused on the linear and temporal kinematics of hoof placement during the equine jump under experimental (Clayton and Barlow, 1989, 1991) and competition conditions (Leach et al., 1984; Deuel and Park, 1991; Barrey et al., 1993; Clayton et al., 1996b). These early studies were followed by research evaluating joint angles within the sagittal plane during jumping (Bogert et al., 1994; Clayton et al., 1995; Powers and Harrison, 2000; Cassiat et al., 2004; Powers 2005). These studies have provided valuable information related to jump technique, but were limited to analysis of two-dimensional (2D) kinematic data, collected using high-speed videography. Analysis of 2D data poses several limitations in comparison to three-dimensional (3D) data, which is currently the preferred method for gait analysis. Firstly, 2D angular data are limited to one degree of freedom (DOF) for joint rotation within the sagittal plane or frontal plane

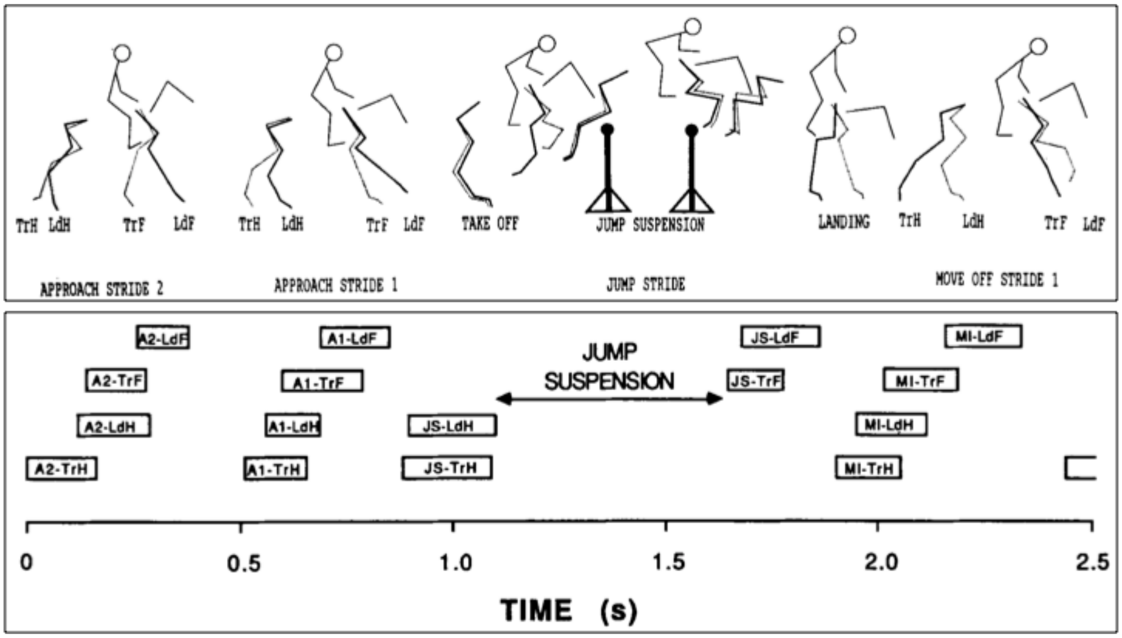
(Richards et al., 2008a; Clayton and Schamhardt, 2013). 2D data are also prone to parallax error and perspective error that occur when subjects move away from the optical axis of the camera or out of the calibrated plane, respectively (McClure et al. 2001; Sih et al., 2001; Stevens et al., 2006; Nielson and Daugaard, 2008; Kirtley, 2006). These errors are more common in studies that employ a single video camera for data collection, as many equine jumping studies have done (Barrey et al., 1993; Bogert et al., 1994; Clayton et al., 1995, 1996b; Colborne et al., 1995; Powers and Harrison, 2000). Parallax and perspective error can be minimized by orienting and calibrating the camera precisely so that its axis is perpendicular to the plane of movement (Richards et al., 2008a; Clayton and Schamhardt, 2013), however the inherent risks cannot be fully mitigated. Correction algorithms for both errors have been described (i.e. Drevemo and Johnson, 1994; Sih et al., 2001; Stevens et al., 2006) However, Sih et al (2001) state that these corrections are often overlooked in literature. Single camera studies are also generally limited to a small field of view unless panning techniques are used, which introduce further errors, unless corrected for appropriately (Drevemo and Johnson, 1994).

As previously stated, several equine kinematics studies have collected 2D kinematic data during competition (Leach et al., 1984; Deuel and Park, 1991; Barrey et al., 1993; Bogert et al., 1994; Clayton et al., 1995, 1996b). Although these studies have had the advantage of collecting data from elite equine athletes, data collection during competition does not permit the use of kinematic markers. Digitization of these data therefore involves manual tracking or marker-less tracking programs, which are based on pattern recognition software that locates and tracks an area of interest (Clayton and Schamhardt, 2013). However, the process of manual tracking videographic images is not only tedious, but is prone to sources of error, most notably: digitizer (observer) error, calibration error, marker error or artefact error (Schamhardt et al., 1993b; Wilson et al., 1999). Manual tracking is also associated with greater digitizing noise than automated systems (Clayton and Schamhardt, 2013).

More recently, research has employed three-dimensional (3D) kinematic data to examine the biomechanical demands of the equine jump technique (Santamaria et al., 2002, 2004a, b, 2005, 2006; Bobbert et al., 2005; Bobbert and Santamaria, 2005). 3D kinematic data acquisition systems mitigate many of the disadvantages associated with 2D data collected using videography (Richards et al., 2008a). Limitations related to camera positioning are not as detrimental for the accuracy of 3D kinematic data, as multiple cameras are synchronized to create a capture volume and laboratory coordinate system (LCS). As a result, subjects are not restricted to movement within the plane of calibration and accuracy is not compromised, as long as each marker is visible to at least two cameras at all times (Clayton and Schamhardt, 2013). 3D kinematic analysis software allows the researcher to construct a 3D segment coordinate system (SCS), which are discussed in greater detail in Chapter 4, but permit analysis of segment and joint kinematics in six DOF. Kinematic data allow the researcher to explore the full range of motion (ROM) and orientation of segments and joints within 3D space, providing a more comprehensive model of the equine jump technique. However, fewer studies have investigated the equine jump technique using 3D techniques, highlighting the need for further research in this area. Techniques for acquisition and analysis of 3D kinematic data are discussed in greater detail in Chapters 4 and 6.

2.6.2 Biomechanical evaluation of the equine jump technique

Standardised terminology for the description of equine jumping kinematics has been described by Clayton (1989). Normal equine locomotion is a cyclic event; where a stride represents a full motion cycle and is generally defined as consecutive impacts of the trailing HL (TrH) (Leach et al., 1984a; Clayton, 1989). The jump technique can be divided into the approach strides, jump stride and move-off strides, which retain the convention of employing TrH impact to define the start and end of each stride (Clayton, 1989). The highly specialised jump stride is characterised by an extended suspension phase and can be further subdivided into take-off, jump suspension and landing phases (Clayton, 1989). Figure 2.3 illustrates the terminology and temporal data that are used to describe the approach, jump and move-off strides. This terminology has been employed by studies evaluating the equine jump technique and will be used to systematically describe and review the literature relating to specific phases of the jump stride.



a. b.

Figure 2.3 a) illustration of terminology and footfall patterns used to describe the equine jump technique, b) temporal data for approach, jump and move-off strides of a horse jumping a 1.55m vertical fence. (Adapted from Clayton, 1989).

2.6.2(i) The Approach Stride

The strides preceding the jump stride are referred to as approach strides and are labelled chronologically as: A3, A2, A1, with A1 representing the final stride before the jump (Clayton, 1989). The horse generally approaches the fence in canter (Clayton, 1989, 1994a; Powers and Harrison, 1999), in which the sequence of limb placements is: TrH, leading HL (LdH) and trailing FL (TrF) synchronously, and leading FL (LdF). It is generally accepted that the stance phases of the LdH and TrF, which represent the diagonal limb pair, occur synchronously. However, studies have shown that slight dissociation of stance phase often occurs (Deuel and Park, 1990; Clayton, 1993, 1994b).

Approach strides are responsible for generating appropriate conditions for take-off, including optimal velocity, angular momentum and body position (Powers and Harrison, 1999). Velocity is adjusted by altering stride length to ensure that the take-off phase is executed from an appropriate position based on fence height and width (Clayton, 1989, 1994a). Approach strides preceding and including A2 are generally executed in a normal three-beat collected canter, with marked elevation of the head and neck observed (Clayton and Barlow, 1991). In a study of four grand prix jumping horses executing a 1.55 m fence, the average horizontal velocity of the A2 stride was 7.3 m/s, which was significantly faster than any other stride in the jumping effort (Clayton and Barlow, 1991).

More experienced jumping horses can execute approach strides at a faster horizontal velocity, due to their increased strength and trained motor skills, which allow them to convert horizontal velocity to vertical velocity more efficiently at take-off (Barrey and Galloux, 1997).

Kinematic alterations to the normal canter stride are apparent during A1, which has been compared to the “gather stride” of human jumping athletes (Clayton and Barlow, 1991), where the transition from approach to take-off elicits a shortened stride and lowered CM (Kelso, 2014). In human high jumpers, the height of CM and vertical velocity at take-off are the main determinants for the height of the trajectory (Hay, 1993; Dapena, 2000; Grieg, and Yeadon, 2000; Isolehto et al., 2007). The most important factor related to the vertical velocity experienced during take-off is the lowering of the CM prior to take-off (Hay, 1993; Dapena, 2000; Isolehto et al., 2007). The “gather” technique is observed in the horse during A1 as the head and neck are stretched forward and lowered, allowing the horse to lower its CM prior to the initiation of upward movement (Clayton and Barlow, 1991; Clayton, 1994a). Significant decreases in stride duration and horizontal velocity have been observed in A1 compared to preceding approach strides (Clayton and Barlow, 1991). The three-beat canter is modified to a distinct four-beat rhythm as the LdH/ TrF diagonal pair is dissociated during deceleration in A1 (Clayton and Barlow, 1991; Clayton 1994a). The deceleration observed during A1 is produced by the FL as they impact the ground with a significantly more acute angle between the palmar aspect of the metacarpus and the ground (Clayton and Barlow, 1991). The strutting action of the FL produces retardatory and vertical forces, which initiate the upward impulse prior to take-off (Schamhardt et al., 1993a).

It has been speculated that the FL behaves like a pole-vaulter’s pole (Leach and Ormond, 1984) or as a pogo stick (Wilson et al., 2001) during A1. These analogies were explored by Bobbert and Santamaria (2005) and are based on the idea that kinetic energy is initially stored in FL tendons and subsequently released during push-off at A1 to create kinetic and potential energy. For these analogies to accurately describe the mechanical energy changes experienced by the FL at lift off, both limbs would have to store approximately 1900 J to account for storage of all energy lost (Bobbert and Santamaria, 2005). Using the segmental model described by McGuigan and Wilson (2003), Bobbert and Santamaria (2005) estimated that the average energy stored by the distal springs (limb below the elbow joint to digit) of both FL was only about 400 J, based on shortening of the distal spring. This underestimation of energy storage for jumping reveals that the predominantly muscular component of the proximal spring dissipates more energy than it stores due to the eccentric activity of muscles, such as the Triceps Brachii. The pogo stick analogy may therefore only be partially true for the push-off of the FL during A1, as concentric contraction of proximal spring muscles will be necessary to generate the energy lost through energy dissipation during FL push-off (Bobbert and Santamaria, 2005). The FL are therefore not entirely utilised as proposed passive springs, which highlights energetic demands of FL push-off (Bobbert and Sanatmaria, 2005). This finding is in accordance with Santamaria et al (2004a), who found no relationship between horizontal velocity of the CM at FL impact and vertical velocity of the CM following FL lift-off, indicating that greater vertical velocity of the CM is not explicitly explained by the pole-vault mechanism. Instead greater vertical velocity of the CM at FL lift-off was more attributed to greater vertical force and power production (Santamaria et al., 2004a).

A key study by Schamhardt et al. (1993a) investigated the GRF patterns of the FL and HL during jumping. During FL stance phase in A1, the TrF produces little propulsion and is principally used to raise the CM, experiencing greater vertical force than the LdF (Schamhardt et al., 1993a). The FL show decreased stance duration during A1 in comparison with other approach strides, with the LdF exhibiting shorter stance duration than the TrF (Clayton and Barlow, 1991). The LdF exhibits mainly retardatory forces due to its shorter stance phase (Schamhardt et al., 1993a). Following lift-off of the FL, the head and neck are elevated to allow the HL to swing underneath the body for optimal power production during take-off phase (Galloux and Barrey, 1997).

2.6.2(ii) Take-off Phase

The jump stride begins with the take-off phase, which is demarcated by impact of the TrH and ends with lift-off of both HL (Clayton, 1989). This phase essentially comprises the stance phases of both HL, which generally impact the ground synchronously (Leach and Ormond, 1984; Clayton and Barlow, 1989; Bobbert and Santamaria, 2005). Longer HL stance phase has been observed at take-off and is associated with the generation of greater impulse (Leach et al., 1984b; Clayton and Barlow, 1989, 1991; Schamhardt et al., 1993a). It is generally accepted that the vertical impulse generated by the HL at take-off is the major factor determining the trajectory of the CM and angular momentum experienced during the jump suspension (Clayton and Barlow, 1991; Bogert et al., 1994; Barrey and Galloux, 1997; Galloux and Barrey, 1997; Santamaria et al., 2004a; Bobbert et al., 2005). The height and vertical velocity of the CM at take-off represent the main factors which determine the success of the jumping effort, highlighting why take-off is generally considered to be the most important phase of the jump stride (Clayton and Barlow, 1991; Clayton et al., 1996b; Galloux and Barrey, 1997; Powers, 2005).

Vertical velocity at take-off is measured as the sum of force produced and the time over which it is applied (Powers and Harrison, 1999). A horse's jumping capacity is therefore determined by vertical impulse at take-off, which is influenced by approach speed, stance duration and muscular force production (Powers and Harrison, 1999). The importance of the HL for power production been supported by studies that have reported peak power output at take-off between 30 W/kg and approximately 100 W/kg (Bogert et al., 1994, Dutto et al., 2004; Bobbert and Santamaria, 2005), with fence height being a large determinant for the amount of power produced (Bobbert and Santamaria, 2005). The importance of the external forces produced at take-off were further supported by Schamhardt et al. (1993a), who reported predominantly propulsory forces in the HL, which were 3-5x greater than those observed in a normal canter. In contrast to the FL, the HL exhibits minimal retardatory forces at take-off and experiences greater vertical GRF amplitude and impulse, which are estimated to be approximately 40% greater at take-off than during a normal canter stride (Schamhardt et al., 1993a). It has also been reported that limb placement at take-off is not affected by fence type or height, suggesting that the horse is more likely to adjust CM trajectory or vertical impulsion, which further justifies the importance of this phase (Clayton and Barlow, 1989).

At take-off, positive work performed by the HL is related to the increase in total limb length from hoof impact and lift-off (Bobbert and Santamaria, 2005). At the beginning of HL stance, the limbs are shortened as HL joints experience flexion under the control of extensor musculature, which contract eccentrically to counteract external forces (Clayton, 1989; Bogert et al., 1994; Dutto et al., 2004; Bobbert and Santamaria, 2005; Denoix, 2014). Thus, the HL has been reported to absorb energy (or create net negative power) during the initial 40% of stance (Dutto et al., 2004). During this phase, energy is absorbed by active and passive elements of the muscle-tendon units (Denoix, 2014). In the second half of stance phase, power is generated as all HL joints are extended, which is aided by concentric contraction of extensor musculature and the release of elastic energy that was stored during limb loading (Clayton, 1989; Bogert et al., 1994; Bobbert and Santamaria, 2005; Denoix, 2014). Bobbert and Santamaria (2005) found that the GRF vector passed between all joints in the latter half of HL stance, indicating that all HL joints contributed to positive work and power production. This contrasts with Dutto et al. (2004), who reported that the stifle joint produced less positive work than the hip, tarsal and metatarsophalangeal joints (MTPJ) during the latter half of stance. These differences may be due to differences in data analysis techniques or differences in fence height, as 0.65 m and 1.10 m fences were employed by Dutto et al. (2004) and Bobbert and Santamaria (2005), respectively.

Kinematic and kinetic studies have revealed that the mechanical energy required to execute the jump is mostly produced by HL muscles during take-off (Bogert et al., 1994; Barrey and Galloux, 1997; Galloux and Barrey, 1997; Dutto et al., 2004; Bobbert and Santamaria, 2005). However, the contribution of stored elastic energy to HL push-off is not fully understood and further work is required to examine its contribution to power production (Bogert et al., 1999). Furthermore, studies have made inferences regarding muscle function during take-off (Bogert et al., 1994; Dutto et al., 2004; Bobbert and Santamaria, 2005), but further work is required to objectively evaluate muscle activity using electromyography (EMG) (Bobbert and Santamaria, 2005). This information will permit further understanding of the complex mechanisms involved in producing mechanical energy at take-off.

2.6.2(iii) Jump Suspension

The jump suspension phase is defined as the time the horse is airborne between lift-off of the TrH at take-off and impact of the TrF at landing (Clayton, 1989). During jump suspension, the horse and rider move as projectiles and alterations to CM trajectory are not possible, further demonstrating the importance of the take-off phase (Powers and Harrison, 1999). As previously stated in Section 2.6.2(ii), the angular momentum established at take-off allows the horse to rotate forward around the CM during jump suspension (Clayton and Barlow, 1991; Galloux and Barrey, 1997; Powers and Harrison, 1999). To the author's knowledge, only one study has examined angular momentum around the CM during jump suspension, reporting that segments of the trunk, FL, HL, and head-neck act in synergy to favour forward rotation around the CM (Galloux and Barrey, 1997). However, little is known about how the rider may influence angular momentum around the CM during suspension and further work is required in this area (Powers and Harrison, 1999).

During jump suspension, the FL and HL joints are initially flexed as the horse passes over the fence and are then extended in preparation for landing (Clayton, 1989). During this phase, differences in technique and style are apparent between horses (Clayton, 1989; Denoix, 2014). As an example, equestrians and studbooks generally exhibit a preference for horses that exhibit "bascule" and flexed FL joints during jump suspension to avoid knockdowns (Cassiat et al., 2004; Lewczuk, 2008; 2013). These stylistic preferences are discussed in greater detail in Section 6.3. It has been postulated that minimal muscular effort is required during jump suspension (Denoix, 2014), however research is required to confirm these claims.

2.6.2(iv) Landing Phase

The landing phase begins with impact of the TrF following jump suspension and continues until impact of the TrH (Clayton, 1989). This phase is essentially comprised of both FL stance phases and is responsible for re-establishing balance by reversing the forward momentum around the CM

(Clayton, 1989; Clayton and Barlow, 1989, 1991; Galloux and Barrey, 1997). This is achieved as the FL absorb load during stance, generating a force vector that is oriented ahead of the CM, which reverses angular momentum and allows the HL to swing underneath the trunk (Clayton and Barlow, 1991). At landing, the FL function asymmetrically. The TrF impacts the ground first at an almost vertical orientation with a metacarpal angle of approximately 89° in relation to the horizontal (Clayton and Barlow, 1991). The LdF impacts the ground further away from the fence than the TrH at a more acute orientation, with a metacarpal angle of approximately 68° (Leach et al, 1984a; Clayton and Barlow, 1991; Hernlund et al., 2010).

Kinematic differences between limbs are related to differences in limb loading patterns. The TrF experiences little, if any, horizontal velocity at impact (Hernlund et al., 2010), which is in accordance with Schamhardt et al. (1993a) who reported minimal retardatory forces. The TrF also experiences the greatest loading of all limbs at landing, with vertical GRF values as high as twice the horse's body weight recorded over a 1.30 m fence (Schamhardt et al., 1993a). Unsurprisingly, this limb also exhibits greater MCPJ extension (Clayton, 1997) and flexor joint moment than the LdF (Meershoek et al., 2001b). The LdF experiences a longer stance and single support phase and therefore greater vertical impulse than the TrF (Leach et al, 1984a; Schamhardt et al., 1993a). The reader is directed to Section 2.3.4 for a discussion regarding injury risks associated with limb loading during landing. To the author's knowledge, no studies have examined the energetic contribution or muscle activation patterns observed in the FL during landing phase.

2.6.2(v) Move-off and Intermediate Strides

The move-off strides follow the landing phase and begin at the first impact of the TrH after the fence (Clayton, 1989). In accordance with approach strides, these strides are named in chronological order following the fence as M1, M2, and so forth (Clayton, 1989). The M1 stride plays an important role for regaining balance and forward momentum (Clayton, 1989; Clayton and Barlow, 1991). Few studies have described the biomechanics of the move-off strides, which represents an area for further research, as these strides represent an important consideration for course design (Clayton and Barlow, 1989; Hole et al., 2002).

Following FL impact at landing, flexion of the hip and lumbosacral joints and thorocolumbar junctions work to bring the HL underneath the trunk in preparation for impact (Denoix, 2014). After impact of the TrH, both HL are loaded in accordance with the description provided in Section 2.6.2(ii), with strong concentric contractions working to re-establish propulsion and forward momentum (Denoix, 2014). However, propulsory forces have been found to differ between HL, as

GRF data for the TrH revealed greater propulsory forces at M1 to re-establish velocity (Schamhardt et al., 1993a). This is in contrast to the LdH, which exhibits longitudinal and vertical forces that are comparable to those observed at canter (Schamhardt et al., 1993a). It has been reported that stride length for M1 is significantly shorter than A1 (Clayton and Barlow, 1991), with TrH impact consistently occurring closer to the fence than LdF (Clayton and Barlow, 1989; Santamaria et al., 2002). The M1 stride has a four-beat rhythm, due to dissociation of the diagonal limb pair, however normal limb placements are generally established by M2 stride (Clayton and Barlow, 1989).

Strides within a jump combination, which is defined as two or more fences with three strides or less between them, are referred to as intermediate strides (Clayton, 1989). To the author's knowledge, only one study has examined the kinematics of the intermediate stride. Hole et al. (2002) kinematically analysed the strides within a two-stride combination, reporting that intermediate stride two (IM2) exhibited significantly greater stride length and duration than intermediate stride one (IM1) with no significant differences observed for stride velocity. Differences in linear and temporal kinematics reveal that IM2 and IM1 behave as A1 and M1 strides, respectively (Hole et al., 2002). These findings reveal how the horse may adjust its stride between fences to execute related distances, which may have implications for course designers who generally assume that intermediate strides are equal in length (Hole et al., 2002).

2.6.3 Biomechanical indicators of performance in the SJ horse

Jump technique in young horses has been linked to performance in SJ competition later in life (Wallin et al., 2003), which is in accordance with kinematic studies on the jumping horse. Research has revealed similarities between linear and temporal kinematics collected from 6-month-old foals during submaximal free jumping and jump technique expressed by mature horses (Santamaria et al., 2002). In a similar study, Santamaria et al (2004b) observed consistent jump technique in horses, which were kinematically measured at 6 months and 4 years of age, reporting high correlation in: vertical acceleration of CM at take-off, vertical displacement of CM during jump suspension and jump suspension time. Consistency in jump technique has also been supported by the finding that in 4-year-old horses with little jumping experience, intra-horse variation was significantly lower than inter-horse variation (Santamaria et al., 2004a). The longitudinal effect of jump training at 6 months of age has also been found to have no long-term effect on jump technique or maximum jumping capacity 5 years of age (Santamaria et al., 2005).

These studies have illustrated the apparent inherent nature of jump technique, suggesting that it may be possible to predict future performance based on kinematics examined at foal age (Santamaria et al., 2002; 2004b). As a result, various researchers have aimed to determine specific kinematic movement traits, which may act as predictors of a horse's ability to perform later in life (Santamaria et al., 2004b; Bobbert et al., 2005). Research has therefore aimed to determine what movement traits constitute a "good jumper" in relation to performance in competition, or simply based on the horses the ability to clear a jump. These studies have particular relevance to the equine industry, as objective selection methods at an early age may facilitate significant reductions in the time and money required to produce young jumping horses (Santamaria et al., 2004b; Bobbert et al., 2005). Kinematic characteristics of quality jump technique are described in detail in Section 6.3 and this Section will therefore form a brief overview.

Studies have reported that horses with superior jump technique exhibit lower vertical displacement of the CM during jump suspension and greater shortening of the FL and HL, which aids fence clearance (Santamaria et al., 2004a, 2005; Bobbert et al., 2005). Sanatmaria et al (2004a) postulate that this technique may be more economical. However, Powers and Harrsion (2000) oppose this finding, reporting that good jumpers exhibit significantly greater vertical displacement of the CM than their poor jumping counterparts and relate this difference to increased strength for trunk elevation. Similar disagreement between studies exists for horizontal velocity at approach. Studies have found that experienced horses are able to approach the fence with lower horizontal velocity (Deuel and Park, 1991; Barrey et al., 1993; Powers and Harrison, 2000) and the faster approach adopted by inexperienced horses has been associated with compensation for the lack of strength and balance required for take-off (Barrey et al., 1993). However, as stated in Section 2.6.2(i), Barrey and Galloux (1997) reported the opposite finding, that experienced horses were able to execute the fence at greater approach speeds. Horses with superior jump technique also exhibit a better "gather" technique during A1 (Barrey et al., 1993), which is in accordance with studies that have observed significantly shorter distances between the LdH and CM during take-off in good jumpers (Colborne et al., 1995; Powers, 2005). The HL is generally placed closer to the fence in better performing equine jumpers (Deuel and Park, 1991; Barrey et al., 1993), with FL being placed closer to the fence at landing (Deuel and Park, 1991). Studies have also highlighted greater vertical velocity (Clayton et al., 1995; Barrey and Langlois, 2000; Powers and Harrison, 2000, 2005; Santamaria et al., 2004a) and vertical displacement (Powers and Harrison, 1999; Powers, 2005) of the CM at take-off as an indicator of quality jump technique. Although these findings have progressed understanding of superior jump technique, further research is required to clarify contradictory findings and to develop ways in which this information can be applied in practice.

A 5-year longitudinal study, which followed the training of SJ horses from 6 months to 5 years of age, produced several publications relating to kinematic indicators of performance and the effect of training on jump technique (Bobbert et al., 2005; Bobbert and Santamaria, 2005; Santamaria et al., 2002, 2004a, b, 2005, 2006). In the study by Bobbert et al. (2005), 3D kinematic data were collected from unridden horses executing submaximal fences at 6 months of age and at 5 years of age, where they were also ridden by their trainer over a 1.15 m fence. At 6 months of age horses were split into two groups, an experimental group, which underwent non-intensive exercise training and free jumping sessions, and a control group, which was raised conventionally on pasture without training interventions (Santamaria et al., 2004a; Bobbert et al., 2005). At four years of age, all horses underwent an intensive 1-year jump-training programme, which is detailed by Santamaria et al. (2004b, 2006).

Findings from Bobbert et al. (2005) revealed that the best jumpers, as characterised by scores from a separate puissance competition, exhibited: lower vertical displacement of the CM during jump suspension, increased shortening of the FL, increased elbow flexion and greater HL retroflexion. Variables associated with CM in good and poor jumpers are discussed in further detail in Section 6.3. Each of these kinematic variables were apparent in kinematic data collected at 6 months of age, which were averaged for good and poor jumping groups (Bobbert et al., 2005). However, data for individual horses did not reflect findings from averaged group data, suggesting that these kinematic variables alone may not be accurate indicators of jumping ability later in life (Bobbert et al., 2005). Interestingly, when these data were analysed according to horses that were placed in control and experimental groups at 6-months old, the experimental group exhibited significantly greater elbow flexion and FL shortening when tested at 4-years-old (Santamaria et al., 2006). However, these training effects do not appear to be permanent, as horses from the experimental group were not amongst the best performers when tested using a puissance competition at 5 years of age (Santamaria et al., 2006). These findings further justify the apparent innate nature of jump technique in horses, suggesting that objective identification of performance at a young age may be possible. However, it is important to note that all studies produced from this research project concluded that it would be premature to assume that these variables may be used to accurately predict performance later in life. Furthermore, kinematic data were collected from horses over submaximal fences and more work is required to study the potential effects of fence height, training and rider on jump technique and performance later in life.

2.6.4 The role of equine muscles in kinematic research

As mentioned throughout Section 2.6, kinematic studies have offered suggestions for which muscles are involved in the generation of mechanical energy required for the jumping effort (Bogert et al., 1994; Dutto et al., 2004; Bobbert and Santamaria, 2005). Bogert et al (1994) stated that the kinematics of individual joints contain information about the lengthening and shortening cycle of muscles, and although this is true to some extent, the suggestions made by researchers are largely speculative (Wentink, 1978). However, researchers have highlighted that a comprehensive understanding of the precise role of equine musculature during jumping requires analysis of both kinematic and EMG data (Bobbert and Santamaria, 2005). To the author's knowledge, no studies have combined kinematic and EMG data to examine equine jump technique, which represents a major gap in knowledge. Furthermore, it is not known to what extent muscular adaptation to training may influence the kinematic variables that have been highlighted as indicators of performance in the jumping horse, which warrants further investigation.

2.7 Electromyography

The electromyogram detects electrical activity associated with muscle contractions, which are induced by the depolarisation of muscle fibres within a motor unit (MU) (Basmajian and De Luca, 1985). The MU represents the basic functional unit of muscle contraction and is comprised of a motor neuron and the muscle fibres it innervates (Hof, 1984). The propagation of an action potential down a motor neuron results in simultaneous depolarization of all innervated muscle fibres, which are surrounded by electrically conductive cell membranes, producing an electrical signal that is detected by electrodes located within their vicinity (Hof, 1984; Basmajian and De Luca, 1985; Kleissen et al., 1998). This electrical signal is often referred to as the motor unit action potential (MUAP) and is detected by either indwelling (needle) or surface electrodes (Basmajian and De Luca, 1985). Electromyography (EMG) refers to the study of electromyograms and surface electromyography (sEMG) will form the focus of this literature review.

Muscle fibres within a MU are randomly distributed throughout the muscle and intertwined with fibres from other MUs (Hof, 1984; Basmajian and De Luca, 1985). Therefore, the sEMG signal represents the interference pattern of MUAPs from a number of MUs located within the detection area of the surface electrodes (Basmajian and De Luca, 1985). Muscle force is controlled by changing the number of MUs recruited and by increasing the firing frequency, or "rate coding", of active MUs (Hof, 1984; Basmajian and De Luca, 1985; De Luca, 1997; Kleissen et al., 1998). MU activity is directly related to muscle force; however, the relationship between electrical activity and muscle force has sparked significant debate between researchers (Richards et al., 2008a). Although it is disputed, research has reported a linear relationship between EMG amplitude and the force of isometric contractions (Inman et al., 1952; Lippold, 1952; Perry and Bekey, 1981; Hof, 1984; Basmajian and De Luca, 1985; Solomonow et al., 1989), with the EMG signal reflecting the number and firing frequency of active MUs. However, the relationship between EMG signal magnitude and the force of concentric and eccentric contractions is less straightforward, due to muscle length changes over time (Soderberg and Cook, 1984; De Luca, 1997; Oatis, 2004; Richards et al., 2008b). In these cases, the EMG signal reflects the relative activity of the muscle, but does not provide a direct measure of muscle contractile force.

The sEMG signal is also greatly influenced by various internal and external factors (De Luca, 1997), which are discussed in detail in Chapter 5. Despite the complexities related to sEMG analysis, the signal undoubtedly provides valuable insight into muscular function and activity patterns (Soderberg and Cook, 1984). Furthermore, the non-invasive nature of sEMG, combined with recent advances in instrumentation and software, has led to its widespread use in clinical and biomechanical studies investigating muscle function and dysfunction in human subjects (Soderberg and Cook 1984; Kleissen et al., 1998).

2.7.1 Surface electromyography in animal research

As previously stated in Chapter 1, EMG has shown increased in popularity in animal research over the last decade. Recent advances in telemetric sEMG technology have enabled researchers to collect EMG signals from animals in a more straightforward manner. However, the user-friendliness of modern sEMG systems has raised concern, as standardised methods for data acquisition, signal processing and analysis have not been developed for animal research, representing a major gap in knowledge (De Luca, 1997; Valentin and Zsoldos, 2016). Lack of standardisation and subsequent differences in methodologies employed by researchers, has made direct comparison of findings between studies difficult (Hermens et al., 2000; Valentin and Zsoldos, 2016). Although methodological differences represent an issue for human sEMG research, substantial developments have been made to standardise data collection and analysis protocols (Hermens et al., 2000). Unfortunately, the developments made in animal sEMG research have progressed at a much slower rate to those observed in human literature (Valentin and Zsoldos, 2016). An extensive review by Valentin and Zsoldos (2016) summarises the limitations and lack of standardised methodology associated with sEMG data acquisition and analysis techniques in animal subjects. The limitations, which are specific to equine sEMG research, are discussed in detail in Chapter 5.

In animal research, sEMG has primarily been used to examine equine locomotion (Valentin and Zsoldos, 2016). However, research has also examined the clinical applications of EMG, which has shown potential as a technique for distinguishing between neurogenic and myogenic disorders (van Wessum et al., 1999; Wijnberg et al., 2003, 2005, 2006; 2011). However, the majority of these studies have employed intramuscular EMG (i.e. Wijnberg et al., 2003, 2006; 2011), which does not form the focus of this literature review. sEMG has also been used to examine the effect of fatigue (Williams et al., 2013), aging (Zsoldos et al., 2014), lameness (Zaneb et al., 2009), dental treatments (Williams et al., 2014) and back stiffness (Peham et al., 2006) on muscle function. sEMG has most commonly been employed in equine research as a tool for examining muscle activation patterns and force of contraction during locomotion (van Wessum et al., 1999). These studies have advanced our knowledge on the role of various muscles for facilitating movement (i.e. Wentink et al., 1978; Jansen et al., 1992; Robert et al., 1999; 2000; 2001a, b, 2002; Hodson-Tole, 2006; Crook et al., 2010; Zsoldos et al., 2010a, b). However, further work is required to fully understand muscle coordination in normal and pathological gait (van Wessum et al., 1999).

2.7.2 Surface electromyography as a method for informing training methods in the sports horse

Although, extensive literature has described muscular adaptations to training in equine athletes (Section 2.3.3), sEMG has not been widely used to explore how muscle function may change according to training demands. Previous studies have made suggestions for training protocols based on findings from sEMG data (Robert et al., 2000, 2001a; Hodson-Tole, 2006; Cottriall et al., 2009; Kienapfel, 2015). For example, Cottriall et al. (2009) reported that popular training aids (side reins and Pessoa training aid), which are generally believed to promote favourable muscular activity in the neck and back, had no significant effect on sEMG intensity in the Longissimus Dorsi. The effects of various head and neck positions, which are a topic of considerable debate and controversy in the equine community (McLean and McGreevy, 2010), have also been explored using sEMG and different HNP were found to target different muscles (Kienapfel, 2015).

Perhaps most relevant to the jumping horse are studies that have investigated the effect of speed and slope on muscle activity (Robert et al., 2000, 2001a, b, 2002; Hodson-Tole, 2006; Crook et al., 2010). These studies have concluded that both speed and incline increase workload on various trunk (Robert et al 2001a, b), HL (Robert et al., 2000, 2002; Crook et al., 2010) and FL (Hodson-Tole, 2006) muscles, which were quantified using integrated EMG (iEMG) and Wavelet analysis techniques. However, these increases in workload are achieved through different mechanisms, which are observed in temporal EMG activity (Robert et al. 2000; 2001a, 2002). Increased velocity was found to lengthen the relative duration of muscle activity, while increased slope generally resulted in maintained or decreased activity duration (Robert et al., 2000, 2001a; Hodson-Tole, 2006). These findings have lead researchers to suggest that both speed and slope training may be used to increase muscle strength, however specific exercises may be more relevant to the type of training (Robert et al., 2000, 2001a, 2002). An effective training programme has been described as one, which employs exercises that replicate the speed and range of joint motion, and the neuromuscular patterns experienced during competition (Clayton, 1991). Robert et al. (2000, 2001a) therefore suggest that, based on muscular responses to speed and slope training, high speed training may be more appropriate for race training, while slope training may be more beneficial to dressage horses as stance and muscle activity duration are maintained whist increasing muscle workload.

These studies have demonstrated the potential for sEMG to be used as a tool for objectively informing current equine training programmes. Unfortunately, many of these studies have been conducted on unridden horses during walk and/or trot on a treadmill (Robert et al., 2000, 2001a, b, 2002; Crook et al., 2010), which may not be fully representative of muscle activity patterns observed during training or competition. To the author's knowledge, Hodson-Tole (2006) and Harrison et al (2012) are the only studies to collect sEMG data during canter, which represents an important gait due to its frequent use in competition and training. Further work is therefore required to increase external validity of sEMG studies, by collecting data under normal training or competition environments. Many of these studies have related muscle activity patterns to temporal kinematics, but few have explored angular kinematics. This represents a major gap in knowledge and future research is required to obtain this information to form a comprehensive understanding of locomotor function.

As previously stated, exercises should mimic the movement and neuromuscular patterns experienced during competition (Clayton, 1991). Therefore, objective optimization of training programmes for SJ horses using sEMG requires baseline knowledge of the muscular activity patterns observed during jump and canter. However, as discussed in Chapter 1, Giovagnoli et al. (1998) and St. George and Williams (2013) are the only known studies to examine the equine jumping effort using sEMG. The study by Giovagnoli et al. (1998) only provided a qualitative description of muscle activity from the Splenius muscle in unridden horses lunged over an 80cm fence at trot, and a 1.10m fence at canter. St. George and Williams (2013) investigated activity of the Superficial Gluteal, Longissimus Dorsi and Triceps Brachii in one horse executing a grid line of four fences. Unfortunately, both studies exhibit methodological limitations, necessitating further work in this area. For example: the removal of all hair from electrode sites is necessary to achieve optimal skin-electrode impedance and will have a significant influence on the fidelity of signals (Hermens et al., 2000). However, in both studies, hair was not fully removed from sensor locations, which will undoubtedly confound results. Furthermore, these studies have not examined sEMG data in relation to kinematic movement patterns, which is required to fully understand how muscles facilitate the jumping effort. Further sEMG research, which examines the kinematic and neuromuscular patterns of the jumping effort in horses with differing jumping abilities, is required to provide baseline data for the functional activity of locomotor muscles during jumping.

Previous equine studies have provided evidence for sEMG as a novel and objective method for investigating locomotion and muscle function in equine subjects. These findings suggest that sEMG represents an appropriate tool for investigating the gaps in knowledge that have been highlighted throughout this literature review, specifically for the development of scientifically evidenced training and selection methods for equine SJ athletes.

Chapter 3. Quality movement and ideal training practices in the equine jumping athlete: an industry perspective.

3.1 Introduction

Previous equine research has used questionnaires to explore the opinions and knowledge of industry professionals regarding equine temperament traits (Momozawa et al., 2003, 2005) learning theory (Warren-Smith and McGreevy, 2008), breeding objectives (Koenen et al., 2004), training surface properties, and risk factors for injury (Murray et al., 2010a, b). However, to the author's knowledge, no study has explored the evaluation of movement and training methods in the equine jumping athlete. Furthermore, no known equine studies have used a questionnaire to inform research design to ensure that research is relevant to the equine industry professional. The issues related to the application of equine research in industry have been previously described (see Section 2.5; Winfield, 2010; van Weeren, 2008). In this study, an original questionnaire was designed, based on design elements of previously validated equine surveys and on information gathered from a review of desired movement traits in current training practices. The aim of this study was to fulfil Objectives 1 and 2 of the thesis through collaboration with experienced, highly qualified equestrians.

Findings from this study were disseminated through an oral presentation at the 9th Annual Myerscough Research Conference (November 7th 2014).

3.2 Questionnaire Development and Implementation

3.2.1 Questionnaire Design

The questionnaire was designed to identify subjective criteria used by industry professionals for identifying optimal movement patterns during canter and jump in equine athletes. This information would provide a framework to identify biomechanical traits associated with, or indicative of, "quality" of movement and would be used to inform future data analysis for the main study of the thesis. Questionnaire results would be used to answer the questions:

- Can these traits be defined biomechanically?
- Has previous work previously defined these traits?
- Are these traits biomechanically apparent in elite and non-elite equine athletes?
- Can these biomechanical variables indicate performance of a particular horse?

Quality movement is assumed to be optimised via training methods (Back et al., 1995c; Williams, 2013). Therefore, the questionnaire would also contain questions, which would uncover traditional training methods utilised by industry professionals. This information would fulfil Objective 2 of the main study of the thesis (Section 1.1).

3.2.2 Target Population

The effectiveness of a question is largely reliant on ability of potential study participants to understand and answer it (Stone et al., 1990). Therefore, the effectiveness of the questionnaire relied on the experience level of participants. The current study targeted the opinions, knowledge and practices of highly trained coaches, riders and trainers, under the premise that they are capable of producing high-level equine performance. As previously described in Chapter 1, the performance and success of racehorses varies significantly by trainer (More, 1999; Verheyen et al., 2009; Ely et al., 2010). Differences in riding strategies between elite and non-elite riders have been established (Peham et al., 2001; Lagarde et al., 2005; Powers and Kavanagh, 2005; Schöllhorn et al., 2006; Patterson et al., 2010; Hall et al., 2014) and the effect of the rider on the horse during jumping has been highlighted as an important area for further research (Powers and Harrison, 2002). These findings highlight the effect of high-level training and riding on equine performance. It was therefore concluded that survey participants would ideally have expert experience in the visual assessment of movement, the design of training programs and the ability to produce successful equine athletes through riding, training or coaching. The ideal target population was therefore defined as: high level coaches and riders affiliated with British Showjumping (BS).

3.2.3 Research Question Development

Once the problem and target population had been established, potential research questions were compiled. Research questions were divided into three sections based on the information required to fulfil the aims of the questionnaire. Sections were titled:

- Evaluating quality movement and performance in the equine jumping athlete.
- Fence type and arrangement for evaluation of jump technique
- Training methods for the equine jumping athlete.

Questions included in the ***Evaluation of Quality Movement*** section would provide objective insight into the elements of equine movement relevant to the industry professional. Questions included in the ***Fence Type and Arrangement*** section would be used to design a methodology for the main study of the thesis, which would replicate industry practice. Similarly, questions included in the ***Training Methods*** section would ensure that research could be linked to aspects of professional training strategies used to maximise performance in the jumping horse.

3.2.4 Question Structure

A series of two-part questions containing a closed-end and a "follow-up open-end" (Peterson, 2000) component were designed to describe "quality" movement based on the opinions and experiences of participants. This question structure has been employed in previous equine research (Momozawa et al., 2003; Warren- Smith and McGreevy, 2008). Closed-end components were derived from a literature review and offered respondents a set of predetermined movement assessment criteria, as described in equestrian literature and various studbooks. A five point Likert scale with response categories on a continuum was employed to measure the participant's opinion relating to the importance of each criterion. The scaling approach has been described as a useful tool for generating a general understanding of a topic during the early and exploratory stages of research (Oppenheim, 1992). The closed approach ensured that respondents considered the same range of content before answering, permitting an accurate comparison of results (Oppenheim, 1992).

Open-ended question components allowed respondents to elaborate on their preferential answer to the criteria provided in the preceding closed-end element. Assessment criteria are well defined among studbooks. However, subjectivity and variation in movement evaluation is often related to the emphasis different evaluators may place on specific traits within each criteria (Koenen et al., 2004; Ducro et al., 2007). Therefore, open-end questions allowed participants to describe and provide examples of specific traits within each assessment criteria. Oppenheim (1992) suggests that open-end questions, which require contemplation and writing, should be kept to a minimum and that every effort should be made to minimise the amount of time spent on the question. Item non-response has been reported to be greater for open than for closed-ended questions due to larger "response burden" (Bailey, 1987, cited by Reja et al., 2003; Galesic et al., 2009). A study by Reja et al., (2003) found that 41% of respondents skipped or provided an invalid answer when faced with an open-ended question. These questions were therefore classified as optional to minimise respondent dropout rate (Knapp and Heidingsfelder, 1999; Reja et al., 2003).

Questions from the remaining sections relating to: fence type and arrangement and traditional training methods, were comprised of: closed-ended multiple choice and rating questions. Pre-determined answer options were based on literature describing traditional training methods and evaluation methods from well-established studbooks. The majority of closed-end questions from these sections included an "other" option where respondents could include any relevant answers, which may not have been included in pre-determined answers.

3.2.5 Online Launch of Questionnaire

The final questionnaire was developed online using SurveyMonkey (SurveyMonkey Inc., California, USA) and consisted of 18 questions, which were initially evaluated by three equestrians of varying levels (see Appendix A for questionnaire design). Feedback from these individuals regarding survey design was considered before its online launch. The launch was carried out in two phases; 1) a reliability study was initially undertaken to validate the design of the questionnaire and 2) the questionnaire was released for the main study.

3.3 Questionnaire Reliability Study

Pilot testing was conducted to validate the design and reliability of the questionnaire. Pilot work simulated the mode of administration, target participants, and answer analysis, which would be employed in actual data collection. The stability reliability of the questionnaire was investigated using a test-retest technique. All re-test surveys were returned within 10 days of the initial baseline survey. Marx et al. (2003) suggest that a time interval ranging from two days to two weeks is an adequate timeframe for test-retest reliability and may mitigate carry over, learning or recall effects.

3.3.1 Reliability Study Data Analysis

Pre and post data from 10 participants were exported to Microsoft Excel (Microsoft Corporation, 2011) using the export option from the SurveyMonkey website (SurveyMonkey Inc., California, USA). Questions containing irrelevant data for reliability analysis (for example classification questions and open-end questions) were removed from the spreadsheet. Data from 13 questions were therefore included for data analysis. Data were coded in Excel and the difference between pre and post values was calculated for each question. Original coded data and difference values were exported to SPSS for statistical analysis.

One-sample t-tests ($P<0.05$), with an input value of zero, were conducted to test whether significant differences occurred between answers from pre and post responses. Additional Percent Similarity and Intra-class Correlation (ICC) tests were run to further compare the agreement scores.

3.3.2 Reliability Study Results

No significant difference ($P>0.05$) was found between answers from pre and post trials (t-test). Results from ICC tests showed good (0.40-0.75) to excellent ($\geq$ 0.75) reliability (Fleiss et al., 1986; Marx et al., 2003; Oremus et al., 2012). A high ($\geq$70%) percentage of similarity was found for most questions with only the type of jump ($\geq$30%) and task used for evaluation of jump technique

(≥40%) producing dissimilar answers between test and re-test results. Results from ICC and percent similarity tests are presented in Appendix A.

3.3.3 Reliability Study Conclusion

Based on the results of statistical tests, it was concluded that the questionnaire was sufficiently reliable for its purpose and that the validated questionnaire could progress onto the main data collection.

3.4 Questionnaire Main Study

3.4.1 Methodology

The survey was made available online on June 6, 2014 for three months. Over this period, the survey was promoted and shared through social media by recognised and respected equine professionals, organisations, publications and academic institutes. All Accredited coaches listed on the BS website were sent a personalised email inviting them to participate. Although it is difficult to generate an exact value for the number of individuals that the questionnaire reached, it is estimated that the questionnaire reached thousands of individuals via social media alone. This estimation is based on the number of followers for social media accounts that shared the questionnaire (i.e. British Showjumping - 128, 944 Facebook followers, as of January 30, 2017).

3.4.2 Quantitative Data Analysis

Two hundred and twenty-five respondents of varying levels and expertise took part in the questionnaire. Data were exported from Survey Monkey into Microsoft Excel and sorted using the eligibility criteria. Inclusion criteria included coaches with: BS Accredited, BHSII, BHSI, UKCC3 accreditation and riders competing at Foxhunter or classes exceeding 1.20 m. Respondents who had answered "other" for the demographic question were scrutinised and those indicating that they were coaching or competing at levels equivalent to the inclusion criteria (i.e. international competition) were included in the target population. Data from the target population were then analysed and incomplete responses were removed from the data set.

Completion rate was calculated as the total number of completed questionnaires relative to the total number undertaken (Warren-Smith and McGreevy, 2008). Respondents who did not complete the questionnaire were accounted for by reporting results as a percentage of the total number of respondents who completed each question. Quantitative data from closed-end questions were separated from qualitative data from open-end questions, which were analysed separately (Section 3.4.3)

3.4.2 (i) Statistical Analysis

Categorical questions using a five-point rating scale were analysed using a Pearson's Chi-squared (X^2) test to identify whether significant differences existed between the observed and expected responses.

3.4.3 Qualitative Data Analysis

Analysis of text from open-ended questions poses several challenges, specifically in relation to the standardisation and coding of data and subsequent reporting of frequencies (Jackson and Trochim, 2002). Content analysis is the preferred code-based approach, which has typically been applied to open-ended questionnaire responses (Jackson and Trochim, 2002). However, scepticism has surrounded the perceived subjective nature of content analysis, where the ability to generate reliable coding is often questioned (Carey et al., 1996; Jackson and Trochim, 2002; Hruschka et al., 2004). It was therefore imperative that data from open-ended questions be analysed using a robust process, which could be explicitly described, recorded and disclosed (Attride-Stirling, 2001).

The analytical framework approach offers a method for undertaking qualitative data analysis in a systematic manner, placing emphasis on the analysis process and disclosing the interconnected stages which lead to answering the research question (Jackson and Trochim, 2002; Daley, 2004). This approach is employed where the aims and objectives of research are *a priori* and analysis occurs in accordance with the predefined topic to identify patterns (Jackson and Trochim, 2002). The analytical framework approach was therefore employed for the analysis of qualitative data in this study, as the research design was *a priori* and an inductive approach would therefore not be suitable.

Thematic networks were employed for this study, as this method falls under the analytical framework approach (Attride-Stirling, 2001) and has the advantage of systematically analysing qualitative data through a series of stages, which can be explicitly described (Jackson and Trochim, 2002; Smith and Firth, 2009). Thematic networks are constructed in conjunction with the thematic analysis approach, which is similar to content analysis, but places more emphasis on the qualitative aspects of the data under analysis (Joffe and Yardley, 2004). Networks provide a system for structuring and representing themes derived through thematic analysis (Attride-Stirling, 2001).

Thematic analysis and the subsequent construction of thematic networks are traditionally conducted on data collected through free-flowing discourse (Attride-Stirling, 2001; Daley, 2004; Hruschka et al., 2004; Smith and Firth, 2011). However, due to the limited response length of the questionnaire, respondents were forced to provide answers in a concise "free list" format, while still having the opportunity to expand using slightly longer "narrative" text (Jackson and Trochim, 2002). To the author's knowledge, no research has constructed thematic networks based on data from open-end survey responses. Therefore, an altered approach to the construction of thematic networks was taken, which combined the original process outlined by Attride-Stirling (2001) with Jackson and Trochim's (2004) concept-mapping analysis for open-ended survey responses.

3.4.3 (i) Thematic Analysis and Networks: Analytic Steps

Data from both target and non-target (respondents who did not meet the inclusion criteria described in Section 3.4.2) populations were analysed separately using the altered thematic network approach. Open-ended responses from the ***evaluating quality movement and performance in the equine jumping athlete*** section were analysed. The adapted process is described below.

Units of analysis were produced by reducing data into segments representing individual words or phrases containing only one concept (Jackson and Trochim, 2002). Data segments were then grouped according to similarity and a provisional coding framework was produced. Provisional codes were based primarily on recurring segments and stages outlined in the "German Training Scale" (GTS), as defined by the German National Equestrian Federation (GNEF) (Belton and GNEF, 1997). The GTS was employed in an effort to ground analysis on generally accepted training principles (Hodgson, 2013). The development of a coding framework following data reduction of free-flowing discourse is contrary to the steps outlined by Attride-Stirling (2001). However, Hruschka et al. (2004) state that it is essential to reduce texts into segments before coding open-ended data. This approach was more appropriate for this study, as it was necessary to dissect text segments first to devise a coding framework capable of encapsulating the wide-ranging response content.

Target-population responses from question 4 (Q4), which aimed to uncover desirable movement traits for canter, will be used as an example to illustrate the analysis process. Three hundred and fifty data segments were separated from 175 responses, with each segment containing a word, phrase or quotation relating to a specific concept. For example, the response "striding forwards under the body with a natural ability to weight bear and push" was reduced into the following text segments: “striding forwards”, “under the body”, “natural ability to weight bear”, “natural ability to push”.

Coding was then conducted by applying the provisional coding framework to data segments. In this study, only a single researcher coded the data. In this case, the representative researcher (LSG, thesis author) had industry experience and a theoretical background similar to the respondents. This is in accordance with selection processes for a “representative researcher” outlined by Jackson and Trochim, (2002), who describe the importance of considering similarities/differences in experience and theoretical knowledge between coders and respondents. This consideration is imperative to encourage accurate interpretation of results (Jackson and Trochim, 2002).

At this stage, codes were placed under scrutiny to ensure that none were interchangeable or redundant (Attride-Stirling, 2001). Codes were then modified so that all data, even segments dissimilar to the set, were represented by a code. Coding was therefore exhaustive and ensured that all text segments were represented by a code. Although no formal inter-rater reliability checks were performed, two research colleagues with relevant experience evaluated data to confirm the consistency of interpretation and face validity of coding techniques.

In continuing with the representative example from Q4: 10 codes were deduced from 350 data segments based predominantly on the GTS and reoccurring segments, which did not explicitly fit into the phases of the GTS. Table 3.1 illustrates the coding framework for Q4 and provides examples of relevant concepts represented by each code.

Table 3.1 Coding framework derived from Q4, examining responses describing desirable movement traits in "quality canter".

Codes	Desirable Traits Discussed
Functional Conformation	• Good Conformation
Collection	• Engaged • Adjustability • Uphill
Impulsion	• Power • Strength • Forward Motion • Active
Joint Articulation	• Flexion • Hock Movement • Shoulder Movement • Joint Angles
Rhythm	• Regularity • Cadence • Even
Relaxation	• Free Moving • Suppleness • Elasticity
Balance	• Well Balanced
Connection	• Round Through Back and Neck • Transfer Movement Through Back
Straightness	• Tracking up • Straight Movement
Influenced by External Factors	• Influenced by Training • Influenced by Breeding

Basic and organising themes were then identified from coded text segments, as described by Attride-Stirling (2001). However, global themes, which encapsulate the main point in the text, were defined *a priori* based on corresponding survey questions. Global themes were therefore defined first and characterised by: ***Qualities Which Comprise Quality Canter*** and ***Qualities Which Comprise Quality Jump***.

Organising themes were identified based on the most prevalent codes and the observation that certain codes were dependent on other codes when practically applied. For example: ***Joint Articulation*** was grouped under the organising theme of ***Functional Conformation***, as it is generally accepted that overall conformation determines the limits for: range of movement, function and subsequent ability to perform in horses (Mawdsley et al., 1996).

The identification of organising themes prior to the identification of basic themes is not in accordance with the process defined by Attride-Stirling (2001), who suggests building organising themes first based on the rearrangement of basic themes. However, this process was not appropriate for this data set, as global themes were defined *a priori* and there was no theoretical way to comply with the original process. It was therefore more appropriate to work backwards, defining global themes first, followed by organising themes and finally basic themes. This alteration to the thematic network method may be justified through the Attride-Stirling's (2001) statement: "it is up to the researcher to identify themes in a manner that is appropriate to her or his specific theoretical interests."

Basic, organising and global themes were revisited prior to their establishment to ensure they met the guidelines of the unaltered process described by Attride-Stirling (2001). Organising themes fulfilled the requirements outlined by Attride-Stirling (2001) by effectively grouping basic themes into clusters of similar issues. For example: the decision to group the basic themes: ***Strength***, ***Power*** and ***Forward Motion*** under the organising theme of ***Impulsion*** conform to the FEI's definition of impulsion: "the term used to describe the transmission of an eager and energetic, yet controlled, propulsive energy generated from the hindquarters into the athletic movement of the Horse" (Fédération Equestre Internationale, 2016). Impulsion has also been described as "developed by good training, by teaching the horse to engage and building up the strength that enables him to do this" (Kidd, 1999) and by "the thrust or "pushing power" of the horse" (Hodgson, 2013). These definitions, along with prevalence of related data segments, justify the assignment of ***Impulsion*** as the organising theme to group these basic themes. The global theme fulfilled the requirements outlined by Attride-Stirling (2001), acting as a theme, which unified the organising themes and represented data in a manner that fulfilled the aim of the questionnaire. This process was repeated for all open-ended responses comprising the previously defined questionnaire sections of interest.

3.4.3 (ii) Content Analysis

Responses obtained from supplementary open-ended questions were invaluable for uncovering the specific traits, which industry experts use to define "quality" movement. Unfortunately, the thematic network approach only serves as a tool in analysis, and does not constitute an analysis itself (Attride-Stirling, 2001). Therefore, descriptive statistics were incorporated into qualitative analysis to facilitate the identification of commonly reported traits, which encompass "quality" movement.

Thematic analysis has been described a flexible method, permitting the integration of qualitative and quantitative evidence (Dixon-Woods et al., 2005). This integration often occurs where data are analysed for themes and then treated quantitatively by reporting the frequency count of each theme (Garcia et al., 2004). A frequency count for each coding category was therefore calculated based on the total number of data segments comprising each code. Percent frequency was calculated by dividing the frequency count of each coding category by the total number of data segments comprising the corresponding global theme. Frequency count for each coding category was used to illustrate specific movement traits, which were prevalent within the broader organising themes. From this information, it would be possible to define the most prevalent movement traits, which industry experts use to evaluate quality movement in the jumping horse.

3.4.4. Quantitative Results

Of 225 participants who undertook the questionnaire, 66.7% (150/225) met the inclusion criteria, while 33.3% (75/225) did not. The combined completion rate for target and non-target population was 48.9% (115). Completion rates from target and non-target populations were 32.7% (49/ 150) and 46.7% (35/75), respectively. Results from each questionnaire section are presented separately in the succeeding sections.

3.4.4(i) Evaluating quality movement and performance in the equine jumping athlete

An initial categorical question explored the level of agreement with the statement "the following criteria play a critical role as "indicators of performance when evaluating sport horse prospects" for each parameter (conformation, pedigree and movement). Figure 3.1 shows the results for this question with the significant differences between parameters for each level of agreement.

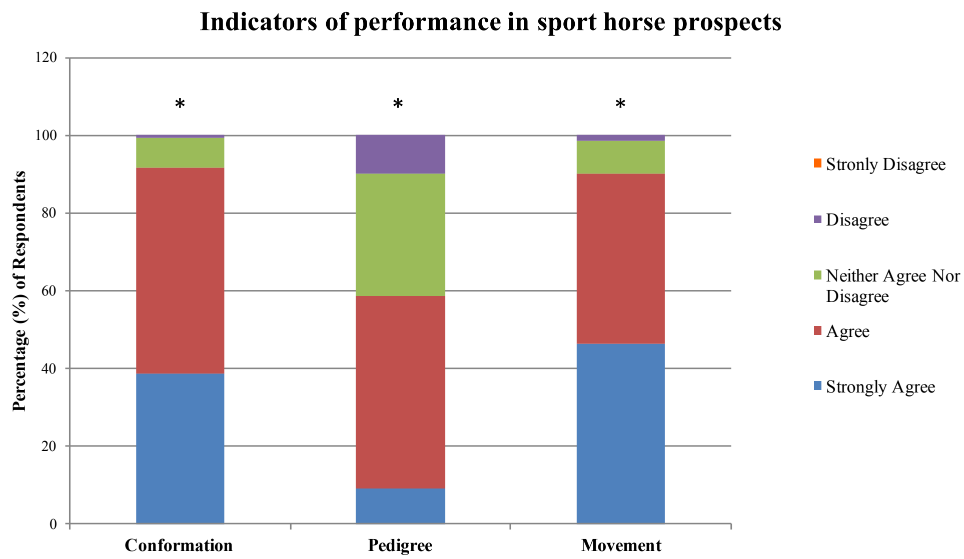


Figure 3.1. Overall respondent ratings for conformation, pedigree and movement criteria based on their role as indicators of performance when evaluating sport horse prospects. *Significant differences were found for all categories (P<0.0001).

Categorical questions explored the contribution of functional parameters (HL, FL, neck and back, and stride length) to the evaluation of quality canter and jump technique. The importance of each jumping phase when evaluating quality jump technique was also explored. Figures 3.2, 3.3 and 3.4 show the results for each question with the significant differences between parameters and phases for each category.

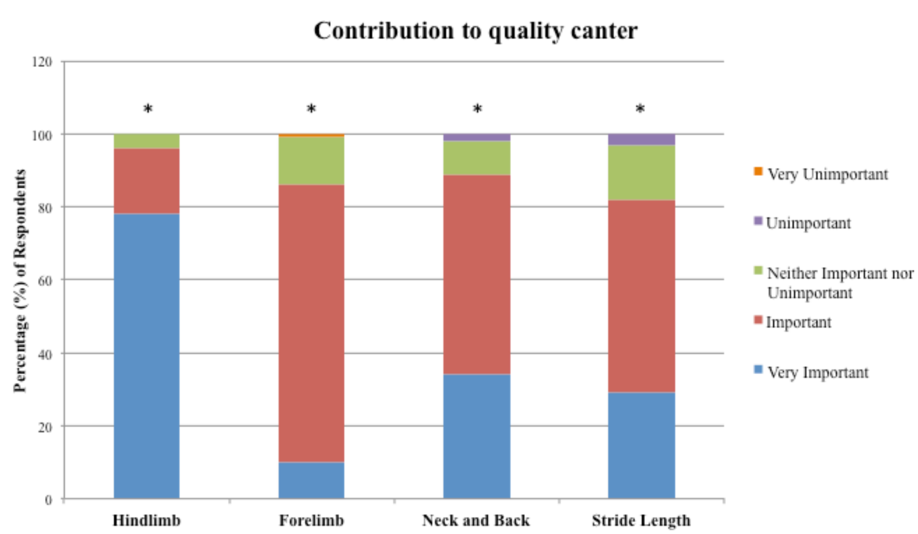


Figure 3.2 Overall respondent ratings for HL, FL, neck and back, and stride length criteria based on their contribution to the evaluation of quality canter. *Significant differences were found for all categories (P<0.0001).

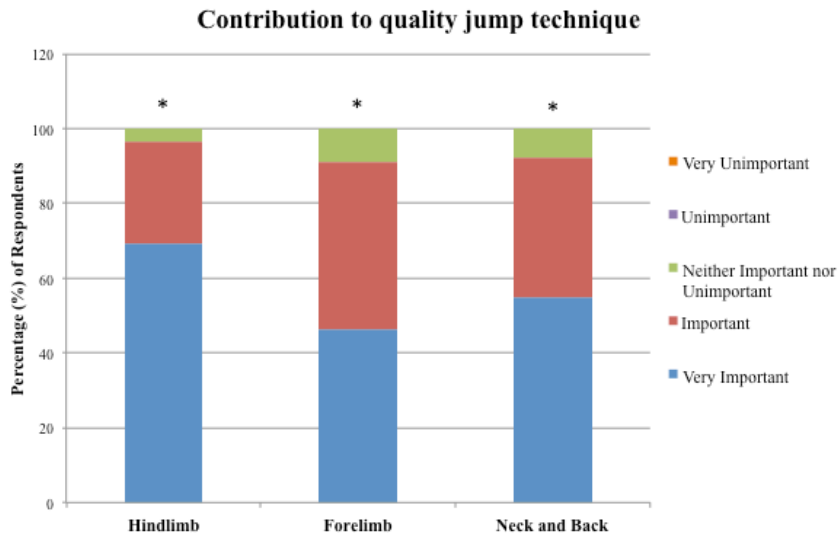


Figure 3.3 Overall respondent ratings for HL, FL and neck and back criteria based on their contribution to the evaluation of quality jump technique. *Significant differences were found for all categories (P<0.0001).

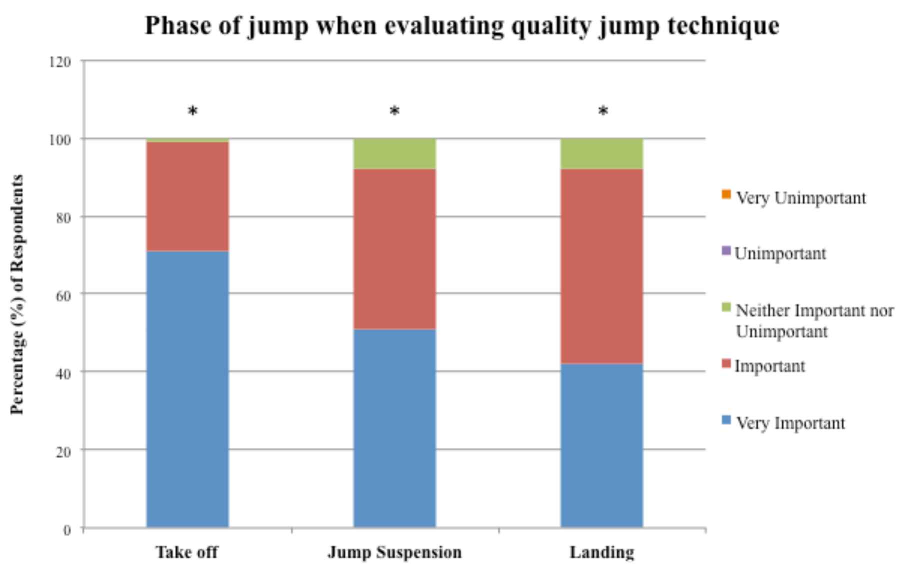


Figure 3.4 Overall respondent ratings for take-off, jump suspension and landing phases of the equine jump and their contribution to the evaluation of quality jump technique. *Significant differences were found for all categories (P<0.0001).

Figure 3.5 illustrates results for a categorical question, which explored the level of agreement with the statement “quality of canter is irrelevant to quality of jump technique in the jumping horse”. A significant difference in was found between each level of agreement ($X^2_{(90)}$=48.11, P<0.0001) .

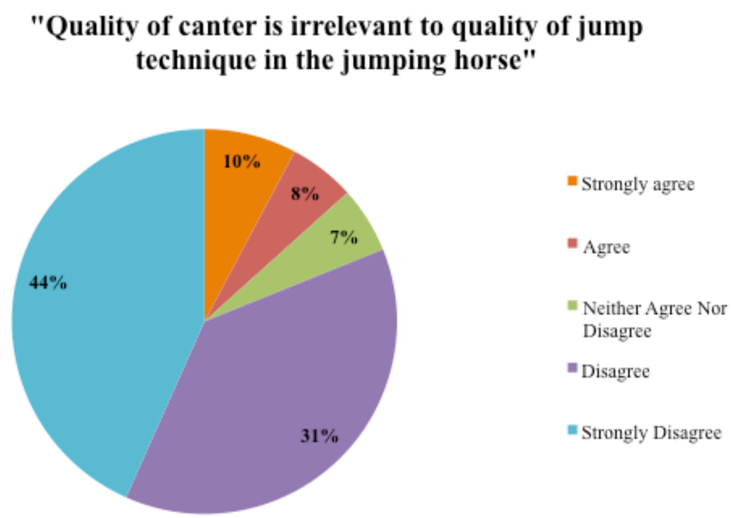
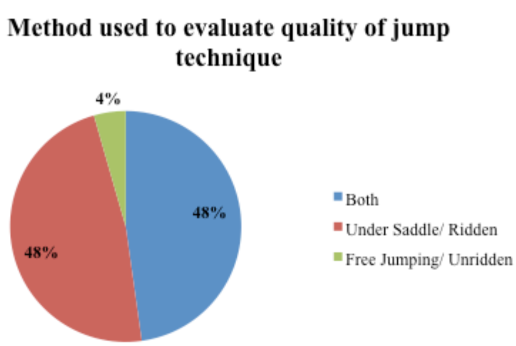


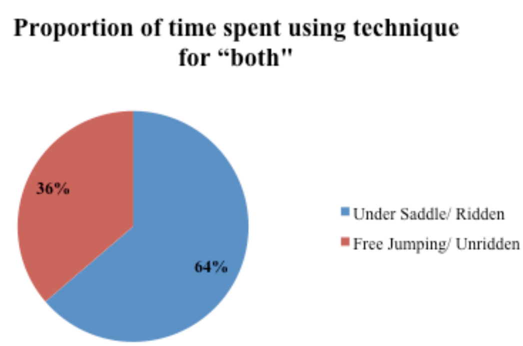
Figure 3.5 Overall respondent results in relation to level of agreement with the statement "quality of canter is irrelevant to quality of jump technique in the jumping horse". Significant differences were found between levels of agreement (P<0.0001).

3.4.4(ii) Fence type and arrangement for evaluation of jump technique

A significant difference in industry preference for method used to evaluate the jump technique was found ($X^2_{(90)}$=22.53, P<0.0001) (Figure 3.6a). In a follow-up question for respondents answering ***both***, the majority of respondents spent a greater proportion of time evaluating the ridden horse compared to the unridden horse (Figure 3.6b).



a.



b.

Figure 3.6 a) Overall respondent results in relation to preferred method for evaluation of quality jump technique. Significant differences were found between methods (P<0.0001). b) Results as a proportion of time from follow up question for respondents expressing a preference for using both methods of evaluation of quality jump technique.

Interestingly, there were no significant differences ($X^2_{(90)}$=0.83, P>0.05) in answers when participants were asked about the fence arrangement used to evaluate jump technique (Figure 3.7). However, the majority of respondents showed a preference for using a ***grid line***, or combination, which is defined in Section 2.6.2(v).

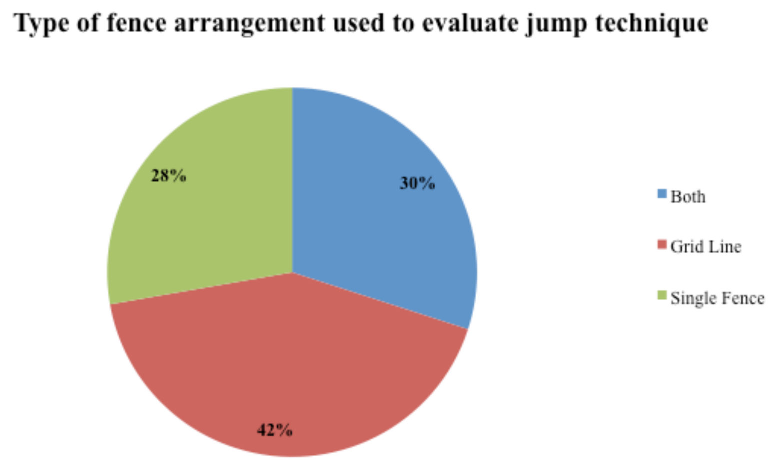


Figure 3.7 Overall respondent results in relation to preference for fence arrangement for evaluation of quality jump technique. Significant differences between each category were not found (P>0.05)

Significant differences in preferences for fence types were found for square oxer (P<0.0001), ascending oxer (P<0.0001) and vertical (P<0.0001) when exploring the effectiveness of common fences for demonstrating jump technique. No significant differences were found for triple bar (P>0.05) (Figure 3.8).

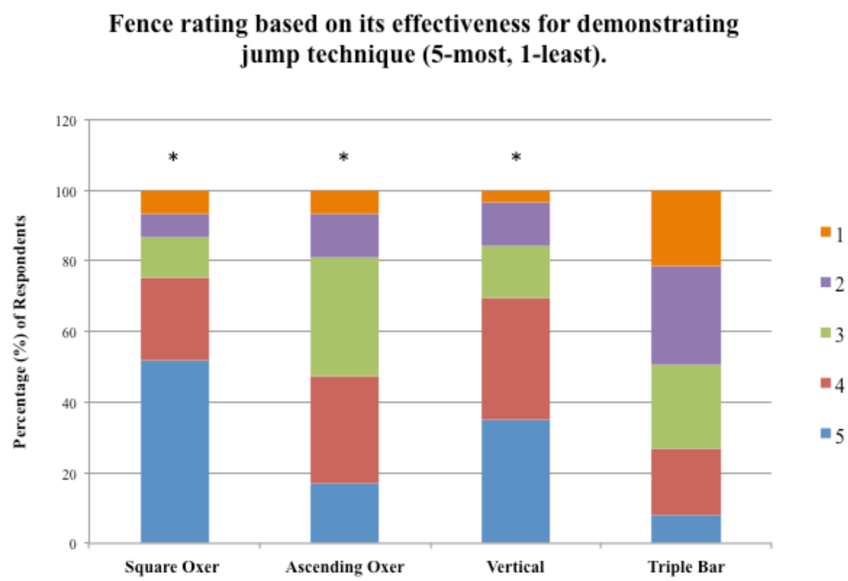


Figure 3.8 Overall respondent results in relation to preference for fence type and its effectiveness for demonstrating jump technique during movement evaluation. Preference demonstrated using a 1 – 5 rating scale, 1 least effective – 5 most effective. *Significant differences were found for square oxer, ascending oxer and vertical (P<0.0001).

3.4.4(iii) Training methods for the equine jumping athlete

The initial question in this section explored the importance of: quality canter, jump technique and stride adjustability in training programmes to improve overall jumping performance. Results are presented in Figure 3.9. Significant differences were found for all categories (P<0.0001).

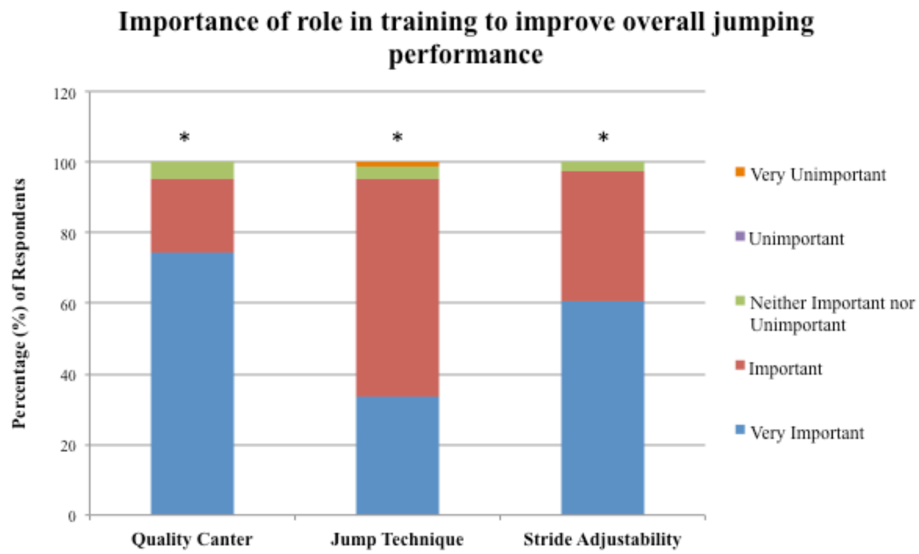


Figure 3.9 Overall respondent ratings for quality canter, jump technique and stride adjustability and the importance of their role in a training programme. *Significant differences were found for all categories (P<0.0001).

Seventy-nine participants completed a question exploring the proportion of time they would employ common training methods in a programme for the jumping horse. Answers were indicated as a proportion of time spent using each exercise (i.e. 0-100%). The most common method used was ***flatwork***, with respondents reporting an average of 39.8±13.28 % of time in a training programme (Figure 3.10).

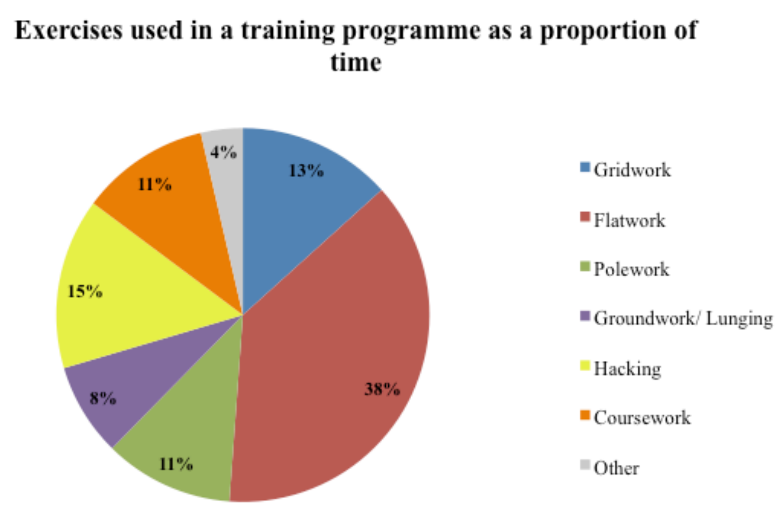


Figure 3.10 Overall respondent results in relation to the proportion of time (0-100%) spent using various training methods in a jump training programme.

An exploration of the range of fence heights used during a typical jump training session for horses competing at BS competition levels revealed significant differences for each level (P<0.0001) (Figure 3.11). Results demonstrated a trend for increased fence height in relation to increased demands of competition level.

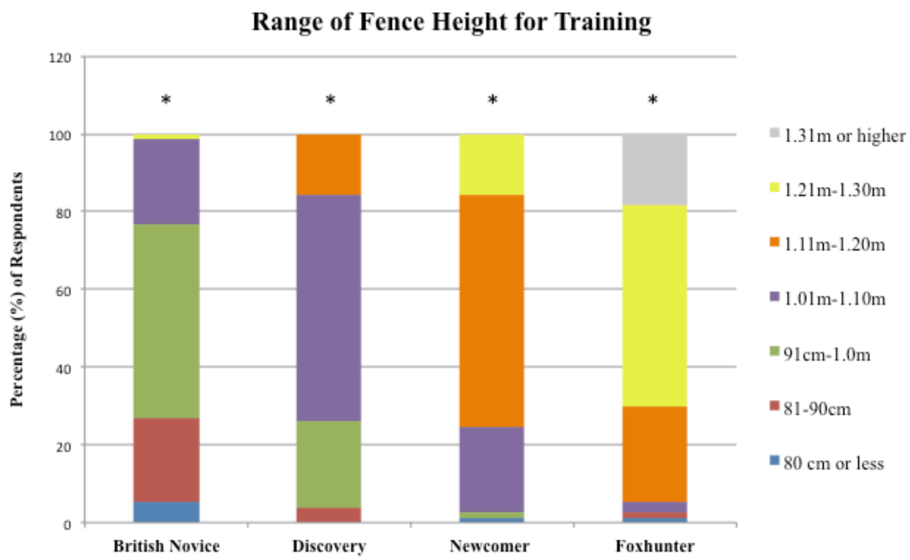


Figure 3.11 Overall respondent results in relation to range of fence height employed during a typical training session for horses competing at BS competition levels. British Novice representing the lowest level and Foxhunter representing the highest level. *Significant differences were found for all categories (P<0.0001).

Industry professionals were asked which exercises would comprise a typical training session before the day of competition for horses training at BS competition levels. Participants were permitted to select all exercises that applied; results are therefore presented as the percent frequency of each exercise calculated from the total number of responses for each competition category. Overall results are displayed in Figure 3.12 Significant differences were found for each competition level (P<0.0001).

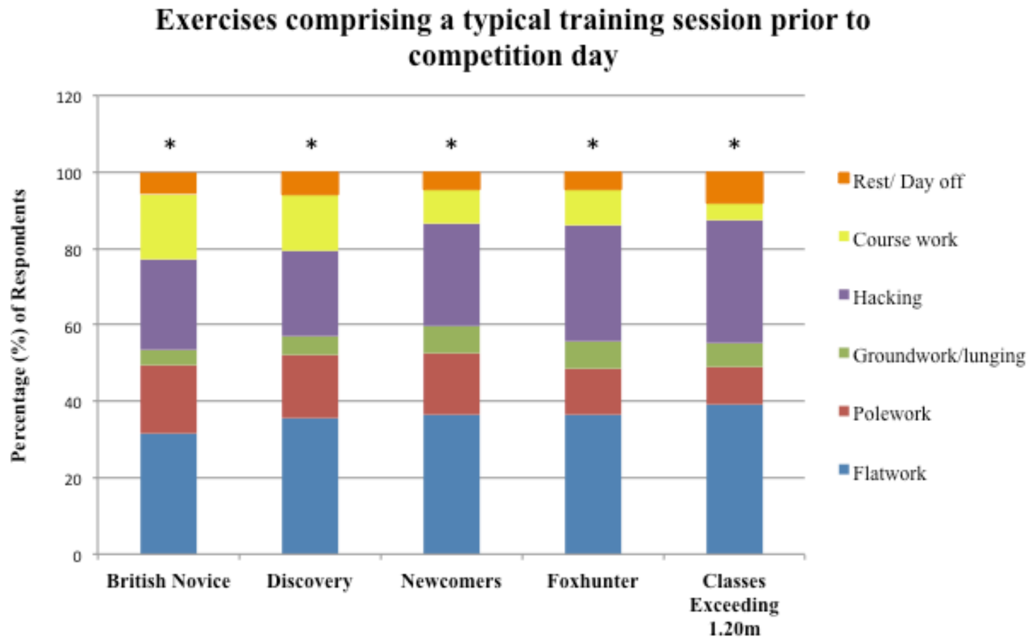


Figure 3.12 Overall respondent results in relation to exercises comprising a typical training session the day before competition for horses competing at BS competition levels. British Novice representing the lowest level and Classes Exceeding 1.20m representing the highest level. *Significant differences were found for each competition level (P<0.0001).

3.4.5 Qualitative Results

Open-ended responses of target and non-target populations to survey questions 4 (Q4), 6 (Q6) and 8 (Q8) were analysed. Of the 66.7% of total respondents comprising the target population, 32.7% (49/150), 28.0% (42/150) and 26.0% (39/150) provided open end responses to Q4, Q6 and Q8 respectively. Of the 33.3% of total respondents comprising the non-target population, only 18.2% (12/75), 21.2% (14/75) and 13.6% (9/75) provided open end responses to Q4, Q6 and Q8 respectively.

3.4.5 (i) Thematic Analysis and Thematic Networks.

Basic, organising and global themes are illustrated in Tables 3.2 and 3.3 Themes in Table 3.2 were derived from Q4, which investigated quality movement in the canter. Themes in Table 3.3 were derived from questions Q6 and Q8, which investigated quality movement in the jump. Basic, organising and global themes from Table 3.2 and 3.3 are presented as thematic networks in Figures 3.13- 3.16 Thematic networks were produced for each global theme (canter and jump) and for target (Figures 3.13 and 3.14) and non-target (3.15 and 3.16) populations.

Table 3.2 Basic, organising and global themes derived from target population responses describing quality movement in canter.

Basic Themes	Organising Themes	Global Theme
• Good Conformation • Joint Articulation	Functional Conformation	Desired Characteristics of Canter
• Engaged • Adjustability • Upward Tendency	Collection	
• Strength • Power • Forward Movement	Impulsion	
• Balance • Regularity	Rhythm	
• Free Moving • Suppleness	Relaxation	
• Flexion • Transmission of Hind Limb Power	Connection	
• Tracks Up	Straightness	
• Training • Breeding	Influenced By External Factors	

Table 3.3 Basic, organising and global themes derived from target population responses describing quality jump technique

Basic Themes	Organising Themes	Global Theme
• Good Conformation • Aesthetics • Joint Articulation	Functional Conformation	Desired Characteristics of Jump
• Adjustability • Lightness • Engaged	Collection	
• Strength • Power • Forward Motion	Impulsion	
• Rhythm • Coordination	Balance	
• Suppleness • Flexibility	Relaxation	
• Desire • Natural • Focus	Carefulness	
• Equal Loading	Straightness	
• Capacity • Jump Suspension	Scope	
• Bascule • Reflex	Technique	

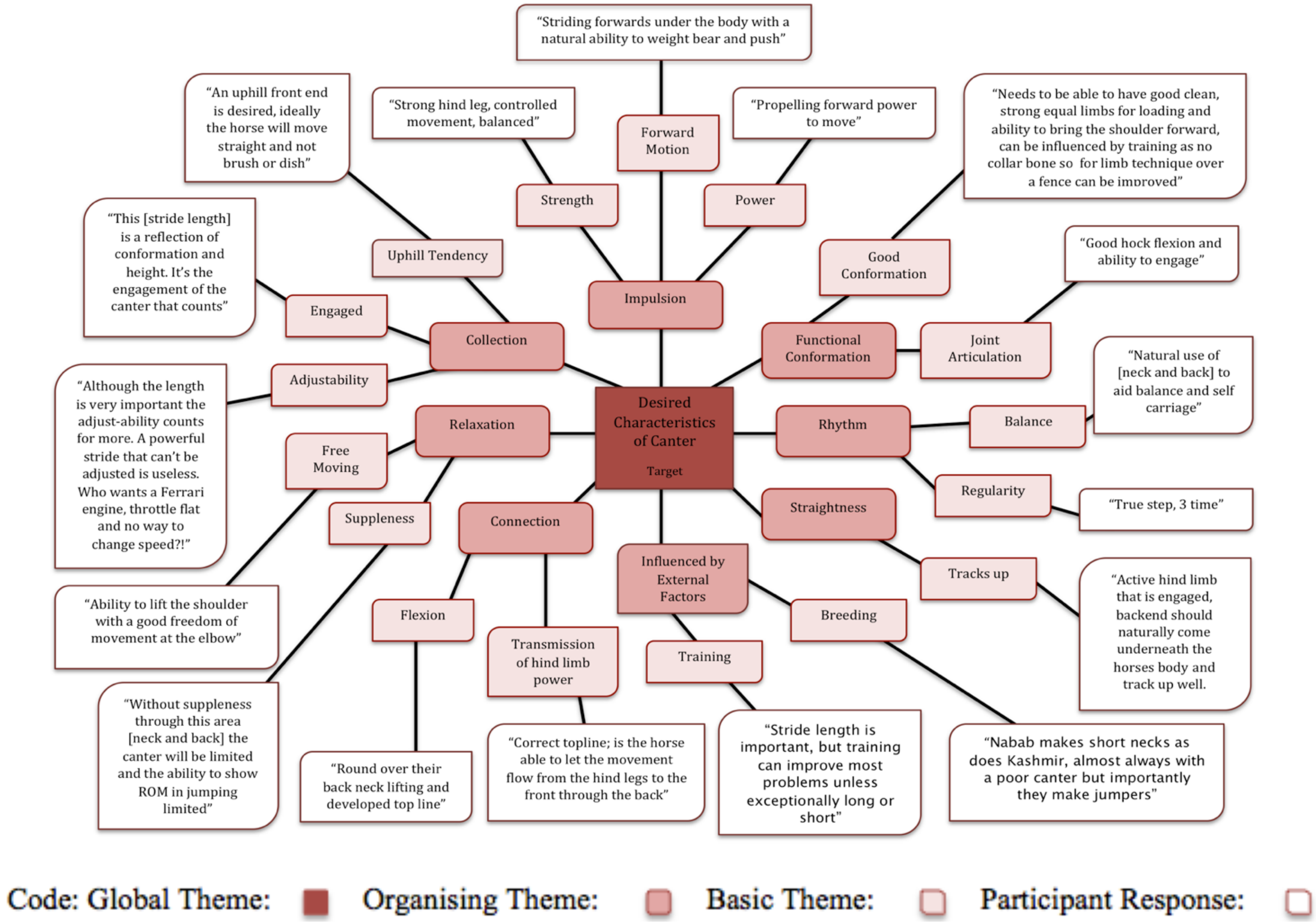


Figure 3.13 Thematic network for "Desired Characteristics of Canter" derived from target population responses.

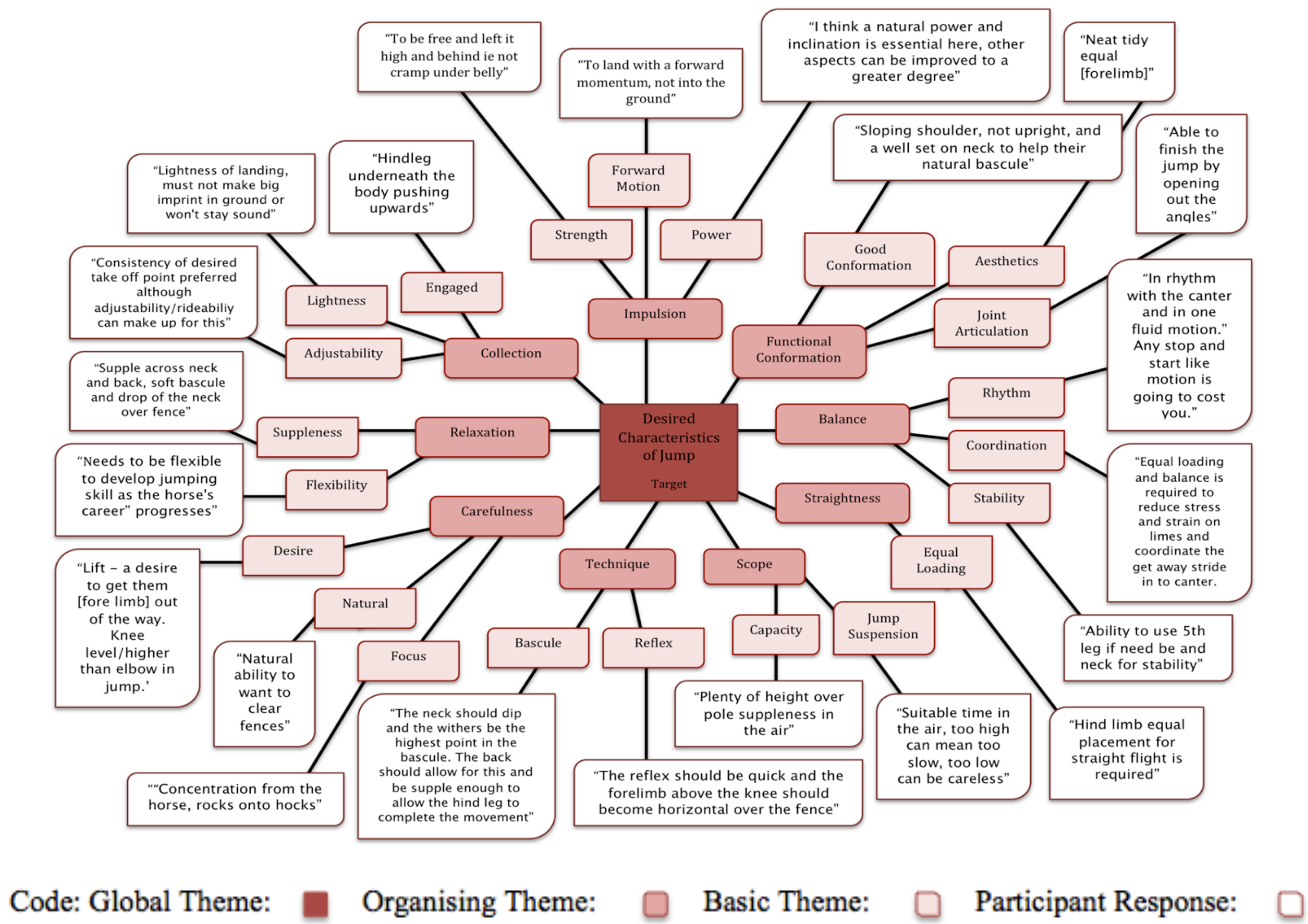


Figure 3.14 Thematic network for "Desired Characteristics of Jump" derived from target population responses.

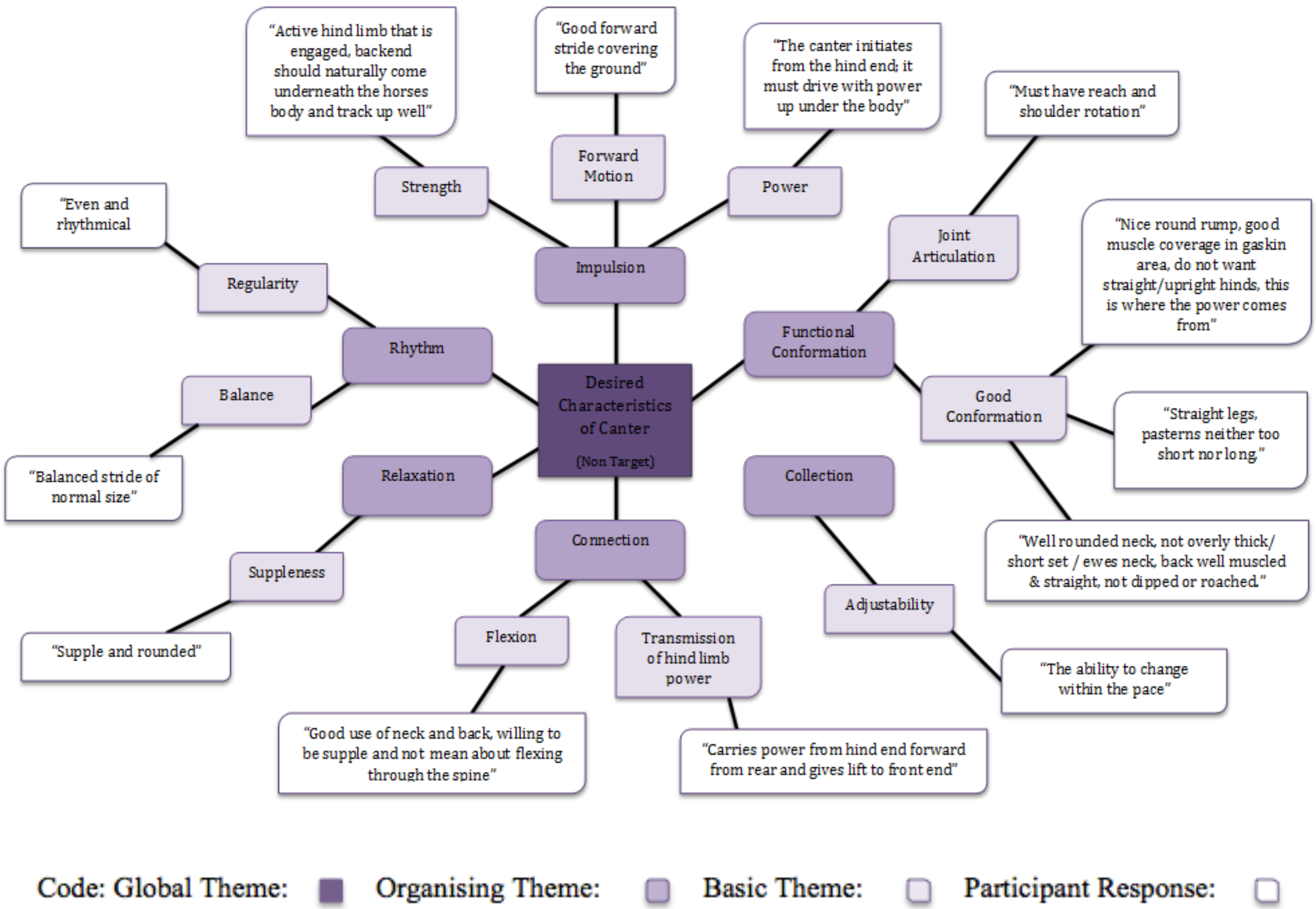


Figure 3.15 Thematic network for "Desired Characteristics of Canter" derived from non-target population responses.

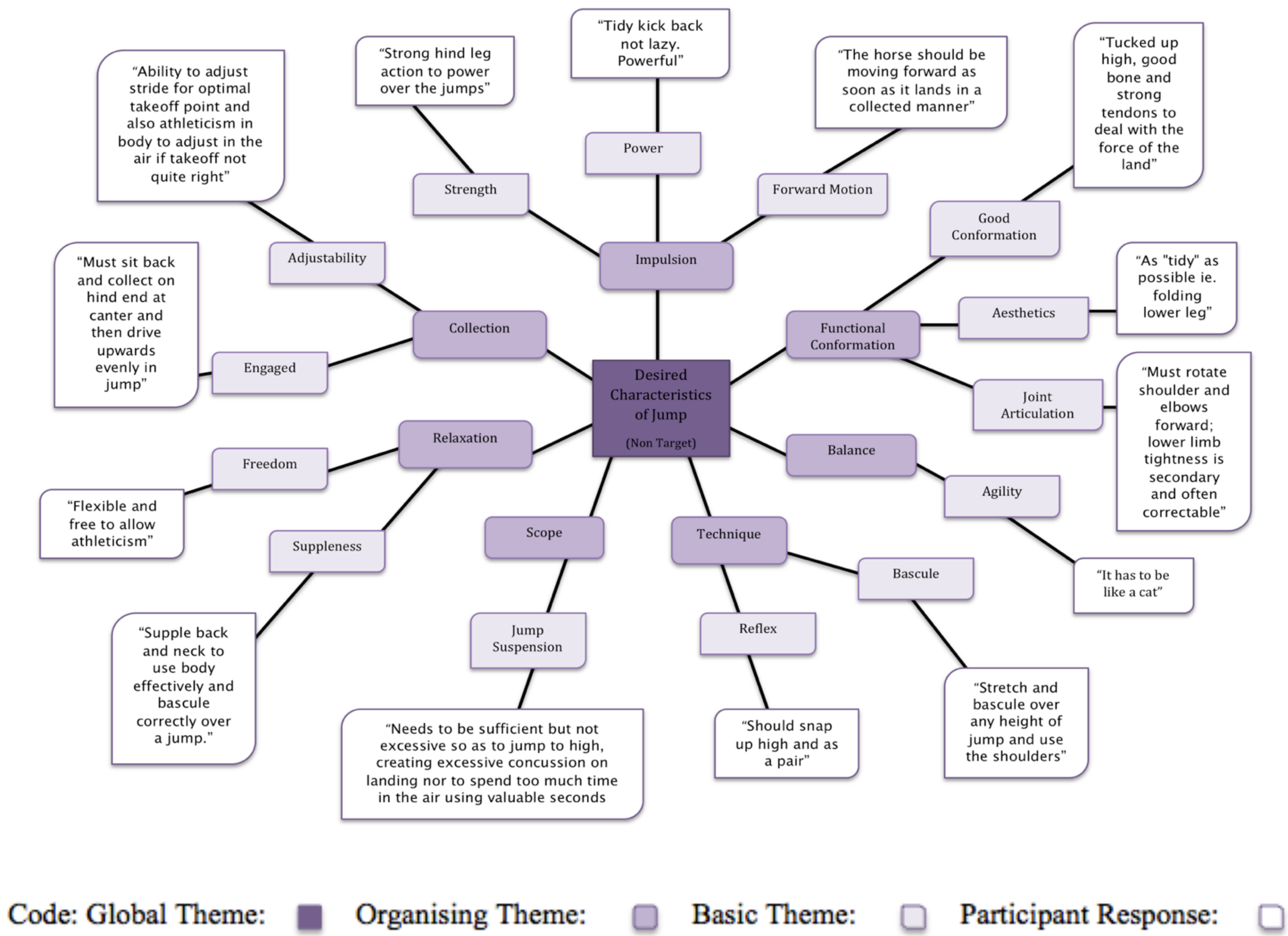


Figure 3.16 Thematic network for "Desired Characteristics of Jump" derived from non-target population responses.

3.4.5(ii) Content Analysis

Frequency count (total number of data segments comprising each code) and percent frequency (frequency count of each code/ total number of data segments comprising the corresponding global theme) values are reported in Tables 3.4 and 3.5 Frequency values reported in Table 3.4 were calculated based on 350 data segments derived from target population responses to Q4.

Table 3.4 Frequency count and percent frequency data for "Desired Characteristics of Canter" global theme.

Codes	Frequency	Percent Frequency
Impulsion	89	25.43%
Functional Conformation	79	22.57%
Collection	66	18.86%
Joint Articulation	37	10.57%
Relaxation	29	8.29%
Connection	15	4.29%
Rhythm	12	3.43%
Balance	10	2.86%
Straightness	10	2.86%
Influenced by External Factors	3	0.86%

Frequency values reported in Table 3.5 were calculated based on 425 data segments derived from target population responses to Q6 and Q8. Both questions investigated quality jump technique and responses were therefore grouped for analysis.

Table 3.5 Frequency count and percent frequency data for "Desired Characteristics of Jump" Global Theme

Codes	Frequency	Percent Frequency
Bascule	72	16.94%
Joint Articulation	66	15.53%
Impulsion	65	15.29%
Reflex	28	6.59%
Balance	26	6.12%
Relaxation	26	6.12%
Aesthetics	24	5.65%
Scope	23	5.41%
Engaged	18	4.24%
Functional Conformation	18	4.24%
Carefulness	13	3.06%
Ability to Judge Take-Off/Landing	9	2.12%
Straightness	8	1.88%
Natural	7	1.65%
Lightness	7	1.65%
Collection	6	1.41%
External Influence	5	1.18%
Rhythm	4	0.94%

3.4.6 Discussion

3.4.6(i) Emerging Trends for Evaluating Quality Movement and Performance in the Equine Jumping Athlete

Findings from this study confirm that equestrians display a preference for specific traits when evaluating "quality" movement. FEI Dressage Rules state that: "the quality of canter is judged by the general impression, i.e. the regularity and lightness of the steps and the uphill tendency and cadence originating from the acceptance of the bridle with a supple poll and in the engagement of the hindquarters with an active hock action – and by the ability of maintaining the same rhythm and natural balance even after a transition from one (1) canter to another" (Fédération Equestre Internationale, 2016). Unfortunately, a definition of quality canter in the jumping horse is not available under FEI Jumping Rules; this is likely because the canter is not judged during competition. In any case, the characteristics of canter, as described by equestrian professionals, show several similarities to the dressage horse.

HL appeared to be the most important criteria when evaluating "quality" movement in canter and jump technique. Further exploration of qualitative results revealed that ***impulsion*** was the most desirable characteristic in the HL in canter, which is defined in Section 3.4.3(i). These findings coincide with literature, which states that the HL as the main contributor to propulsion in canter, with the forelimbs acting as support and impact absorption (Merkens et al., 1993; Schamhardt, 1993a; Dutto et al., 2004b; Baxter and Stashak, 2011).

Impulsion was the third most desirable characteristic in the HL over fences and was also described as a desirable trait during the take-off phase (Table 3.5), which was the highest rated phase for evaluating technique (Figure 3.4). These findings also coincide with literature, as push-off by the HL at take-off has been described as the major factor contributing to the success of the jumping effort and overall performance (Bogert et al., 1994). This is discussed in detail in (Section 2.6.2(ii)). The similarities between industry perception and scientific literature in relation to the hindlimb's contribution to canter and jump would suggest that the anecdotal nature of equestrian knowledge is in agreement with equine biomechanics research.

Contrary to the HL, there appears to be dissociation between industry perception and scientific literature in relation to the importance of the FL when evaluating jump technique. A properly executed preparation by the FL at take-off is required for optimal power production from the HL (Bogert et al., 1994), which is a major determinant for the trajectory of the jump (Clayton and Barlow, 1991; Barrey and Galloux, 1997; Powers and Harrison, 2000). Although the importance of

FL at take-off has been outlined in literature (see Section 2.6.2(i)), it received the lowest rating in relation to importance when evaluating quality jump technique (Figure 3.3). Qualitative data revealed that 15.5% of respondent answers were coded using ***joint articulation*** (Table 3.5). Of these answers, FL characteristics such as: ***symmetry***, ***neatness*** and ***tucking up*** were prevalent and would imply that industry professionals place more emphasis on the aesthetics of the FL rather than the biomechanical traits, which affect the technical execution of the jump.

Forty four percent of industry professionals strongly disagreed with the statement: "quality of canter is irrelevant to quality of jump technique in the jumping horse" (Figure 3.5). This finding is also in agreement with research, which has demonstrated a strong genetic correlation between quality of canter and jumping ability in sport horses (Wallin et al., 2003; Thorén Hellsten et al., 2006). Results from this section clearly indicate the levels of agreement and disagreement between industry perception and equine research.

3.4.6(ii) Emerging Trends for investigating fence type and arrangement for the evaluation of jump technique

Results revealed a preference for evaluating jump technique in the ridden horse over the unridden horse (Figure 3.6). This preference was apparent in 48% of industry professionals and in 64% of those stating that they used "both" ridden and unridden methods to evaluate jump technique. It is anecdotally accepted that the rider influences the horses jump technique (Kilmke, 1989, cited by Powers and Harrison, 2002; Steinkraus, 2012) and the effect of a rider on the horse's jumping kinematics have been previously described (Powers and Harrison, 2002, 2004, 2005; Lewczuk et al., 2006). Significant differences in the linear kinematics of ridden and loose jumping horses have been reported (Powers and Harrison, 2002; Lewczuk et al., 2006). The repeatability of linear kinematics are greater under ridden conditions than in unridden, conditions, implying that the evaluation of jump technique in the ridden horse would require fewer jumping attempts (Lewczuk et al., 2006). These findings may explain why industry professionals prefer evaluating jump technique in the ridden horse. Evaluation of the ridden horse may also be related to the ability to mimic conditions of jumping competition, however this information was not explicitly described in responses and requires further investigation.

Responses revealed no significant difference ($P>0.05$) in the preference for type of fence arrangement used to evaluate jumping technique (Figure 3.7). However, the majority of respondents (42%) displayed a preference for using ***grid lines***. This is in accordance with stallion performance tests, which employ a jumping line of three fences to evaluate jump technique in the ridden and unridden horse. This combination of fences is used to help horses find the correct distances and speed required to jump the main obstacle (Lewczuk et al., 2006). A ***square oxer*** was the preferred fence type, with 51.7% of respondents considering it to be the most effective for demonstrating jump technique (Figure 3.8). Previous studies have reported that ***square oxers*** are the most difficult fence for a horse to jump, which is likely due to the decreased visibility of the parallel back pole (Stachurska et al., 2002; Bochiş, 2011). This finding coincides with general practical knowledge (Bochiş, 2011), which is why it is surprising that the majority of industry professionals assigned the ***square oxer*** the highest rating for its ability to demonstrate jump technique. Interestingly ascending spread fences ranked lowest, with only 16.9% and 7.9% of respondents awarding ***ascending oxer*** and ***triple bar*** the highest rating respectively. Stachurska et al., (2002) and Bochiş (2011) have described the ***ascending oxer*** and ***triple bar*** as the easiest fences for a horse to jump, as horses tend to willingly jump them without faults. This is also in accordance with practical knowledge, as the upward curvature of ascending fences is assumed to encourage the horse's natural bascule. Results from this study may indicate that industry professionals prefer to evaluate the horses jumping ability over more difficult fences.

3.4.6(iii) Emerging Trends for investigating "traditional" training methods in the jumping horse

The second aim of this study was to explore "traditional" training methods based on the perceptions and common practice of industry professionals. Findings from the related questionnaire section conclude that the majority equestrians place great emphasis on the development of quality canter through flatwork. This is in accordance with Ely et al. (2010), who investigated exercise regimes of National Hunt racehorses, reporting that all trainers employed a system of daily cantering but found significant variation in the number of jump-schooling training days. It was postulated that trainers were less likely to jump-school more competent jumpers, due to their decreased risk of falling at obstacles (Ely et al., 2010).

A greater emphasis on flatwork may also be attributed to the increased risk of injury associated with jumping, which is described in Section 2.3.4. Due to the increased injury risks, it would seem appropriate for equestrians to reduce the number of jump training days in "good jumpers". Interestingly, horses exhibiting "quality" jump technique are likely to experience similar GRFs over low fences to those experienced during canter (Schamhardt et al., 1993a). This may further advocate the reduction of jump training for "good jumpers", as cantering exercises may mimic musculoskeletal loading patterns experienced during jumping without introducing increased injury risks. This represents an area of research that should be explored further.

The trend for employing increased flatwork with reduced jump training was evident in several survey question responses. Non-jumping exercises ***flatwork*** and ***hacking*** accounted for the highest proportion of time in a training programme at 38% and 15%, respectively (Figure 3.10). Jumping exercises, such as ***coursework*** and ***grid work***, constituted an average of 11% and 13% of a typical training regime, respectively. These findings are in accordance with Lönell et al. (2014), who reported that flatwork accounted for 41% of the total time exercised, followed by hacking at 19% and jumping at 10% at professional show jumping yards across Europe. A similar study reported that the strategy of jump training varied between riders from mainly grid work/ low fences to full courses set at competition height (Lönell et al., 2010). These studies are described in detail in Section 2.3.1. This would imply that, although exercise strategies vary between trainers, the fundamental proportion of jumping and non-jumping exercises are similar in the majority of training programmes.

Interestingly, a similar trend was observed where participants described the exercises that comprise a typical training session on the day prior to competition. The percentage of respondents who employ non-jumping exercises prior to a competition increased with increasing competition levels. ***Flatwork***, ***hacking*** and ***rest/ day off*** were employed by 31.7%, 23.6% and 5.69%, respectively in participants with horses competing at British Novice. However, more emphasis appears to be placed on non-jumping exercises in higher-level competition, with 39.1%, 31.8% and 8.18% of participants employing ***flatwork***, ***hacking*** and ***rest/ day off***, respectively in horses competing in classes exceeding 1.20m. The opposite trend was observed in relation to jumping exercises prior to competition, with 17.0% of participants employing ***coursework*** for horses competing in British Novice as opposed to 4.55% of participants with horses competing in classes exceeding 1.20m. Several participants took the opportunity to elaborate on their answers using the open-ended section of this question:

"If the horse is experienced I would prefer not to jump before a show. If the horse is a novice it may need a tune up over a course or to work on things such as straightness with poles."- UKCC2 level coach with experience competing in classes exceeding 1.20 m

Some participants defended their answers by discussing the prioritisation of rider needs:

"It entirely depends on the horse and rider combinations, and is not related to the competition level. At the lower levels it may be more relevant to support the rider needs and not he horse's need

to school/ train." – FBHS and UKCC3 level coach with experience competing in classes exceeding 1.20 m.

Differences in rider skill and ability have been explored using kinematic analysis (Eckardt and Witte, 2016; Münz et al., 2014; Patterson et al., 2010; Powers and Kavanaugh, 2005; Lagarde et al., 2005; Peham et al., 2001; Terada, 2000), but fewer studies have explored the differences of novice and advanced riders when jumping. Kinematic studies have reported that both novice and advanced riders have the ability to execute successful jumps when riding an experienced horse (Powers and Kavanaugh, 2005; Patterson et al., 2010). However, on an inexperienced horse, novice riders display a more unbalanced jumping position than their experienced counterparts (Patterson et al., 2010). Novice riders also exhibit decreased ability to maintain balance during landing on experienced and inexperienced horses (Patterson et al., 2010). It has been anecdotally suggested that a rider will require between 1000 and 2000 correctly performed jumps to develop an automatic muscle memory (Marks, 2013). It would therefore seem appropriate for skill development to occur on an experienced horse (Powers and Kavanagh, 2005). However, questionnaire responses indicated that jumping exercises comprise a smaller proportion of an experienced horses training programme. As a result, the incorporation of riding simulators into training regimes has been suggested to develop balance and skill without placing extra stress on the experienced horse's musculoskeletal system (Marks, 2013). Riding simulators were not discussed in questionnaire responses and may be an area for future research to inform equestrian coaching.

Participants ranked ***jump technique*** less important than ***quality canter*** and ***stride adjustability*** for its role in a jump-training programme (Figure 3.9). This may also reflect the apparent prioritisation of non-jumping exercises. As discussed in Section 2.6.3, longitudinal kinematic studies have described jump technique as innate, with individual horses possessing a unique technique (Santamaria et al., 2004a, b; 2005). Industry experts may also consider jump technique as an intrinsic trait that cannot be drastically improved through training. Show jumping trainers may therefore be in agreement with NH trainers, who minimise jump schooling in "good jumpers" (Ely et al., 2010).

A question investigating the range of fence heights employed during a typical training session revealed an interesting trend. A significant difference in fence heights was reported across all competition levels ($P<0.0001$) with the majority of industry experts setting fences at heights equivalent to, or lower than, competition height (Figure 3.11). BS rules describe the maximum fence heights for first round (qualifiers) as 0.90 m, 1.00 m, 1.10 m, 1.20 m for British Novice, Discovery, Newcomers, and Foxhunter classes respectively (British Showjumping, 2011). However, fences may be increased by 10cm from upper height limits in jump off courses (British Showjumping, 2011). For each competition level, the majority of industry professionals reported setting fences at maximum first round and jump off heights. The second most commonly observed trend was that respondents consistently reported setting fence heights lower than maximum competition height. For example: 58.4% of respondents reported setting fences at Discovery competition height range (1.01 – 1.10 m) for training, with the second highest percentage of respondents (22.1%) employing a lower range of heights (0.91-1.00 m). The only exception was British Novice, where 50% of respondents reported setting fences at competition height (0.91 m – 1.00 m) and 21.8% of respondents setting fences both lower (0.81-0.90 m) and higher (1.01-1.10 m) than competition height.

The percentage of respondents setting fence heights lower than competition height increased with increasing competition level. For example respondents using lower fence heights increased from 21.8% in horses training for British Novice to 24.7% in horses training for Foxhunter. This may be the result of a variety of factors, which are highlighted in the following open-end responses:

"Lower for new/fox with a couple of bigger fences every now and then. By this level it should be more work on the technical aspects, which can be worked on using jump exercises over smaller fences rather than constantly jumping the horse over big fences adding more injury risk"- Experience competing in classes exceeding 1.20 m.

Respondents also described the effect of rider skill level on fence height:

"In using gymnastic exercises the horse does not need to be jumped over excessively large fences. By all means in competition week practise over the height of the class if confidence building is required, but for training purposes generally I would work at a small height"- Experience competing in Foxhunter classes.

Based on these responses, it may be appropriate to assume that rider training plays a large role in the frequency and height of jump exercises undertaken in a training programme. However, more experienced riders, who do not require the same level of skill training may use lower fences to minimise the known injury risks associated with repetitive jumping efforts over larger fences (Schamhardt et al., 1993a; Meersoek et al., 2001a). The opposite trend was observed, in respondents who reported setting fences higher than competition height for British Novice (21.8%), Discovery

(15.6%), Newcomer (15.6%) and Foxhunter (18.2%). These results are supported by corresponding open-ended responses from these participants:

"I like them to be training slightly higher than they are going to compete in. However, I use a lot of small fences to improve gymnastic work and keep them on the ball with differences of height when I get to a show" – UKCC3 level coach with 1.60 m Grand Prix and International experience.

"The ranges are out by 10cm as the jump off requires this skill set e.g. for training at a class level I would be working about 10cm higher at home, not at the level required in competition. So Newcomers range would be between 1.05 - 1.20 m at home."- FBHS level coach with experience in classes exceeding 1.20 m.

These responses were not as common, with most respondents employing a lower range of fence heights for training. It is however, interesting to note that a Fellow of the British Horse Society (FBHS) provided these responses, which is the highest coaching qualification awarded by the British Horse Society, and an International rider also holding a coaching qualification. These answers may be associated with the coaching experience of these participants and answers may be influenced by their experience with developing rider skill.

Findings from survey questions investigating "traditional" training highlight the differences in reasoning behind the largely anecdotal training regimes of jumping horses. Significant differences occurred for each question, implying that industry professionals display a preference for certain training practices. Open-ended responses and a review of the literature, suggests that different training practices are the result of a variety of factors, such as: rider skill at lower levels (Powers and Kavanagh, 2005; Patterson, 2010), the horse's level of training (Santamaria et al., 2004a, b, 2005, 2006), inherent jump technique or ability (Santamaria et al., 2004a, b, 2005) and the increased injury risk of jumping higher fences (Schamhardt et al., 1993; Meersoek et al., 2001a). There appears to be an emphasis on non-jumping exercises, with skilled jumping horse being less likely to require the level of proprioceptive skill training as an unskilled horse (Marlin and Nankervis, 2002). However, the development of rider skill and confidence was commonly discussed as a reason for increased jump training. This represents a tendency in equestrian training where rider skill development may be prioritised over the needs of the experienced or inherently skilled equine athlete, which may not require frequent jump training. This information may be used to inform equestrian coaching and suggests that alternative skill training exercises should be considered.

3.4.6(iv) Face Validity of Questionnaire

The thematic networks presented in this study lacked the ability to reveal the most prominent themes reported by industry professionals. However, the networks did permit the assessment of the face validity of the questionnaire. Face validity refers to "expert opinion concerning whether scale items represent the proposed domains or concepts the questionnaire is intended to measure" (Rattray and Jones, 2007). The importance of reporting both quantitative and qualitative evidence regarding the face validity of a test has been described (Nevo, 1985). Thematic networks therefore served as a systematic process, which was used to check the face validity and to further validate the original questionnaire design.

Examination of the questionnaire's face validity was especially important for this exploratory study, as most expert equestrian knowledge is tacit (Winfield, 2010), and therefore generally difficult to communicate (Polanyi, 2009). The ability to categorise reoccurring and prominent responses into related themes would imply that the questionnaire design was effective and that industry experts were able to interpret and answer the questions as the design intended. The inclusion of participant responses in the thematic networks further illustrated the face validity of the questionnaire design, as answers displayed understanding of the question through appropriate answers (Patton, 2002 cited by Freeday and Muir-Cochrane, 2006).

3.4.6(v) Emerging patterns of tacit knowledge between groups

A comparison of thematic networks from target and non-target populations highlights interesting patterns, which may relate to the development and level of tacit knowledge in non-target subjects. Tacit knowledge has been described as: unarticulated, abstract knowledge that is required to work effectively, but that is not explicitly taught and is generally gained through experience (Polanyi, 2009; Sternberg and Hovarth, 1999; Sternberg, 2003; Nash and Collins, 2006; Zappavinga, 2012; Chugh, 2015). Thematic networks offered the opportunity to explore differences in the level of tacit knowledge in expert equestrians and in their novice counterparts.

Expert coaches generally solve problems by retrieving a known solution from long-term memory (Nash and Collins, 2006). This recall ability increases with personal experience as expertise progresses (Ericson et al., 2000). Coaches are expected to have declarative knowledge, relating to tactics and training techniques, as well as procedural knowledge, which relates to knowing how to perform certain activities (Nash and Collins, 2006; Cassidy et al., 2008). The expert coach will have an extensive foundation of declarative and tacit knowledge, which will allow him/her to instinctively make decisions based on knowledge, experience and memory from similar situations

(Nash and Collins, 2006). A similar decision making process has been described in elite athletes, where instinctive, reactions are made through experience and overlearned skilled motor responses, allowing the athlete to perform in an "automatic" manner (Russell and Salmela, 1992).

In addition to required formal coach education courses, the majority of coaches learn through mentoring experienced coaches (Nash and Collins, 2006). However, knowledge development experienced through this type of environment can be slow (Nash and Collins, 2006). This may indicate why non-target thematic networks do not display the full proliferation of knowledge exhibited in target population networks. From these networks, it becomes evident that fundamental declarative knowledge is shared between both populations, which are illustrated in the similarities between organising themes. For example: the same organisational themes were derived for the global theme ***desired characteristics of jump*** in both target and non-target responses. However, the broader, richer responses of the target population resulted in ***straightness*** and ***carefulness*** as additional organising themes. Target population responses also resulted in a more extensive array of basic themes, such as: ***capacity***, ***lightness***, ***flexibility***, ***equal loading***, ***desire***, ***focus*** and ***natural***, all of which stem from fundamental deductive base knowledge of training techniques. However, it is likely that these additional themes were reported due to the greater level of experience and subsequent recall ability of target population equestrians.

Capacity offers a relevant example of this knowledge divide, as this basic theme was only reported by the target population under the organising theme of ***scope***. ***Scope*** is defined as "the ability of the horse to jump upward with power while at the same time developing forward direction" (KWPN-NA, 2015). ***Capacity*** is often used in conjunction with scope by various studbooks to describe and evaluate the horse's capacity for bigger tasks (Dansk Ride Forbund, 2013). The target population's knowledge of ***capacity*** may therefore be linked to increased experience and knowledge of jumping evaluation procedures. On the other hand, ***Jump suspension*** represented a basic theme for both populations under the organising theme of ***scope***. Jump suspension may therefore represent a component of fundamental declarative knowledge.

From these examples, it becomes clear that shared knowledge between target and non-target populations is in the form of fundamental declarative knowledge. However, target responses exhibit more richness and variety. These differences are to be expected as the non-target population undergoes progression towards expert levels by obtaining tacit knowledge through experience. Further work should be conducted in this field in an effort to translate tacit equestrian knowledge into explicit knowledge (Winfield, 2010). The externalisation (Nonaka and Takeuchi, 1995) of equestrian tacit knowledge may allow researchers to better understand and incorporate this important aspect into their work. Furthermore, coaches who operate in a tacit manner have been described as potentially ineffective coach educators, as their knowledge is largely unarticulated (Nash and Colins, 2006). Therefore, future work should be conducted on a larger population to further refine and understand equestrian tacit knowledge and to determine whether this tool may be effective in informing current equestrian coach training.

3.4.6(vi) Limitations

Several limitations were present in this study. However, these limitations were similar to those reported in previous survey research conducted in the equestrian industry and were mitigated as extensively as possible throughout the study. Although over 200 equestrians undertook the questionnaire, a completion rate of only 32.7% (49/ 150) of the target population completed all questions. This completion rate is in accordance with similar equestrian survey research, which has reported completion rates of 22.5% (Murray et al., 2010a, b), 24.8% (Warren-Smith and McGreevy, 2008) and 33.3% (Quinn and Bird, 1996). The completion rate did however; vary depending on the question, with completion rate decreasing due to dropout with progressing questions. This was accounted for by reporting results as percentages of the total number of responses to specific questions. This method has been used in previous equine survey research to account for participant dropout (Murray et al., 2010a). However, it is possible that the decreasing number of responses may have affected the accuracy of findings and further research should be conducted to ensure that results from this study are consistent within the larger equestrian population.

Target population response rates were also low for open-end questions. However, this may partially be due to the fact that industry professionals within this population function tacitly and may therefore struggle to articulate responses (Sternberg, 2003; Nash and Collins, 2006). This assumption may be further justified by the greater percentage of non-target participants who provided open-end responses, as novices are less likely to function tacitly (Nash and Collins, 2006).

The training of show jumpers is an extensive, multi-factorial task and closed-end response options may have neglected to incorporate some of these factors. However, every effort was made to ensure that the questionnaire design included the most relevant content through extensive research, development and pilot testing. Many of the questions, particularly those comprising the “training methods” section, were highly dependent on individual horses. It is widely accepted that training schedules and methods are largely related to the educational level of the horse (Eisersiö et al., 2015) and in some cases to the rider. The difficulty associated with providing a generalised answer was highlighted during the development stages and the following instructions were provided to mitigate this issue:

"All questions from this section should be answered in relation to a horse training at a minimum competition level of BS Discovery. We recognise that answers will vary greatly depending on individual horses. However, please answer based on methods which you would most frequently use under ideal circumstances (i.e. ideal facilities, availability of jump equipment and soundness of horse)."

Findings from this study link closely to those reported by Lönnell et al. (2014), who investigated the training regimens of 263 horses from 28 professional show jumping yards across Europe. The close compliance of results would imply that results from this study are valid in relation to industry training practices. These similarities may also mitigate concerns in relation to the number of respondent dropouts and subsequent missing data points.

3.4.7 Conclusion

This study offers a novel insight into the opinions and ideas of highly qualified equestrians, which relate to the evaluation of movement and training of the equine jumping athlete. Findings from this study demonstrate that experienced equestrians display obvious preferences for specific traits when evaluating "quality" movement. The majority of equestrians strongly agreed that movement was the most important indicator of performance, further justifying the investigation of quality movement in relation to muscle activity in the main study of the thesis. Questionnaire results also revealed that industry professionals display a preference for certain training practices, with the majority of equestrians placing emphasis on flatwork. Open-end responses uncovered differences in tacit knowledge between expert and novice equestrians, revealing interesting patterns about how knowledge transfer may occur between the groups. To the author's knowledge, this is the only study to explicitly describe differences in tacit knowledge of equestrians. The information collected from this study offers an original contribution to knowledge and will provide a basis from which "quality" movement and "traditional" training methods can be defined. This information will be invaluable for the thesis, as it will be used to inform the collection and interpretation of data in a manner that is relevant to the industry professional.

Chapter 4. Review of Methods

This chapter provides an overview of the equipment and techniques employed for data collection throughout the thesis. This chapter will focus on the general methods employed for pilot work, which employed telemetric sEMG and 3D motion capture technology. However, detailed methods are described separately for the main study of the thesis (Chapter 7) and for development of methods studies (Chapters 5 and 6).

4.1 Ethical Approval

Ethical approval for this project was obtained from the University of Central Lancashire's Animal Projects Committee under approval number RE/13/04/SH (Appendix B). All researchers involved adhered to procedures and risk assessments for the safe handling of equipment and horses. Participant information and consent were obtained from: horse owners, riders and supervisory members of yard staff where applicable.

4.2 Surface Electromyography Measurement Technique

A detailed description of the Delsys Trigno (Delsys Inc., Boston, USA) system, which was used to collect sEMG data from equine subjects, is provided in Chapter 5 (Section 5.2.2(i)). Sensor placement and subject preparation techniques employed for sEMG data collection are described in Sections 5.2.2(ii) and 5.2.2(iii), respectively.

4.3 Kinematic Measurement Technique

4.3.1 System

A Qualisys Oqus camera system (Qualisys Medical AB, Göteborg, Sweden) was used to collect 3D kinematic data from equine subjects. The system uses infrared light emission to reconstruct 3D coordinates of retro-reflective markers positioned on anatomical landmarks. Eight Oqus 300 series cameras were used for all data collection sessions throughout the thesis.

The Qualisys Oqus system can be used both indoors and outdoors, making it ideal for collecting data from equine subjects when indoor facilities are not available. An active filtering setting is available, which increases the cameras ability to capture passive markers under daylight conditions where light pollution may become problematic. Continuous mode is the standard mode for the active filtering setting and filters out background light by capturing a second image, without infrared flash, prior to each actual infrared image (Qualisys AB, 2011). This image is subtracted from the infrared image, which filters out background light from each image used by the camera (Qualisys AB, 2011).

4.3.2 Calibration

The system must be calibrated to provide Qualisys Track Manager (QTM) (Qualisys Medical AB, Göteborg, Sweden) software with information about the lens parameters (internal parameters) and orientation and position (external parameters) of cameras relative to the LCS (Richards et al., 2008a). Calibrating the system creates a measurement volume where marker coordinates can most accurately be reconstructed. The origin of the LCS and the positive direction of the X and Y-axis are defined using a static reference L-frame (Figure 4.1) (Richards et al., 2008a). A dynamic wand calibration was used for this research, which uses calibration algorithms based on two-dimensional coordinates, generated from wand movement, to detect the position and orientation of cameras (Richards et al., 2008a). Specifications for the calibration kit, which consisted of the L-frame and calibration wand, are detailed in Figure 4.1. An extended calibration was conducted throughout the thesis to provide a large capture volume, which was required to collect kinematic data from consecutive canter strides and from the jump stride. In an extended calibration, the L-frame reference structure is only visible to certain reference cameras and the remaining cameras are calibrated based on their overlap with the frame of view of the reference cameras (Qualisys AB, 2011).

4.3.2(i) Camera position and calibration technique

Eight Oqus cameras were positioned side-by-side, in a linear configuration, and the L-frame reference structure was positioned in front of camera 5, so that it was visible to cameras 4 – 6. Retro-reflective markers were then placed on the ground on either side of the L-frame, to define the longitudinal area for the extended calibration. Cameras were angled accordingly so that retro-reflective markers were visible at the bottom of each cameras field of view. This was done to ensure that the hoof marker was captured during data collection. The marker threshold defines the threshold intensity level for markers and was set in the range of 15 - 17% for data collection. This threshold ensures that pixel values brighter than the threshold are identified as markers and was lowered from default 20%, allowing cameras to identify markers with less difficulty under outdoor conditions. Retro-reflective markers were removed from the calibration area and a wand calibration was conducted in accordance with instructions for an extended calibration (Qualisys AB, 2011). The researcher performing the calibration ensured that wand was positioned so it was visible to a minimum of three cameras at any given time during the procedure. The camera system was calibrated for 90 seconds and a separate calibration was performed for each data collection session. During data collection sessions, a recalibration was conducted if calibration quality warnings occurred in QTM.

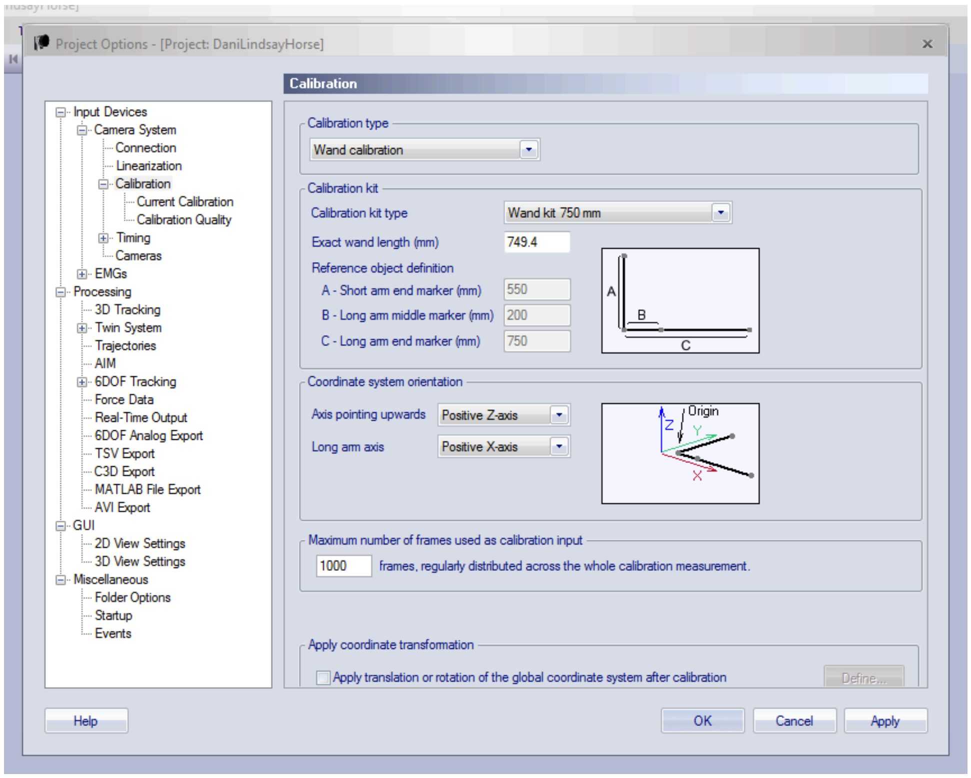


Figure 4.1 Calibration specifications

4.4 Technique for synchronous collection of sEMG and kinematic data

In order to fulfil the aims of the thesis, it was necessary to investigate the relationship between muscle activity and movement patterns in equine subjects. As a result, synchronisation of kinematic and sEMG data were required. An external trigger (Delsys Trigger Module, Delsys Inc., Boston, USA) was employed to ensure time-synchronisation of kinematic and EMG acquisition systems. The trigger was connected to the master camera (camera 1) and to the trigger port on the Delsys Trigno system. The "use external trigger" option was selected in QTM under camera settings (timing), specifying that the start of the capture be delayed until the external trigger event occurs (Figure 4.2).

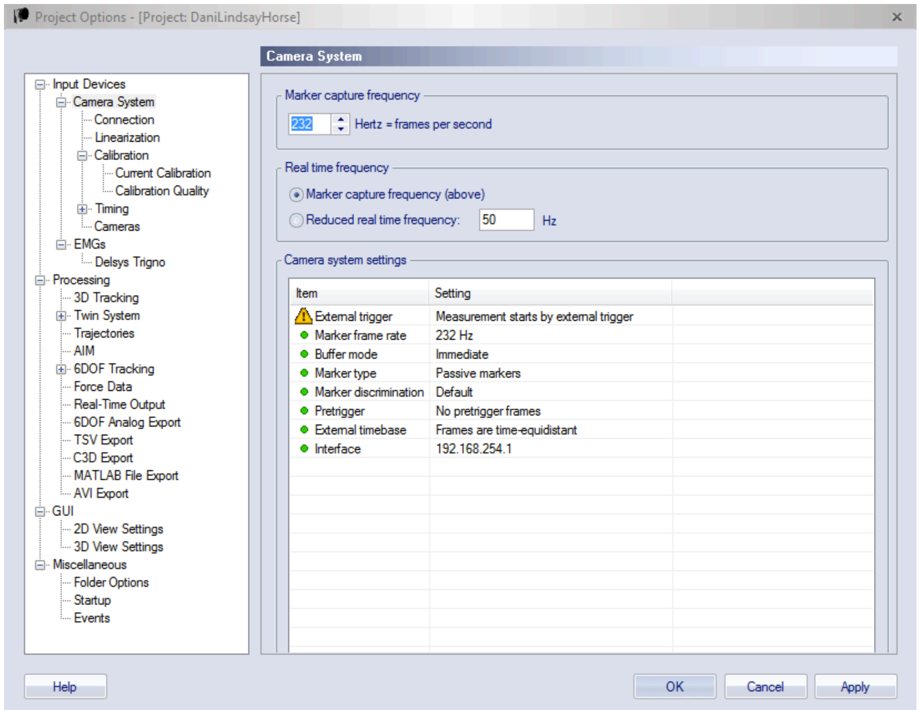


Figure 4.2 Camera settings page, specifying the use of an external trigger device to initiate capture.

A constant delay of 20ms between kinematic and EMG acquisition systems is known. This constant delay is corrected for by shifting EMG signals forward by 5 frames during data processing.

4.5 Pilot Work

Pilot tests were conducted to determine the feasibility of 3D kinematic and sEMG data collection techniques in the ridden horse during canter and jump. Pilot testing was conducted in December 2014 at Myerscough College (Bilsborrow, Preston, UK).

4.5.1 Animals

Four horses (age: 7.3 ± 2.6 years, height: 155.0 ± 8.2 cm, breed: ISH, WB, Welsh Cross, sex: 2 mares, 2 geldings), which were all currently in work and competing, were used for pilot work. All horses were physically fit, were deemed sound by their riders, and were capable of performing the physical demands required for testing. Different riders, each with similar experience (10+ years riding experience) and riding ability (competed minimum BE 80) rode each horse. Each horse had competed over a minimum fence height of 0.80 m (BE 80, unaffiliated SJ 0.85 m).

4.5.2 Animal Preparation

4.5.2(i) Warm Up

The horses firstly completed a typical warm up session. Warm up consisted of walk, trot and canter. The duration of warm up was dependent on each horse's specific needs, and determined by its rider. Warm up generally lasted approximately 15 minutes. During this time, each horse was habituated to the camera system. sEMG sensors and retro-reflective markers were attached to pre-determined positions following warm up to ensure optimal adhesion. Procedures for sEMG sensor and kinematic marker attachment are detailed below.

4.5.2(ii) Kinematic marker preparation

Fifteen spherical retro reflective markers, 25mm in diameter were used for kinematic data collection. Markers were positioned on anatomical landmarks on the right side of the horse's FL in accordance with Hjerten and Drevemo (1994) and HL in accordance with (Hodson et al., 2001). The simple marker set is illustrated in Figure 4.3 and markers were placed on the following anatomical locations: FL; proximal end of the spine of the scapula, greater tubercle of the humerus (centre of rotation of the shoulder joint), lateral epicondyle of the humerus (centre of rotation of the elbow joint), lateral tuberosity of the radius, lateral styloid process of the radius, proximal end of metacarpal IV, centre of rotation of the MCPJ and the lateral hoof wall, approximately over the centre of rotation of the DIPJ. HL; the most ventral part of the tuber coxae, greater trochanter, lateral epicondyle of the femur, talus, the centre of rotation of the MTPJ and the lateral hoof wall. One marker was placed on the croup to track speed during the trials. Retro-reflective markers were attached to the horse using double-sided tape (Mammoth Carpet Fix Cloth Tape, Everbuild, UK). Any excessive hair over anatomical landmarks was trimmed to ensure optimal adhesion.

Figure 4.3 Retro-reflective marker positions, comprising the simple marker set employed for data collection. Note: EMG sensor placements were part of a larger study and do not reflect the locations used in this thesis (except Triceps Brachii and Cervical Trapezius)

4.5.2(iii) sEMG Sensor Preparation

Electrode-skin interface preparation and sEMG sensor application procedures are detailed in Chapter 5 (Section 5.2). Sensors were applied to muscles on the right-hand side of each horse.

4.5.3 Equipment set up and calibration

Eight infrared cameras (Qualisys Medical AB, Göteborg, Sweden) were secured to tripods and positioned in a straight line, approximately 8.0 m away from the outside wall of an indoor riding arena (Myerscough College, Bilsborrow, Preston). This arrangement ensured that the capture volume was approximately situated on the centre line of the arena, which made it easier for riders to approach the volume from both right and left canter leads. The camera system was calibrated using the extended calibration technique described in Section 4.3.2(i). The calibration volume for pilot testing was approximately 8.0m in length and is illustrated in Figure 4.4. Calibration quality was accepted if the average residual value was within the range of 0.5 to 1.5 in accordance with Qualisys AB (2011). Calibration results for pilot work are detailed in Figure 4.5.

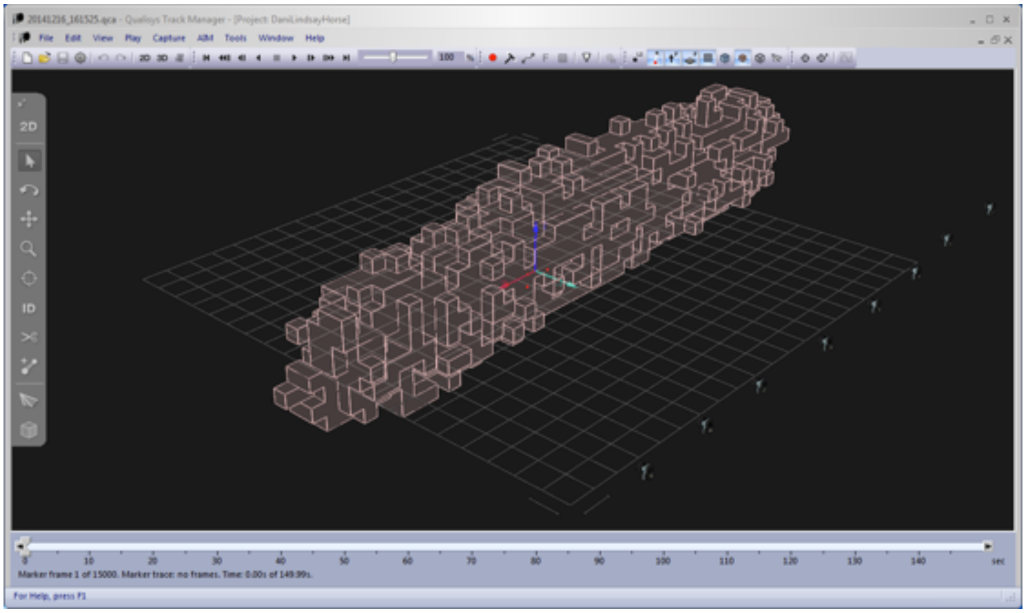


Figure 4.4 Camera configuration and calibration volume for the extended calibration technique.

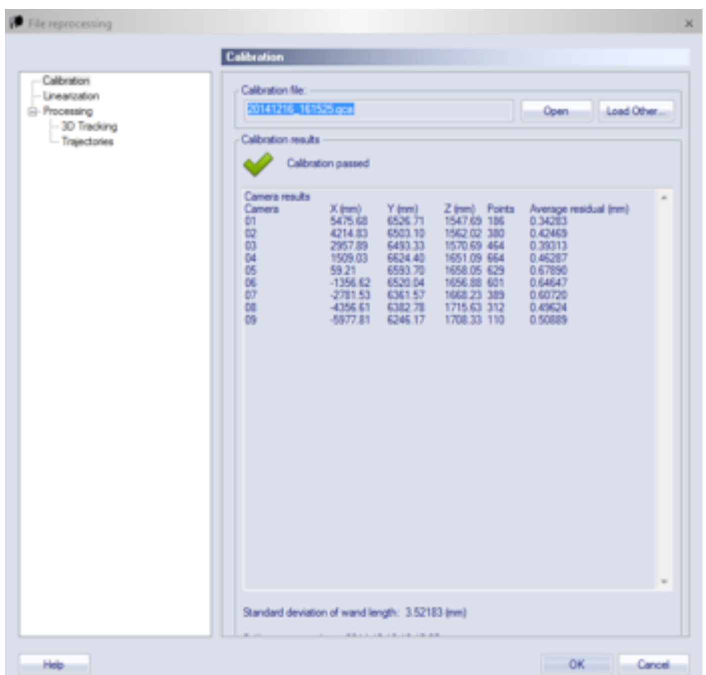


Figure 4.5 Calibration results for the extended calibration used during pilot work data collection.

The Delsys Trigno base station, external trigger system and laptop were all safety situated beside camera one. All equipment and wiring was enclosed behind barriers to ensure the safety of equine and human participants. The general set up of equipment is illustrated in Figure 4.6. Poles were placed on the ground approximately 4.5 m from the cameras to define the calibrated volume and were used to ensure that riders positioned their horses within the calibrated area. Riders were instructed to ride horses as close to the poles as possible.

Figure 4.6 Camera system configuration and set up for pilot work.

4.5.4 Jump Set Up

Jump set up was informed by results from the ***Fence type and arrangement for evaluation of jump technique*** section of the questionnaire (Chapter 3). Results revealed a preference for evaluating movement in the ridden horse over a grid line. A two-stride combination was therefore used to collect jumping data and was composed of a cross rail and vertical fence set approximately 11m apart, depending on the horse. Jump data were collected from the vertical fence, which was positioned in front of camera six, with the cross rail set up slightly before camera one to allow for the 2-stride distance. The centre of each fence was placed approximately 4.5 m from the cameras over the optimal calibrated volume, where the poles were originally placed for canter trials. Poles were moved to the side for jump trials and moved back to the same position for canter trials.

In order to make direct comparisons between elite and non-elite groups for the main study of the thesis, it was necessary to establish a fence height that could be executed by both groups. Data were therefore, collected over a 1.0 m vertical fence, as the forces required for horses to jump a fence lower then this height are not much greater than those observed in canter strides (Schamhardt et al., 1993; Clayton and van Weeren, 2013). Furthermore, this fence height offered an obstacle that non-elite horses could realistically jump without overexerting themselves. Questionnaire results revealed that vertical and square oxer fences were considered to be the most effective for demonstrating jump technique. However, the jumping capability of some non-elite horses did not permit data collection over a 1.0 m spread, which is why the vertical fence was chosen for data collection. Additional data were collected over a square oxer in horses that were capable of executing this fence type. Jump arrangement and equipment set up are illustrated in Figure 4.7. The jump arrangement could be quickly set up and was easily deconstructed for canter trials.

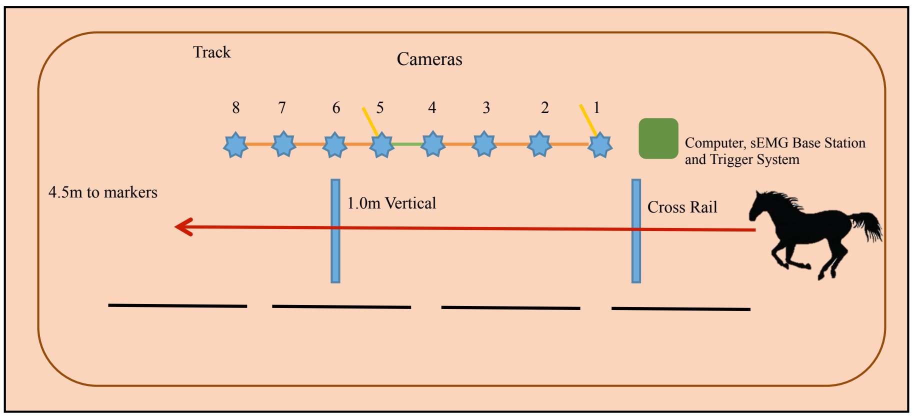


Figure 4.7 Jump arrangement and equipment set up for data collection. Between cameras (blue stars), horizontal lines represent bundled data and power cables (orange), data cable (green), power cables (yellow), Ethernet cable (blue). The diagonal purple line represents the external trigger from camera 1. The red arrow indicates the direction of the track.

4.5.5 Procedure

A static trial was recorded from each horse prior to dynamic trials. For static trials, each horse was ridden to the centre of the calibration volume and stood as still, and as square as possible for capture. Static and dynamic trials were recorded using QTM software (Qualisys Medical AB, Göteborg, Sweden) and recordings were initiated using the external trigger system. Each horse was ridden through the capture volume at canter and riders were instructed to position horses adjacent to the poles, which demarcated the optimum volume of the calibrated area (Figure 4.8). Kinematic data were collected at 232 Hz and sEMG data were collected at 2088 Hz. A minimum of six canter trials were collected from each horse, with three trials collected from the left and right lead. If necessary, extra canter trials were collected to ensure that sufficient stance phase data were recorded within the optimal capture volume.

Following canter trials, the jump combination was set up in accordance with Section 4.5.4. Horses were permitted to warm up over smaller fences, depending on their requirements. Jump trials began when riders felt their horses were ready to execute the 1.0 m vertical fence. A minimum of six jump trials were collected, of which three were collected from a left lead approach and three from a right lead approach. A researcher recorded details for each trial, including approach lead and details on jump execution i.e. when a rail was rubbed or knocked down. Only successful jump trials were used for data analysis. sEMG sensors and kinematic markers were checked between trials to ensure optimum adhesion and were replaced at any sign that adhesion had been compromised. Aftercare of subjects was in the form of adequate cool down, un-tacking and grooming procedures.

Figure 4.8 Data collection during one canter trial.

4.5.6 Data Analysis

4.5.6(i) EMG Data Analysis

sEMG data from pilot work were processed and analysed in Visual 3D (V3D) software (C-motion Inc., USA). Data were used to examine the fidelity of signals and to develop signal processing and analysis methods for optimal: filtering techniques (Section 5.3), sensor locations (Section 5.5) and detection of muscle activity onset and offset (Section 5.4). Data analysis techniques are described in detail in each respective study.

4.5.6(ii) Kinematic Data Analysis

Kinematic data were digitised in QTM software using a custom label list, which included FL and HL markers described in Section 4.5.2(ii). Digitised files were exported as c3d. files and opened in V3D software, for further analysis. The origin of LCS was defined as follows: X-axis as cranio-caudal (direction of movement), Y-axis as medio-lateral, and Z-axis as vertical. For each subject, a segment model of the fore and HL was created using the static trial, and was applied to all dynamic trials from that subject. In accordance with previous jumping studies (i.e. Bogert et al., 1994; Dutto et al., 2004; Bobbert and Santamaria, 2005; Santamaria 2004a, b, 2005) a rigid-body model was used, which assumed that the limbs were rigid segments articulated to one another with hinge joints. The joint axes and rigid segment lengths were defined using marker coordinates from the static trial. Virtual landmarks were generated to produce medial markers for each marker described in Section 4.5.2. Medial and lateral markers were then used to define the proximal and distal ends of each fore and HL segment. A segment coordinate system (SCS) was defined for each segment based on the LCS and was defined with the: X-axis as medio-lateral, Y-axis as cranio-caudal and Z-axis as axial. Joint angles were calculated based on the static trial using the cardan sequence xyz. Joint angles were measured in the sagittal plane, where flexion was defined as rotation about the SCS X-axis, and was positive when the distal segment rotated towards the palmar aspect of the proximal segment.

A full body model was not employed and therefore calculation of the CM using segmental inertial properties, as described by Butchner et al. (1997), was not possible. However, a virtual marker was created to represent the CM based on methods described by Bogert (1994). The virtual marker was projected midway between the croup and greater tubercle of humerus markers, and was offset in the axial direction by 50%. Figure 4.9a, b illustrates the rigid body model including the SCS for each segment, joint angles and the virtual CM marker used for kinematic data analysis.

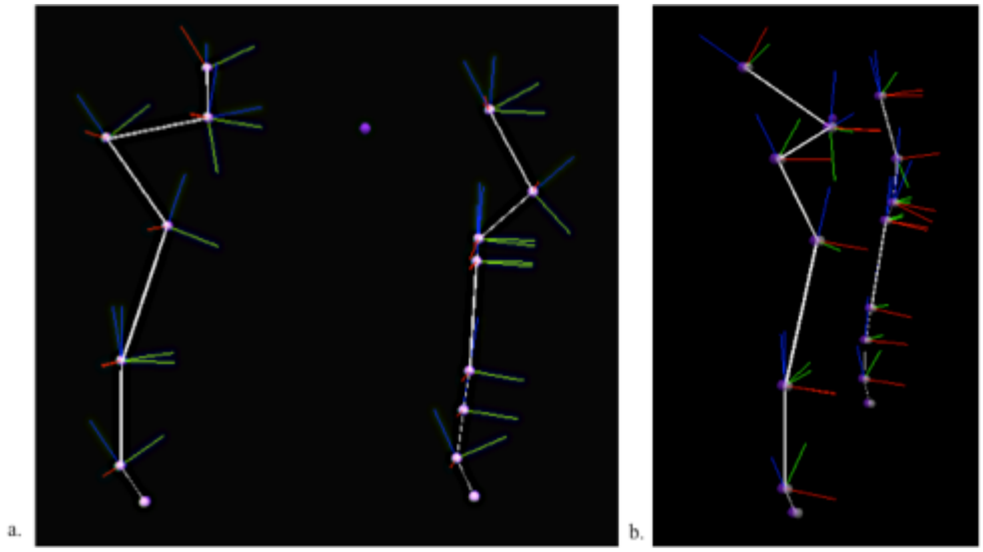


Figure 4.9 a.) Rigid segment model created for each subject, including the SCS for each segment and the virtual CM marker used for kinematic data analysis b.) a more posterior view of the model, which better illustrates the SCS for each segment.

Kinematic data from dynamic trials were interpolated to a maximum gap of 10 frames. Pilot data were then used to determine optimal methods for kinematic: signal filtering (Section 6.1), gait event detection (Section 6.2), and measurement of quality movement traits described by industry professionals in the questionnaire study (Section 6.3).

5. Method Development for the Collection and Analysis of sEMG Data

5.1 Introduction

“To its detriment, electromyography is too easy to use and consequently too easy to abuse” (De Luca, 1997). This quote from De Luca’s (1997) key paper describes the enigmatic state of sEMG research and the many challenges associated with progressing the discipline towards a more scientifically based state. In this paper, De Luca (1997) raises several questions, which the investigator must be aware of to ensure proper usage of sEMG technology. These questions include:

- Is the EMG signal detected and recorded with maximum fidelity?
- How should the EMG signal be analysed?
- Where does the detected EMG signal originate?
- Is the EMG signal sufficiently stationary for the intended analysis and interpretation?

(De Luca, 1997)

These questions are especially important in equine sEMG research, which is growing in popularity, but still exhibits a lack of standardised data acquisition and analysis protocols (Valentin and Zsoldos, 2016). Several researchers have used sEMG to assess muscle activation patterns when evaluating equine gait and locomotion (Colborne et al., 2001; Crook et al., 2010; Robert et al., 2001a, b; Zsoldos et al., 2010a, b). However, the aforementioned lack of standardised protocols makes it difficult to develop consensus on procedures and represents a major gap in knowledge (Zaneb et al., 2007; Valentin and Zsoldos, 2016; Vögele et al., 2016). Equine researchers have employed data analysis methods described in human research for equine sEMG data. For example, Harrison et al. (2012) employed the methods described by Hortobágyi et al. (2009) for analysis of equine sEMG data. However, to the author’s knowledge no studies have validated these methods for use on equine sEMG data. An investigation of previous equine sEMG methods is therefore warranted to examine them for use in this PhD. Four studies are presented in this chapter, which aim to investigate questions posed by De Luca (1997).

Study 5.2 aimed to answer questions related to how the sEMG signal is detected and recorded with maximal fidelity by exploring: ideal electrode configuration, skin preparation, sensor adherence and protocol for collecting data from dynamic movements in equine subjects. This investigation was used to inform and develop methodology for the main study of the thesis.

Studies 5.3 and 5.4 aimed to answer questions relating to how the equine sEMG signal should be analysed. Study 5.3 presents an original investigation into optimal signal filtering of equine sEMG data and was conducted in an effort to determine the ideal filtering techniques for removing low-frequency noise. Study 5.4 was conducted to establish a method for accurate detection of muscle activity onset and offset events in the equine sEMG signal.

Study 5.5 aimed to determine the origin of the desired EMG signal, by investigating optimal sensor locations for selected superficial equine muscles. This study explored the baseline noise level and muscle onset/ offset activity pattern to determine sensor locations, which produced the highest fidelity signal.

The aim of these studies was to explore methods for accurate sEMG detection and analysis in equine subjects. These findings would then inform the methods employed in the main study of the thesis and would offer a starting point for the standardisation of sEMG protocols in equine research.

5.2 Development of a standardised protocol for the collection of equine sEMG data

5.2.1 Introduction

The Surface EMG for Non-invasive Assessment of Muscles (SENIAM) project was developed to provide recommendations on sensor properties and placement protocol, based on a consensus of sEMG experts (Hermens et al., 2000). The SENIAM project has been described as the first step towards the standardisation of sensor properties and placement protocols for human EMG research (Hermens et al., 2000). sEMG is widely accepted as a valuable tool, which has been employed by many researchers to investigate muscle function in horses (van Wessum et al., 1999; Licka et al., 2009; Zsoldos et al., 2010). However, sEMG data acquisition from animal subjects poses several limitations for researchers, which include but are not limited to: skin preparation and adhesion on coats with excessive hair, oil, and dirt (Valentin and Zsoldos, 2016). Furthermore, the majority of equine sEMG studies do not provide justification for the sensor properties and sensor placement procedures employed in research. This may be partially due to the absence of approved protocol for sEMG in equine research (Zaneb et al., 2007; Valentin and Zsoldos, 2016; Vögele et al., 2016). The validation of sEMG sensor properties and placement is therefore warranted for equine sEMG data collection.

In this study, pilot work was conducted to investigate and develop methods for collecting sEMG data for the main study of the thesis. The aim of this study was to identify optimal: skin preparation, sensor adherence, sensor placement and protocols for sEMG data acquisition in equine subjects.

5.2.2 Methods

Pilot work was conducted at Myerscough College (Bilsborough, Preston, UK) and is described in Chapter 4. Briefly, four horses (age: 7.3 ± 2.6 years, height: 155.0 ± 8.2 cm, breed: ISH, WB, Welsh Cross, sex: 2 mares, 2 geldings) were used for pilot work. Different riders, each with similar experience (10+ years riding experience) and riding ability (competed minimum BE 80) rode each horse.

5.2.2(i) EMG system and sensor characteristics

The Delsys Trigno™ (Delsys Inc., Boston, USA) telemetric sEMG system was employed for this study, which allowed subjects to move with little to no restrictions. This system was chosen based on features, which made it ideal for indoor and outdoor collection from equine subjects. Telemetric systems require a high level of transmission robustness to ensure data packets are not lost due to interference from external frequencies, i.e. radio frequencies and Bluetooth (Richards, in preparation). The Trigno system was an ideal system for both indoor and outdoor data collection, as it ensures robust transmission up to 40 m by operating within the 2.4 GHz spectrum to minimise interference from products operating on radio frequency communication schemes (Delsys, 2014). The system amplifies original low-voltage EMG signals by a factor gain of 909, with a full dynamic range of ±5 V, and measures EMG signals at a sampling frequency of 1925.93 Hz (Delsys, 2014). Both amplification and sampling frequency values of the Trigno system conform to general recommendations of a gain between 1000–10,000 and a minimum sampling frequency of 1000 Hz (Hermens et al., 1999; Merletti and Hermens, 2004; Konrad, 2006; Richards et al., 2008b). A minimum sampling frequency of 1000 Hz is necessary to avoid signal loss by accurately translating the complete frequency spectrum of a sEMG signal into a digital signal (Stegemen and Hermens, 1998; Hermens et al., 1999; Merletti and Hermens, 2004; Konrad, 2006; Richards, in preparation). The systems internal bandwidth of 20-450 Hz is in line with general recommendations for investigation of dynamic contractions, as it is generally accepted that sEMG signals do not contain frequencies greater than 450 Hz (Merletti and Hermens, 2004; De Luca et al., 2010). Furthermore, this bandwidth ensures mitigation of noise and motion artefact, which typically occur at frequencies less than 20 Hz (Merletti and Hermens, 2004; Potvin and Brown, 2004; Konrad, 2006; Richards, in preparation).

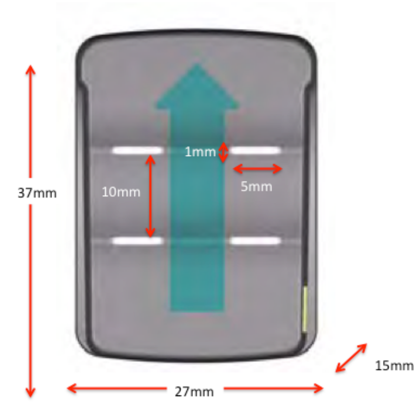
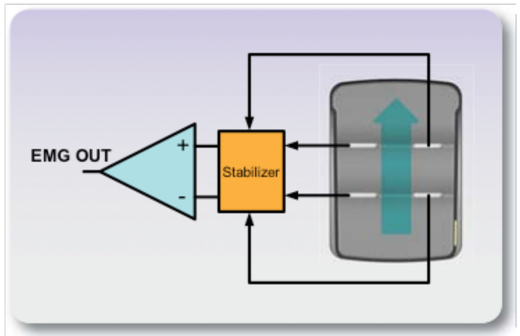


Figure 5.1 Dimensions and configuration of Delsys Trigno telemetric sEMG sensor. (modified from Delsys Incorporated, 2014)

Single differential, or bi-polar, electrodes with four silver (Ag) bar contacts (Delsys Inc., Boston, USA) were employed for this study. Sensor and electrode dimensions and configurations are illustrated in Figure 5.1. The bi-polar configuration is generally preferred due to its superior ability to remove external noise (De Luca, 1997; Richards, in preparation). The bi-polar configuration contains two electrodes, which detect and remove the differential signal with respect to a reference electrode prior to amplification (De Luca, 1997; De Luca et al., 2012). Typically, external noise signals are equal in phase and amplitude, as they contact both electrodes with no phase shift, and are therefore eliminated during the subtraction of both detected signals (De Luca, 1997; Konrad, 2006). The sensors employed for this study included two stabilising reference electrodes and two bi-polar EMG electrodes, in the form of four electrode bars. This configuration eliminates the need for a separate reference electrode and allows immediate recognition of noise sources detected on the skin surface (Delsys, no date) (Figure 5.2a). The quality of signals detected from this configuration is reported to be superior to other configurations with just two electrodes (Delsys, no date) (Figure 5.2b).

a.) 

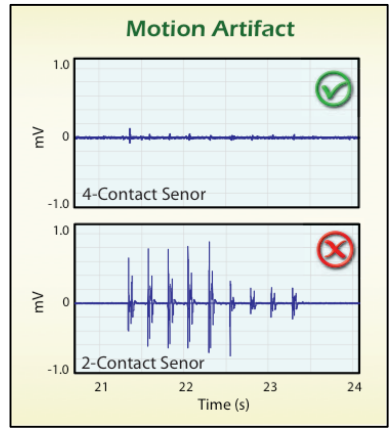
b.) 

Figure 5.2 a.) The unique stabilising reference configuration of Delsys Trigno sensors, illustrating how four electrodes act as two stabilising references. b.) The effects of the unique configuration of four electrodes on the minimisation of external noise sources. (Modified from Delsys Incorporated, no date)

Electrode size and inter-electrode distance (IED) are important considerations when choosing a sensor (Hermens et al., 2000), as the distribution of frequencies and the bandwidth are affected by the configuration (De Luca, 1997). An electrode with a greater surface area will detect a greater number of muscle fibres and therefore produce greater EMG signal amplitude (De Luca, 1997). However, this is not always desirable, as a large IED and electrode surface area will decrease the ability to detect and remove common signals (De Luca, 1997; De Luca et al., 2012; Richards, in preparation). SENIAM recommendations describe an optimal IED of 20 mm (Stegeman and Hermens, 1998; Hermens et al., 1999; 2000). However, this recommendation has been criticised for not conclusively considering the minimisation of crosstalk (De Luca et al., 2012) and a fixed IED of 10 mm is now commonly recommended, as this has been reported as the most effective distance for minimising cross-talk contamination (De Luca, 1997; De Luca et al., 2012). Fixed spacing between electrodes is recommended, as electrodes that are separately attached to skin are susceptible to alterations in IED due to skin displacement (Hermens et al., 2000; Richards, in preparation). The sensors employed for this study contained electrodes with a fixed parallel spacing of 10 mm. The fixed parallel bar design of the sensors is superior to other designs, as it allows the bars to be oriented perpendicular to the muscle fibres to record the electrical signal as it propagates along the longitudinal muscle fibres (Richards, in preparation).

Previous equine sEMG studies have employed non-fixed IED of 3 cm (Wakeling et al., 2007; Zsoldos et al., 2010a, b; Kienapfel, 2015) and 4 cm (Licka et al., 2009), which is not in accordance with recommendations by De Luca et al., (2012) and Hermens et al., (2000). It could be argued that

IED recommendations for human research may not directly apply to equine research, as it may be necessary to alter IED in accordance with the larger musculature of equine subjects (Valentin and Zsoldos, 2016). However, in humans, force-producing muscles, like the gastrocnemius, contain both slow and fast MU’s with an innervation ratio of 1000-2000 muscle fibres per motor neuron (Purves, 2001). Snow and Valberg (1994) postulate that, in the muscles of the equine limb, one motor neuron is also likely to innervate between 1000 and 2000 muscle fibres. These similarities in MU architecture require further investigation, but provide evidence for employing IED recommendations for human subjects in the main study of the thesis. These similarities also highlight the importance of considering IED for equine sEMG research, as IED that are too small may cause electrical shunting, resulting in decreased: signal amplitude, signal-to-noise ratio (SNR) and high-frequency components (De Luca, 1997). This may also suggest that a minimum IED of 10 mm should be used in equine subjects, as cross-talk contamination from adjacent muscles is less likely due to the larger musculature (Valentin and Zsoldos, 2016). However, this is an area requiring further research.

5.2.2(ii) Selection of superficial muscles of interest and determination of sensor locations

The muscles selected for this study were determined based on their; superficial location, size and recognized contribution to movement during canter and jump (Robert et al., 2001b). Splenius, Trapezius (cervical head), Triceps Brachii (long head), Superficial Gluteal and Biceps Femoris (vertebral head) were selected for investigation. Electrode positions for each muscle were determined based on a review of published sensor locations from previous equine EMG research (Tokuriki et al., 1999; Robert et al., 1999, 2001a, b; Schuurman et al., 2003; Hodson-Tole, 2006; Zaneb et al., 2007; Zsoldos et al., 2010a, b). Electrode positions, as defined by the literature review are described in Table 5.1

Table 5.1 Electrode positions, as defined by a review of previous equine EMG research.

Muscle	Origin	Insertion	Position of sEMG electrode
Splenius	Spinous processes T3-T5 (Pattillo, 2007)	Nuchal crest, mastoid process, atlas and transverse processes C3-C5 (Patillo, 2007)	Into midpoint and 10 cm lower from base of mane (Tokuriki et al., 1999)
			Placed over muscle at level of C2 (Zsoldos et al., 2010b; 2014)
			10 cm ventral to the dorsal border of the neck and 15 cm caudal to wing of atlas (Robert et al., 2001b)
***Trapezius* (cervical head)**	Nuchal ligament funicular portion (cord) from C2-T3 (Patillo, 2007)	Entire cranial surface of the scapular spine. Blends with the shoulder and arm fascia (Patillo, 2007)	Description of position unavailable from literature. To be determined.
***Triceps Brachii* (long head)**	Caudal border of scapula (Watson and Wilson, 2007)	Olecranon (Watson and Wilson, 2007)	Midway between the olecranon and the proximal point of the scapular spine, measured at an angle of 50° from a line drawn between the olecranon and the intermediate tubercle of the humerus (Hodson-Tole, 2006)
Superficial Gluteal	Gluteal fascia (Payne et al., 2005)	3rd trochanter of femur (Payne et al., 2005)	Midway between the lumbosacral joint and greater trochanter (Zaneb et al., 2007)
***Biceps Femoris* (vertebral head)**	Ischiatic tuber and ischium (Payne et al., 2005)	Blend with femoral and crural fascia and insert into patella ligament, patella tibial crest and calcaneal tuber via calcaneal tendon (Payne et al., 2005)	2 cm cranial to and halfway between third trochanter and patella (vertical) and 6 cm cranial to margin of semitendinosus (in ponies 50% increase in distance for KWPN) (Schuurman et al., 2003)
			Between femur and poverty line joining lower end of tuber coxae and greater trochanter of the femur (Zaneb et al., 2007)

Proposed electrode sites for the current study are described in Table 5.2 and illustrated in Figures 5.3-5.7. Location descriptions refer to the location of the geometrical center of the sensor. Due to muscle size, two sensor locations were defined for Trapezius (cervical head), Triceps Brachii (long head), Superficial Gluteal and Biceps Femoris (cranial head) to investigate optimal sensor position and whether the use of one sensor would suffice. However, only one sensor location was defined for the Splenius. This decision was based on Splenius being a non-compartmental muscle (Gellman et al., 2002) and the fact that its location between the Cervical Trapezius and Brachiocephalicus was easily palpated and visually identified.

It was expected that anatomical measurements described in previous research might differ significantly depending on the size, breed and fitness level of an individual horse. Therefore, records were kept for each horse to document where measurements were altered to ensure consistent positioning over the muscle belly (De Luca, 1997; Hermens et al., 2000; Konrad, 2006). Sensor positions were determined by one researcher (LSG, thesis author) throughout the thesis. Proposed sites were located by palpating anatomical landmarks and a flexible measuring tape was used to determine distances between landmarks. The determination of sensor locations in all subjects used for pilot work resulted in revised sensor location descriptions. Revised descriptions included a range of anatomical measurements, which were necessary to ensure consistent positioning over the muscle belly in a variety of equine subjects.

Table 5.2 Final descriptions for sEMG electrode locations in selected superficial muscles.

Muscle	Site 1 (a)	Site 2 (b)
Splenius	12 – 18 cm ventral to midpoint of neck	n/a
***Trapezius* (cervical head)**	10 cm ventral from point measured ¾ of the length of neck (closest to wither)	4 – 5 cm cranial to Site 1
***Triceps Brachii* (long head)**	As described by Hodson-Tole, (2006) in Table 5.1.	4.5 – 6 cm caudal to Site 1
Superficial Gluteal	As described by Zaneb et al., (2007) in Table 5.1	Midway between dorsal aspect of tuber coxae and greater trochanter. 12 – 18 cm ventral to Site 1.
***Biceps Femoris* (vertebral head)**	4cm cranial to and halfway between third trochanter and patella (vertical) and 12 -18 cm from cranial margin of semitendinosus (Schuurman et al., 2003)	Between femur and poverty line, on a line joining lower end of tuber coxae and greater trochanter of the femur (Zaneb et al., 2007). 14 – 18 cm ventral to Site 1.

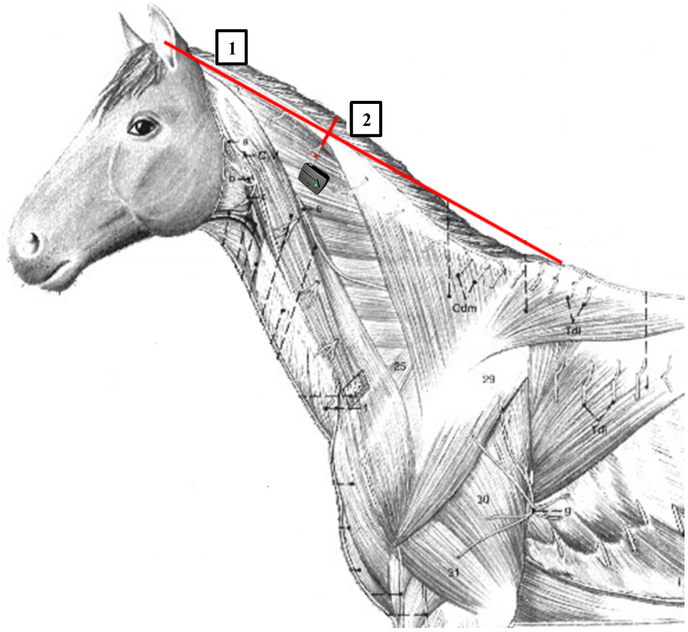


Figure 5.3 Electrode locations and positioning for Splenius muscle. Numbers are representative of anatomical measurements: 1. length of neck measured from poll to withers, 2. midpoint of neck. Adapted from: Budras et al. (2009).

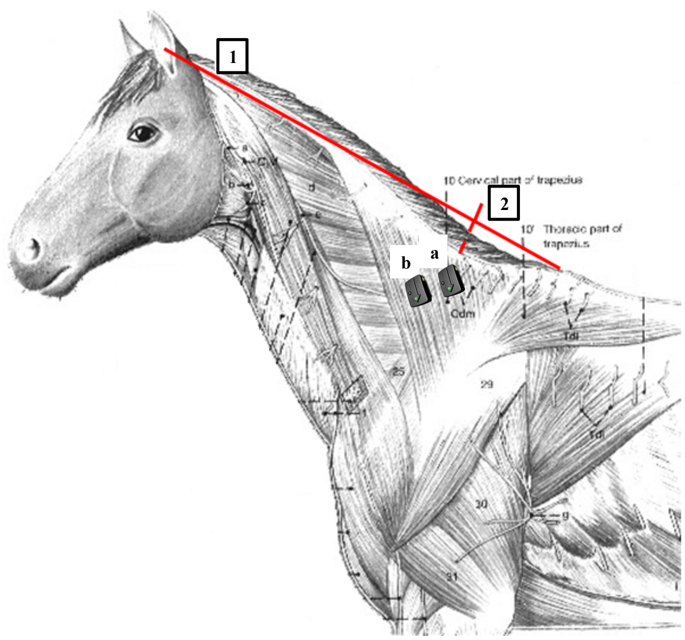


Figure 5.4 Electrode locations and positioning for Trapezius (cervical head) muscle. a.) Site 1, b.) Site 2. Numbers are representative of anatomical measurements: 1.) length of neck measured from poll to withers, 2.) ¾ of the length of neck. Adapted from: Budras et al. (2009).

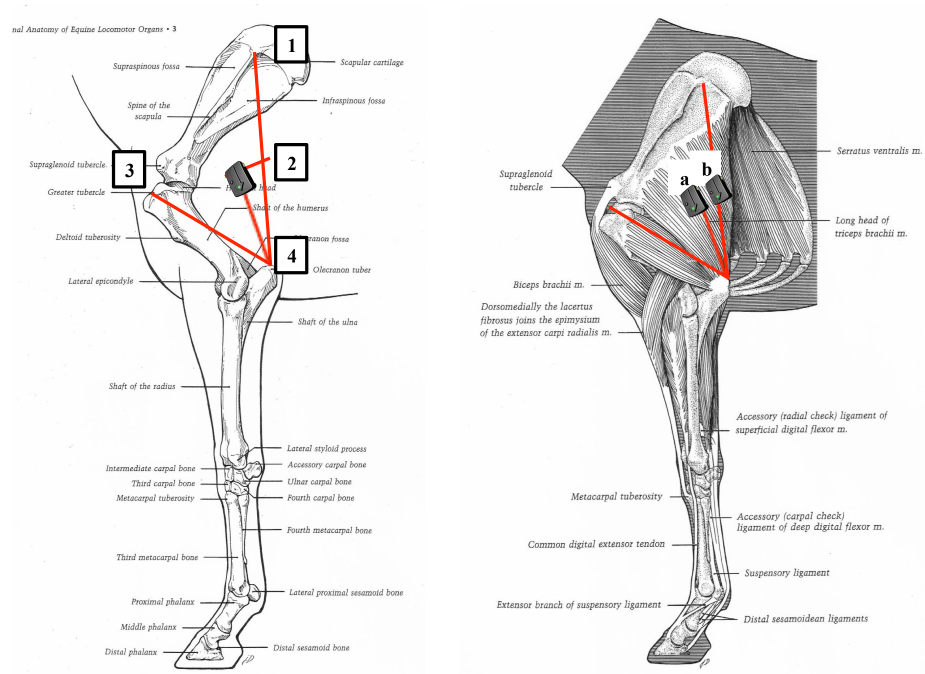


Figure 5.5 Electrode locations and positioning for Triceps Brachii (long head) muscle. a.) Site 1, b.) Site 2. Numbers are representative of anatomical measurements: 1.) length from olecranon to proximal point of scapular spine, 2.) midpoint between olecranon and proximal point of scapular spine, 3. line between olecranon and intermediate tubercle of humerus, 4.) 50° angle from 3. Adapted from: Stashak (1987).

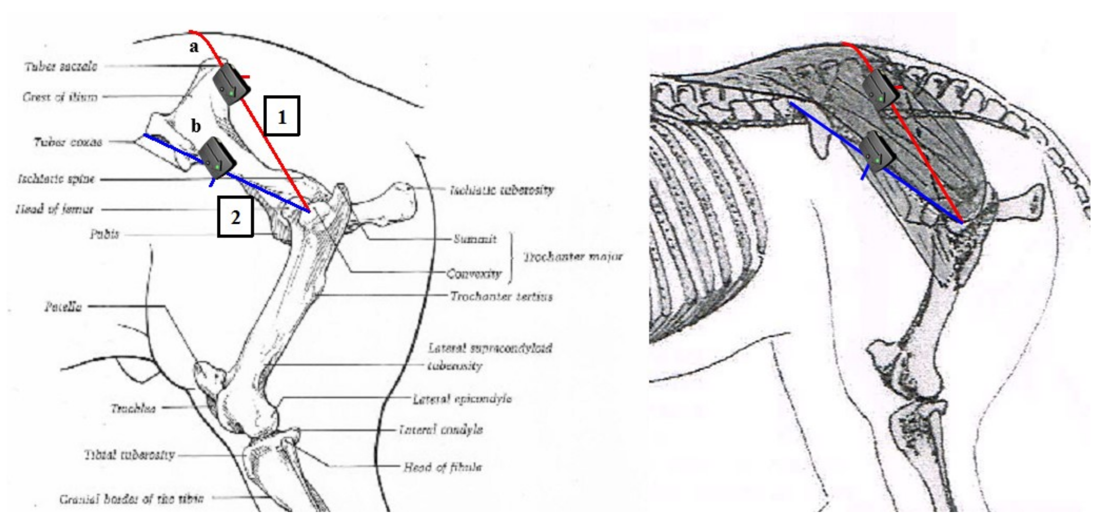


Figure 5.6 Electrode locations and positioning for Superficial Gluteal muscle. a.) Site 1, b.) Site 2. Numbers are representative of anatomical measurements: 1.) length from lumbosacral joint and greater trochanter, 2.) length from dorsal aspect of tuber coxae and greater trochanter. Adapted from: Stashak (1987) and Pattillo (2007).

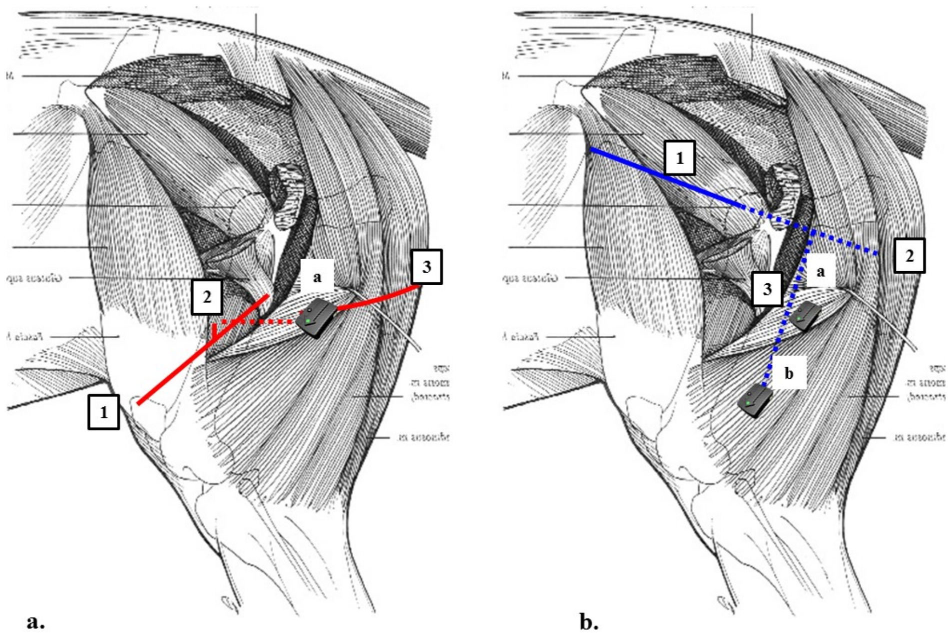


Figure 5.7 Electrode locations and positioning for Biceps Femoris (vertebral head) muscle. a.) Site 1, b.) Site 2. Numbers are representative of anatomical measurements. For a.): 1.) length from third trochanter and patella (vertical), 2.) 4cm cranial to and halfway between 1., 3.) 12 - 18 cm from cranial margin of semitendinosus. For b.): 1.) line joining lower end of tuber coxae and greater trochanter of the femur, 2.) line between femur and poverty line, 3.) 14 – 18 cm ventral to Site 1. Adapted from: Stashak (1987).

5.2.2(iii) Skin preparation and skin-electrode interface

Achieving good electrode-skin contact is essential for obtaining high fidelity EMG signals through minimization of external noise and movement artifact, resulting in a better SNR (Hermens et al., 2000; Richards, in preparation). It is recommended that hair be completely removed from electrode sites to facilitate a strong adherence and reduce movement during data collection (Hermens et al., 2000). Therefore, all hair was completely removed from established electrode positions using a small clipper (20 mm in length) and a razor, where necessary. To produce low skin impedance, shaved sites and EMG electrode bars were cleaned with isopropyl alcohol wipes to remove: dirt, oil, dead skin cells, and sweat (Cram and Rommen 1989; Konrad, 2006). Alcohol wipes were used in a rubbing motion on the skin until they came away clean. A small amount of saline solution was applied to electrode bars to act as an electrolytic solution, which has been shown to reduce impedance and to assist current flow (Cram and Rommen, 1989; Clancy et al., 2002; Richards, in preparation). Once skin was prepared, subjects were placed in a "square" standing position, which permitted accurate determination and palpation of anatomical landmarks to establish sensor location.

Following recommended electrode-positioning protocol; electrode bars were placed perpendicular to underlying muscle fibre orientation to ensure maximum detection of EMG signals at the skin surface (De Luca, 1997; Hermens et al., 2000; Merletti and Hermens, 2004; Richards, in preparation). Cross talk is generally more relevant in small, closely related muscles and previous studies have stated that it may be negligible in equine research due to the large size of the superficial muscles under investigation (Robert et al., 1999; Licka et al., 2004; Hodson-Tole, 2006; Valentin and Zsoldos, 2016). However, further research is required to validate these claims and care was taken to ensure electrodes were placed on the muscle belly to avoid "cross talk" (Konrad, 2006; Merletti and Hermens, 2004; Delsys, 2012). Figure 5.8 illustrates the recommended placement of electrodes aligned in the direction of underlying muscle fibres. Positioning the electrodes centrally is especially important for dynamic movement studies, as muscle migration below the electrode site may result in variations in readings from different motor units within the target muscle (Basmajian and De Luca, 1985; Konrad, 2006).

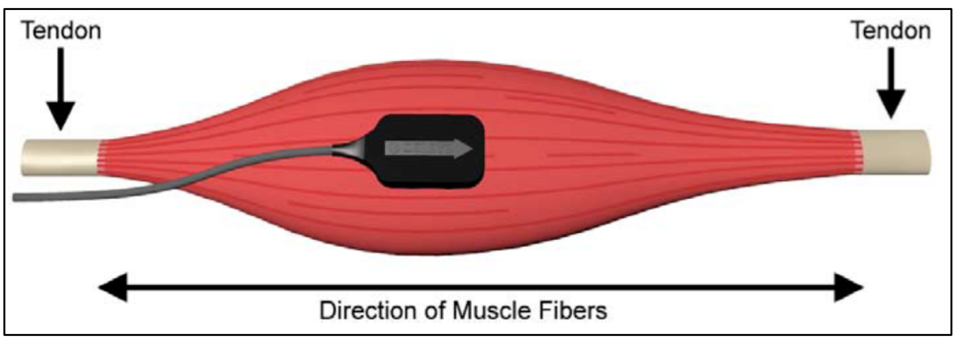


Figure 5.8 Appropriate positioning of sEMG electrodes over muscle belly. Adapted from: Delsys Incorporated (2012).

5.2.2(iv) Sensor fixation

A variety of adhesive tapes were tested to determine which type would ensure sensors remained securely attached and made good contact with the skin during dynamic movements. Medical adhesives, Opsite Flexifix™ (Smith and Nephew™) and Tegaderm™ (3M™) were tested but did not produce the desired results. Mammoth Carpet Fix Cloth tape (Everbuild, Leeds, UK) offered the best adhesive qualities, as electrodes remained adhered to the skin for the greatest number of repetitions, even on subjects who produced a significant amount of sweat. The skin-electrode interface was therefore composed of a combination of non-irritant Delsys Adhesive Sensor Interface strips (Delsys Inc., Boston, USA) and the heavy-duty double-sided carpet tape.

5.2.2(v) Recording procedure

sEMG and kinematic data were collected synchronously using an external trigger. Data collection procedures are described in Chapter 4.

5.2.3 Results

Pilot data collected from this study are utilised and presented in Studies 5.3 – 5.5. sEMG data will therefore not be presented in this section, as the quality of data collected using the methods described in this study is represented in Studies 5.3 - 5.5.

5.2.4 Conclusion

The aim of this study was to explore optimum: skin preparation, sensor adherence and protocol for collecting data from the dynamic movements of the equine athlete. The exploration of these areas developed a methodology for the main study of the thesis. An investigation into recommended technical specifications and properties of sEMG systems revealed that the system and sensors chosen for this study conform to all technical recommendations described by SENIAM and in scientific literature (De Luca, 1997, De Luca et al., 2012). These considerations were paramount for this study, as to the author's knowledge; no equine studies have reported attention to such detail. This study has fully explored how the EMG signal is detected and recorded with maximum fidelity in equine subjects, as recommended by De Luca (1997) in Section 5.1. This study has also highlighted the importance of considering optimal: sensor positioning and orientation, sensor properties and skin preparation for equine sEMG research. These considerations are especially relevant if sEMG in animal research is to emulate progress in human research by moving towards standardised protocols for data acquisition.

5.3 Optimal high-pass filtering of the equine sEMG signal

5.3.1 Introduction

Determining the band-pass in EMG analysis has been previously described as a compromise between reducing noise and artefact contamination, and preserving the desired information from the signal (Winter, 2009; De Luca et al., 2010). The low-frequency component of the sEMG frequency spectrum is highly susceptible to contamination from baseline noise and movement artefact noise sources, with these issues becoming especially prominent when the signal is obtained during dynamic contractions (De Luca et al., 2010). Movement artefact may contaminate the sEMG signal through unwanted movement of the surface electrode due to deformation or stretching of the underlying skin (Clancy et al., 2002; De Luca et al., 2010) or as a result of force impulses, travelling through muscle and underlying skin (De Luca et al., 2010). A suitable high-pass filtering technique is therefore recommended to reduce movement artefact and to preserve the EMG signal (Potvin and Brown, 2004; De Luca et al., 2010).

It is generally recommended that raw sEMG signals are high-pass filtered with a cut-off frequency at, or below 30 Hz (Potvin and Brown, 2004), with values ranging from 5 - 30 Hz reported in the human literature (Winter et al., 1980; Stegemen and Hermens, 1998; Merletti, 1999; Potvin and Brown, 2004; De Luca et al., 2010). A maximum cut-off of 20 Hz has been recommended for human data to avoid approaching the median frequency of the signal (Clancy et al., 2002; De Luca et al., 2010). However, De Luca et al. (2010) recommend increasing this value for applications involving dynamic movements. This is further supported by Wittek et al (2001), who state that recommendations for high-pass cut-off frequencies are primarily applicable to medicine, sport and physiology research; however, investigation of movements which exceed body segment accelerations and loading patterns of general movements require a higher cut-off frequency value. Optimal cut-off frequencies for high-pass filtering equine sEMG data have not been adequately explored. As a result, a variety of cut-off frequencies have been employed in equine sEMG research, highlighting a gap in knowledge.

Previous equine sEMG studies have reported high-pass filters with cut-off frequencies of 10 Hz (Harrison et al., 2012), 20 Hz (Hodson-Tole., 2006; Crook et al., 2010; Harrison et al., 2012) and 40 Hz (Kienapfel, 2015). However, many studies have not applied, or have not described the application of a high-pass filter to raw sEMG data (Valentin and Zsoldos, 2016). A lack of high-pass filtering may be especially problematic in equine sEMG studies, as no attempt has been made to minimise the inherent low-frequency noise sources associated with force impulses and skin displacement (DeLuca et al., 2010; Richards, in preparation), which may be significantly greater during dynamic equine movements than in humans. An investigation into optimal high-pass filtering techniques for sEMG data collected from highly dynamic equine movements was therefore justified to inform data analysis for the main study of the thesis.

Previous quadruped studies have employed cut-off frequencies much higher than the recommended range when high-pass filtering raw sEMG data. Barnes (1977) reported that the use of a high-pass filter with a cut-off of 80 Hz was ideal for use on equine EMG data collected during walk. A more recent study investigating MU recruitment using fine-wire EMG during level walking, trotting and galloping in African pygmy goats (*Capara hircus* L), reported a cut-off frequency of 70 Hz to exclude low-frequency noise (Lee et al., 2013). Additional studies have reported a similar cut-off frequency (69.92 Hz) for investigating MU recruitment in the running rat (*Rattus norvegicus*) (Hodson-Tole and Wakeling, 2007) and feline (Hodson-Tole et al., 2012). Lee et al. (2013) and Hodson-Tole and Wakeling (2007) have justified cut-off frequencies of ~70 Hz based on previously reported slow MU mean frequencies of ~185 Hz in the rat (Wakeling and Syme, 2002) and central frequencies of ~150 Hz in the African pygmy goat (Lee et al., 2011), respectively, confirming that signals from slow MU are preserved. Higher cut-off frequencies of 100 Hz have been reported by studies employing fine-wire electromyography in the African pygmy goat (Caroll et al., 2008; Lee et al., 2011) and the rat (Gillis and Biewener, 2001, 2002). Fine-wire EMG studies investigating locomotion in bipedal animals have also reported high-pass cut-off frequencies as high as 100 Hz in guinea fowl (Daley and Biewener, 2003) and 150 Hz in turkey (Gabaldón et al., 2004). These studies suggest that a cut-off frequency above the recommended range in human sEMG research may be necessary to eliminate low frequency noise in quadruped movement.

It should be noted that fine-wire electrodes detect EMG signals generated by a small number of motor units within close proximity to the electrode, as opposed to the interference pattern of numerous motor units detected by surface electrodes (Richards et al., 2008b). The close proximity of the fine-wire electrodes to the electrical signal, and the subsequent removal of the capacitance effect of skin and subcutaneous fat, results in a higher frequency spectrum of intramuscular EMG signal compared to the sEMG signal (Jacobson et al., 1995; Richards et al., 2008b; Richards, in preparation). However, a study investigating the effect of high-pass filtering of signals from intramuscular and surface electrodes, obtained during impact biomechanics experiments, reported that a cut-off frequency of 50 Hz was necessary to remove movement artefacts from both electrode types (Wittek et al., 2001). Although there is a degree of conjecture when comparing signal processing of intramuscular and sEMG data, these findings indicate that higher cut-off frequencies reported in intramuscular animal research may be used to justify the use of cut-off frequencies, which exceed the recommended values reported in human sEMG literature. Furthermore, the forces and accelerations associated with equine canter and jump movements would undoubtedly warrant cut-off frequencies of ≥50 Hz, which is required to remove movement artefacts associated a low-speed car collision simulation with an impact speed of 1.667 m/s (Wittek et al., 2001). Average approach speeds of 6.3 - 7.3 m/s (Clayton and Barlow, 1991; Clayton et al., 1995) and loads of twice the horses body weight in the FL at landing (Schamhardt et al., 1993) have been reported for horses jumping 1.50 m and 1.30 m fences, respectively. It can therefore be argued that the movements associated with the equine jumping effort would produce higher frequency movement artefact than those in the study by Wittek et al. (2001) and that higher cut-off frequencies may be necessary to attenuate low-frequency noise sources.

To the author's knowledge, no studies have reported or described the use of high-pass filtering to analyse EMG data collected during the equine jump. Therefore, the application of a cut-off frequency that exceeds the recommended range may be further justified by considering the methods of previous quadruped ungulate studies, which have explored the dynamic movements of interest to the current study. Caroll et al. (2008) investigated muscle function in the Triceps Brachii of goats (*Capra hircus*) during jumping and landing, applying a 100 Hz cut-off to exclude low frequency noise. This may suggest that the application of a cut-off frequency of around 80 Hz (Barnes, 1977) is warranted for sEMG data from the equine jump and rationalises further exploration of the effect of this less aggressive high-pass filter on sEMG data. Lee et al. (2013) investigated the gallop in goats (*Capra hircus*), applying a high-pass filter of ~70 Hz to raw EMG. The use of a higher cut-off may therefore be warranted for the canter, which is the gait of interest in the main study of the thesis and is classed with gallop as an asymmetrical gait that occurs at comparable speeds (Barrey, 2013). Therefore, canter and gallop would be expected to produce low frequency artefacts within a similar frequency spectrum, implying that a similar cut-off frequency around 70 Hz would be necessary for canter trials. These studies better replicate quadruped locomotion studied in this PhD, which justifies further exploration into the application of a higher cut-off frequency for high-pass filtering equine sEMG data. The aim of this study was to determine the optimal cut-off frequency required to attenuate low frequency artefacts in equine sEMG signals obtained from dynamic movement trials.

5.3.2 Methods

sEMG data presented in this study were collected during pilot work in accordance with the protocol described in Study 5.2 and Chapter 4. Raw EMG signals were DC offset removed and high-pass filtered using a Butterworth 4^{th} order zero-lag filter. Three representative high-pass filter cut-off frequencies (30, 60, 80 Hz) were applied based on previously reported cut-off frequencies from human and quadruped studies. An examination of the effect of each cut-off frequency on EMG signals was used to determine which filter setting elicited the highest signal quality through reduction of intrinsic noise sources (De Luca et al., 2010).

5.3.3 Results

The effect of different high-pass cut-off frequencies on signal quality are illustrated in Figure 5.9 Data presented in Figure 5.9 clearly demonstrate that, as cut-off frequency increases sEMG noise and movement artefact signals decrease, in accordance with De Luca et al (2010).

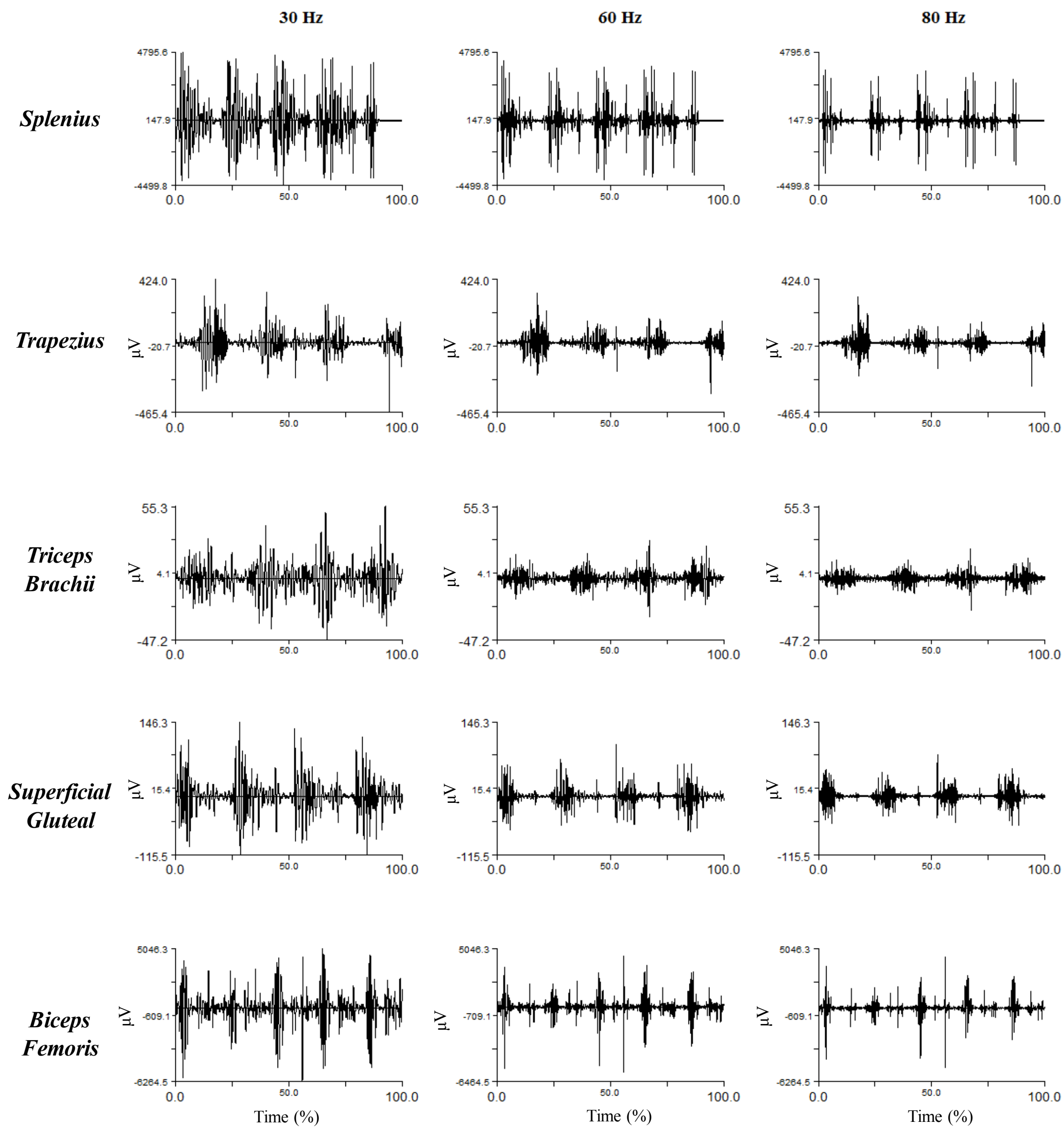


Figure 5.9 Examples of high-pass filtered sEMG data from each muscle of interest. Data filtered using cut-off frequencies of 30 Hz, 60 Hz and 80 Hz are presented. All signals were collected during canter trials and are normalised to the duration of one trial.

Although a cut-off frequency of 80 Hz exceeds the recommended range of 10 – 30 Hz in human studies, this cut-off produced the best quality signal and was able to remove low frequency noise to reveal the muscle activity pattern in equine subjects. Figure 5.10 provides further evidence for this claim by illustrating the clearer onset and offset patterns revealed when raw data were filtered at 30 Hz, 60 Hz and 80 Hz.

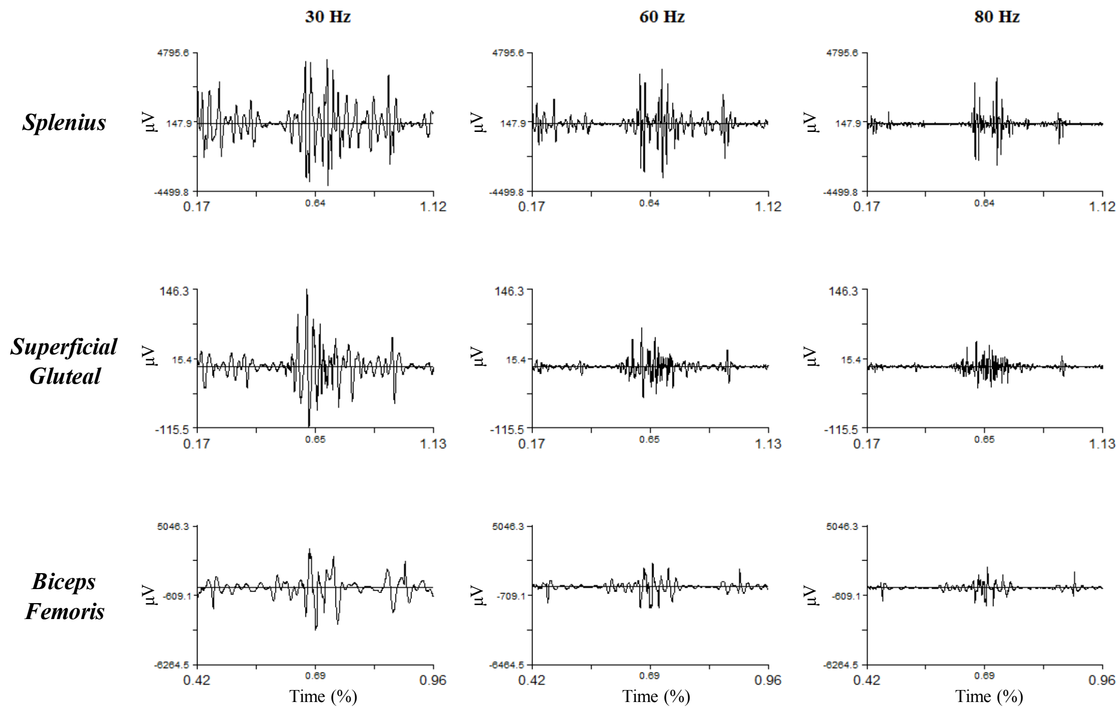


Figure 5.10 Data from selected superficial muscles, illustrating the increased signal quality and subsequent ability to identify muscle activation time (onset and offset) when high-pass filtered at 80 Hz. Data filtered using cut-off frequencies of 30 Hz, 60 Hz and 80 Hz are presented. All signals were collected during canter trials.

5.3.4 Discussion

Movement artefacts are to be expected during dynamic equine movement, with skin displacement as large as 12 cm reported in the proximal limb (van Weeren et al., 1990a). This is highlighted in Figure 5.11, where dynamic movements and forces associated with canter and jump have introduced movement artefact into the sEMG signal. Figure 5.11 illustrates examples of movement artefact and the effect of the three cut-off frequencies (30, 60, 80 Hz) on reduction of the artefact component. EMG traces reveal that the 30 Hz cut-off frequency does not effectively attenuate the movement artefact component. In contrast, the 80 Hz cut-off frequency exhibits effective attenuation of the movement artefact component without causing significantly detrimental attenuation of the low-frequency components of the actual EMG signal (DeLuca et al., 2010). It is therefore highly probable that movement artefact noise occurs at a higher frequency in equine subjects than in human subjects, which justifies the necessity for using cut-off frequencies above the recommended range in human literature.

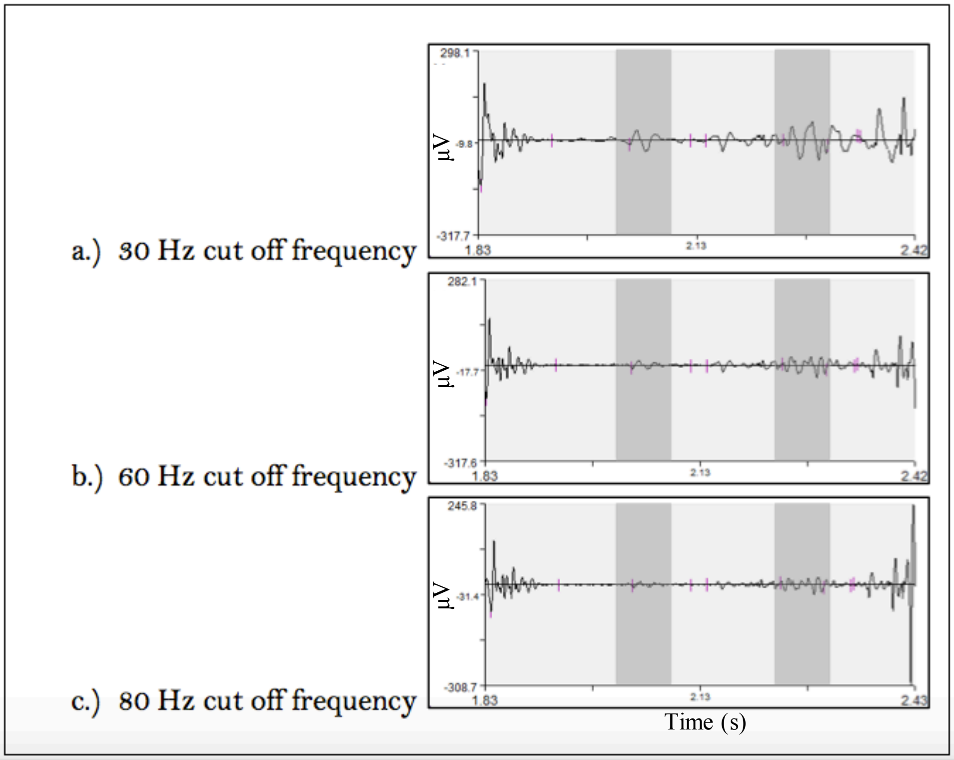


Figure 5.11 Reduction of movement artefact (grey shaded areas) following application of a high-pass filter with a.) 30 Hz, b.) 60 Hz and c.) 80 Hz cut-off frequencies.

5.3.5 Conclusion

Findings from this study, along with previous methods reported in literature on quadruped animals, suggest that a high-pass filter with a cut-off frequency of 80 Hz is best suited for removing low frequency noise from equine sEMG data collected during highly dynamic movements, specifically canter and jump. Additional studies are required to further develop standardised methods for high-pass filtering equine sEMG data and to determine whether this cut-off frequency is appropriate for less dynamic movements. Data from previous equine research, which has not attenuated low frequency noise sources, should be considered with caution, as the majority of the low-frequency spectra overlaps with the EMG signal of interest (De Luca et al., 2010). It is therefore recommended that future equine studies consider the application of appropriate high-pass filtering techniques before conducting further analysis, particularly when investigating high velocity movements. This will ensure that results are obtained from analysis of uncontaminated EMG signals.

5.4 Development of a method for onset and offset detection in sEMG signals

5.4.1 Introduction

Determination of accurate onset and offset timing of a muscle contraction is one of the most common parameters employed for sEMG research investigating motor control (Hodges and Bui, 1996; De Luca, 1997; Staude et al., 2001). Understanding onset/ offset activity patterns provides insight into muscle function for performing motor tasks, which becomes especially informative when combined with kinematic and kinetic parameters (Benedetti et al., 1999, 2012). Several methods have been developed for determining sEMG onset and offset, however to the author's knowledge no comparative study has established the optimal detection method (Hodges and Bui, 1996; Staude et al., 2001). The lack of a standardised method for muscle onset/offset detection represents a major gap in knowledge and does not permit accurate comparison of results from different research (Hodges and Bui, 1996). This gap is especially prevalent in equine sEMG research, which has generally employed gait events determined using kinematic data to investigate muscle activity patterns. To the author's knowledge; only one study has explored muscle activity onset/ offset using equine sEMG signals (Harrison et al., 2012).

Researchers evaluating the temporal parameters of muscle activation often do not to report muscle activity onset detection methods, with numerous studies reporting visual assessment of EMG signals for onset determination (Di Fabio, 1987; Hodges and Bui, 1996). Visual assessment of temporal parameters is generally conducted by an experienced examiner using subjective criteria, which is usually not described in full (Hodges and Bui, 1996; Di Fabio, 1987). However, it is known that much variation in EMG onset determination occurs when it is performed visually and is dependent on the experience and skill of the examiner (Hodges and Bui, 1996). Computer-based onset detection methods have become the preferred choice for researchers, as they mitigate the inherent subjectivity of visual assessment (Hodges and Bui, 1996). However, there is little agreement on a computer-based method, which produces the best accuracy for identification of onset and offset (Hodges and Bui, 1996; Staude et al., 2001; Merlo et al., 2003).

Computer-based detection algorithms commonly identify muscle activity onset where the magnitude of the EMG signal exceeds the baseline activity value by a pre-determined threshold of nSD for a given number of time/samples (Staude et al., 2001; Konrad, 2006). This technique is referred to as the single threshold method and is generally applied to an enveloped signal, which provides a clearer representation of time-varying EMG amplitude (Winter et al., 1980; Soderberg and Cook, 1984; Staude et al., 2001; Richards, in preparation). The benefit of this method is that the threshold is based on a statistical deviation from the mean resting value of a specific muscle, ensuring that it is normalised to the baseline activity level of individual muscles (Di Fabio, 1987; Hodges and Bui, 1996). The threshold is also normalised to any changes in baseline activity, which is generally not silent in postural tasks (Hodges and Bui, 1996). However, single-threshold methods have been criticised for their reliance on good SNR for accurate onset detection, and are therefore not considered to be suitable for onset detection in signals with slowly increasing muscle activity (amplitude) or with low SNR (Merlo et al., 2003).

A double threshold method has been described by Bonato et al. (1998) and Merlo et al., (2003). This method involves the application of two thresholds to conditioned signals, which allows the user to establish probabilities for false positive and correct event detection (Bonato et al., 1998; Merlo et al., 2003). Thresholds are based on the statistical properties of the EMG signal and post-processing procedures allow the user to automatically remove false positive detections (Bonato et al., 1998). This method has been described as a more accurate means of detecting temporal activity patterns in the stochastic EMG signal (Bonato et al., 2003; Merlo et al., 2003; Benedetti et al., 2012). However, to the author's knowledge, no study has offered a conclusive recommendation for the: optimal method, threshold value and signal conditioning parameters for onset/offset detection using computer-based algorithms.

As previously stated, Harrison et al., (2012) is the only known study to investigate onset/offset patterns in equine sEMG signals using a computer-based detection method. This study employed the detection method described by Hortobágyi et al. (2009), which is intended for use on human myoelectric signals. Harrison et al. (2012) do not justify the use of this method and it is therefore assumed that it has not been validated for use in equine sEMG signals. Optimal signal conditioning parameters have not been explored in equine research for sEMG onset detection, and the optimal cut-off frequency for enveloping equine sEMG signals using a low-pass filter (LPF) is not known. The majority of equine sEMG research appears to apply an arbitrary cut-off frequency of 10 Hz, based on a study by Peham et al. (2001b) (i.e. Licka et al., 2009; Groesel et al., 2010). However, Peham et al. (2001b) used a 10 Hz cut-off frequency as a reference standard and did not specifically recommend its use for equine sEMG data processing. An investigation into appropriate low-pass filtering and onset/offset detection parameters for equine sEMG signals is therefore warranted and will provide an original contribution to knowledge.

Accurate detection of temporal parameters equine sEMG signals is required for Study 5.6 to explore the intricacies of muscle activity patterns from signals collected at different locations in the same muscle. This information would be used to determine optimal sensor location for the main study of the thesis. Optimal LPF parameters would also be required for sEMG data analysis in the main study of the thesis. The aim of this study was therefore to establish a method for identifying muscle activity onset and offset events from equine sEMG data by determining optimal: a) LPF parameters for smoothing and b) pre-determined threshold parameters used to identify onset and offset timings.

5.4.2 Method

sEMG data from one equine subject, collected during pilot work, was used for this study (age: 8 years, height: 166 cm, breed: ISH, sex: gelding). The subject was used in a riding school for novice to advanced riders. The horse was ridden by an experienced amateur rider. sEMG data was collected in accordance with the protocol described in Study 5.2 and Chapter 4. Data from Splenius, Trapezius, Triceps Brachii, Superficial Gluteal and Biceps Femoris muscles were collected in accordance with sensor locations described in Section 5.2.2(ii).

Three LPF parameters were investigated to determine the optimal degree of smoothing required for onset/offset identification. Butterworth (4th order) LPF with cut-off frequencies of 6 Hz, 15 Hz and 25 Hz were applied to signals from each sensor location, which had been DC offset removed, high-pass filtered (Butterworth 4th order, 80 Hz cut-off, see Section 5.3) and full-wave rectified. Previous studies have used these cut-off frequencies to transform full-wave rectified EMG signals into a linear envelope: 6 Hz (Arsenault et al., 1986; Steele, 1994; Lloyd and Besier, 2003; Herrington et al., 2005), 15 Hz (Zeller et al., 2003) and 25 Hz (Kleissen, 1990; Hof et al., 2002; Richards et al., 2008c). It is postulated that low-pass filtering at 6 Hz would remove data from the EMG signal itself (Hodges and Bui, 1996). However, this cut-off frequency has been recommended as an alternative to RMS smoothing (Konrad, 2006; Clancy et al., 2016), which is commonly employed to produce a linear envelope for onset detection (i.e. Edwards et al., 2008; Patil et al., 2011). A cut-off frequency of 6 Hz was therefore used to illustrate the effect of excessive filtering. It is not known which cut-off frequency will minimally smooth data, therefore, intermediary cut-off frequencies of 15 Hz and 25 Hz were chosen to investigate a higher level of smoothing and the effect on onset/offset detection.

Average resting value was calculated based visual identification of a quiescent period during the static trial. The quiescent period was identified where all muscles demonstrated the same quiet activity, which ensured that average resting value was calculated from the same number of data points for each muscle (Figure 5.12). Data from each sensor location were DC-offset removed, high-pass filtered (Butterworth 4th order, 80 Hz cut-off, see Section 5.3), full-wave rectified and enveloped using each low-pass frequency parameter (zero lag Butterworth 4th order, cut-off frequencies of 6, 15 and 25 Hz). Average resting value was then calculated for the quiescent period, which lasted for 1.15 seconds, at each cut-off frequency for each muscle, resulting in three average resting values for each sensor location (Table 5.3).

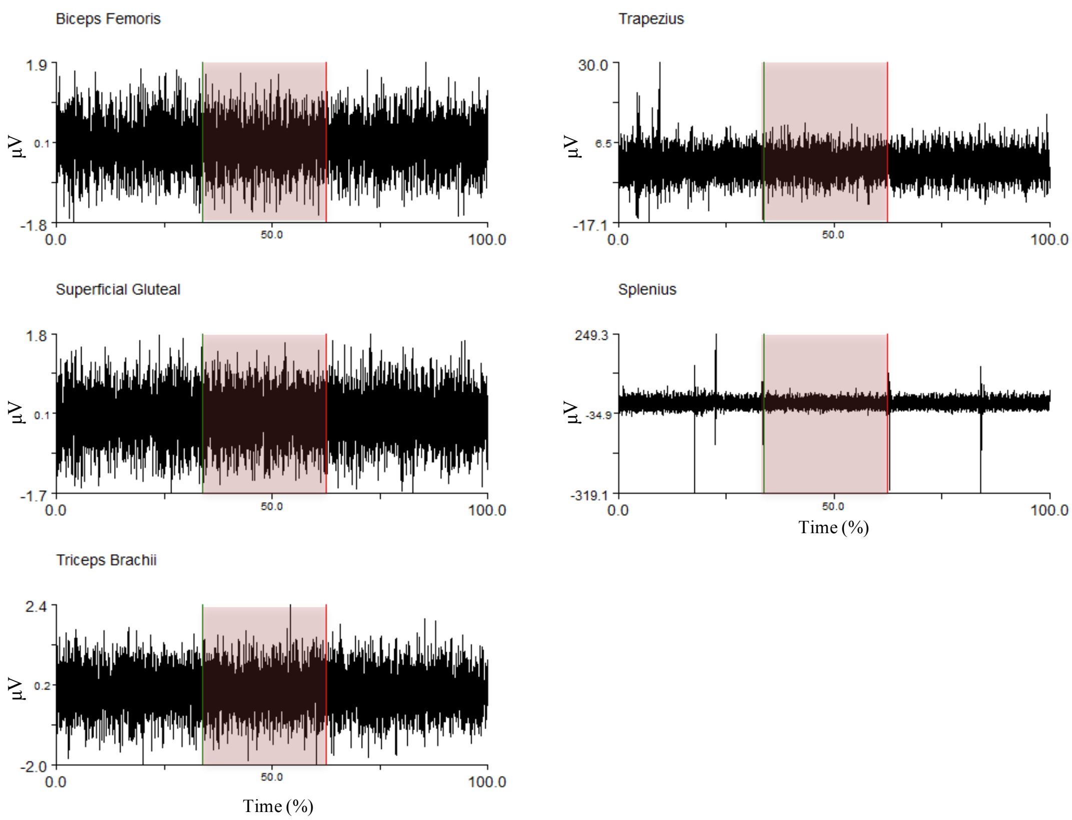


Figure 5.12 Areas of quiet baseline activity (red shaded) used to determine average resting values for each muscle of interest. Note: only one sensor location for each muscle is included in this figure.

Table 5.3 Mean ±SD (μv) baseline activity level (average resting value) for each muscle and sensor location. Separate average resting values were calculated for each of the three LPF filter parameters applied to sEMG data from each muscle.

Muscle	Cut-off Frequency		
	6Hz	15Hz	25Hz
Splenius	11.10 ± 2.13	10.79 ± 1.68	10.66 ± 1.13
***Trapezius* Cranial (Site 2)**	2.90 ± 0.17	2.90 ± 0.34	2.90 ± 0.43
***Trapezius* Caudal (Site 1)**	2.05 ± 0.31	2.02 ± 0.37	2.03 ± 0.45
***Triceps Brachii* Cranial (Site 1)**	0.44 ± 0.04	0.44 ± 0.06	0.44 ± 0.08
***Triceps Brachii* Caudal (Site 2)**	0.45 ± 0.04	0.45 ± 0.06	0.45 ± 0.08
***Superficial Gluteal* Dorsal (Site 1)**	0.41 ± 0.03	0.41 ± 0.06	0.41 ± 0.07
***Superficial Gluteal* Ventral (Site 2)**	0.39 ± 0.03	0.39 ± 0.05	0.39 ± 0.07
***Biceps Femoris* Dorsal (Site 1)**	0.41 ±0.04	0.41 ± 0.07	0.41 ± 0.09
***Biceps Femoris* Ventral (Site 2)**	0.47 ± 0.05	0.47 ± 0.07	0.47 ± 0.09

One canter trial was selected for investigation and sEMG data from each sensor location (Section 5.2.2(ii)) were used to explore the effect of different parameters on the detection process. sEMG data from the canter trial were DC-offset removed, high-pass filtered (Butterworth 4th order, 80 Hz cut-off, see Section 5.3), full-wave rectified and enveloped using each low-pass frequency parameter (zero lag, Butterworth 4th order, cut-off frequencies of 6, 15 and 25 Hz). A double-threshold technique was employed to determine the active or inactive status of EMG signals, in accordance with previous studies (Bonato et al., 1998; Merlo et al., 2003; Benedetti et al., 2012)

5.4.2(i) Initial detection process

Six different combinations of LPF and threshold parameters were investigated in this study. Activity onset events were detected for each muscle using the first threshold, which was defined as the point where the signal exceeded the average resting value from the corresponding LPF parameter by more than *n*SD (De Luca et al., 1997; Hodges and Bui, 1996). The optimal magnitude of deviation from the average resting value was investigated using threshold parameters of 1SD and 2SD, in accordance with previous studies (Hodges and Bui, 1996; Dixon and Howe, 2007) (Table 5.4). A second threshold was defined by the time required for the signal to exceed the first threshold for the muscle to be accepted as active (Bonato et al., 1998; Benedetti et al., 2012). Muscle onset was therefore detected at the point where the signal exceeded average resting values by *n*SD for over 30ms, which is in accordance with previous studies (Bonato et al., 1998; Hortobágyi et al., 2009; Dixon and Howe, 2007; Patil et al., 2011; Benedetti et al., 2012). Muscle activity offset was determined as the point where the signal was less than, or equal to the mean resting value plus *n*SD for more than 30 ms (Hodges and Bui, 1996; Bonato et al., 1998; Edwards et al., 2008; Patil et al., 2011; Benedetti et al., 2012). For example: the muscle was considered "inactive" when the onset deviated from the first threshold for less than 30 ms and was rejected as a false positive due to randomly occurring high magnitude values in the signal.

Table 5.4 First threshold values (µV) calculated as the magnitude of deviation from the baseline (average resting value) (see Table 5.3) for each sensor location, threshold parameter (*n*SD) and LPF parameter (6 Hz, 15 Hz, 25 Hz).

Muscle	6Hz		15Hz		25Hz	
	1SD	2SD	1SD	2SD	1SD	2SD
Splenius	13.23	15.37	12.47	14.15	11.78	12.91
***Trapezius* Cranial (Site 2)**	3.07	3.24	3.24	3.58	3.33	3.75
***Trapezius* Caudal (Site 1)**	2.36	2.67	2.40	2.77	2.48	2.92
***Triceps Brachii* Cranial (Site 1)**	0.48	0.51	0.50	0.56	0.52	0.59
***Triceps Brachii* Caudal (Site 2)**	0.49	0.53	0.52	0.58	0.54	0.62
***Superficial Gluteal* Dorsal (Site 1)**	0.44	0.47	0.47	0.53	0.48	0.55
***Superficial Gluteal* Ventral (Site 2)**	0.42	0.45	0.44	0.48	0.46	0.52
***Biceps Femoris* Dorsal (Site 1)**	0.45	0.49	0.48	0.55	0.51	0.6
***Biceps Femoris* Ventral (Site 2)**	0.52	0.57	0.54	0.60	0.56	0.65

5.4.2(ii) Post processing procedure

Post processing techniques were performed following initial detection in accordance with previous studies (Bonato et al., 1998; Merlo et al., 2003; Benedetti et al., 2012). Temporal distances between off and on events, which were less than 30 ms were considered to belong to the same contraction and were merged. (Bonato et al. 1998) (Figure 5.13). Following post processing, data were visually checked to ensure that marked artefacts were not falsely detected as onset events in accordance with previous studies (Dixon and Howe, 2007; Edwards et al., 2008; Patil et al., 2011).

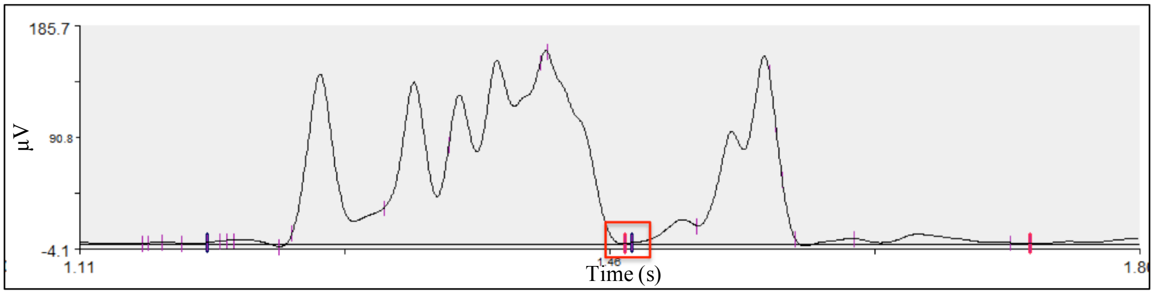


Figure 5.13 Example of false positive detection during post processing. Blue ticks indicate on events and red ticks indicate off events. The on/off transition highlighted in the red box illustrates a transition <30 ms, which was removed as a false positive due to randomly occurring low magnitudes.

5.4.3 Results

5.4.3(i) Optimal low-pass filter parameter

Figures 5.13 – 5.16 illustrate typical findings from the ventral sensor location (Site 2) on the Superficial Gluteal muscle. Figure 5.13 shows the effect of different LPF parameters on the signal and onset/offset events. The 6 Hz filter parameter produced a markedly smoother EMG profile, than 15 Hz and 25 Hz parameters and consisnently produced Type II errors across all muscles investigated (Figure 5.14a). The number of trials where no onset or offset events were detected were greatest in the 6 Hz cut-off frequency paramenter, for both 1SD and 2SD thresholds, as illustrated in Figures 5.14a and 5.15a. On one occasion a cut-off frequency of 15 Hz also failed to detect any onset and offset events in the Trapezius (Site 2) (Figure 5.15b). However, this occurred much less freqently than the 6 Hz parameter, which failed to identify events in 33% of investigated sensor locations. In trials where events were detected using a the 6 Hz parameter, the initial detection process produced an average of 6.6 ± 4.6 and 9.2 ± 5.4 fewer events than 15 Hz and 25 Hz parameters, respecitvely. Different filter parameters produced time delay for both onset and offset detection (Figure 5.16), with 6 Hz consistently producing inaccurate onset detection due to the excessive level of smoothing. Based on these findings, 6 Hz was considered to lack accuracy and consistency for determination of onset and offset events in equine sEMG data and therefore only data from 15 Hz and 25 Hz parameters were included in further analysis.

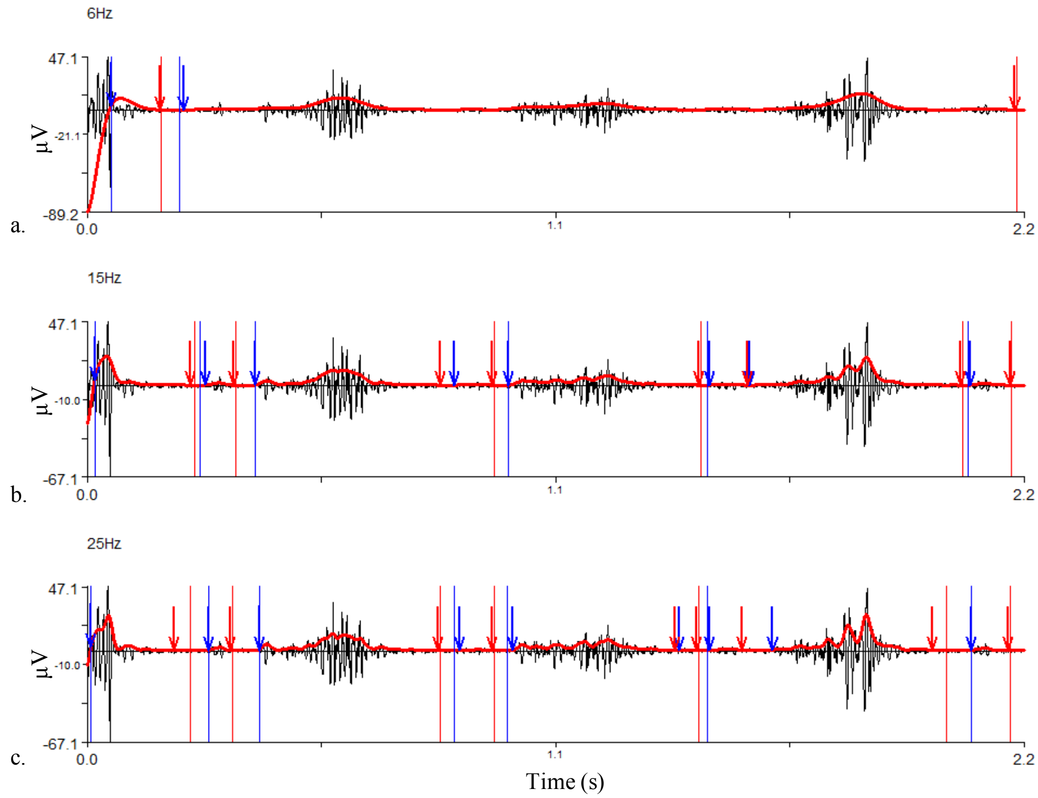


Figure 5.14 Effect of different LPF and threshold parameters on initial detection process in sEMG data collected from the Superficial Gluteal (ventral sensor location). Blue and red vertical lines indicate onset and offset events, respectively, which were derived from a first threshold of 1SD. Blue and red arrows indicate onset and offset events, resepectively, which were derived from a first threshold of 2SD. LPF parameters are indicated by bold red lines overlaid on high-pass filtered EMG signals (black). LPF filter parameters are illustrated in a.) 6 Hz b.) 15 Hz c.) 25 Hz.

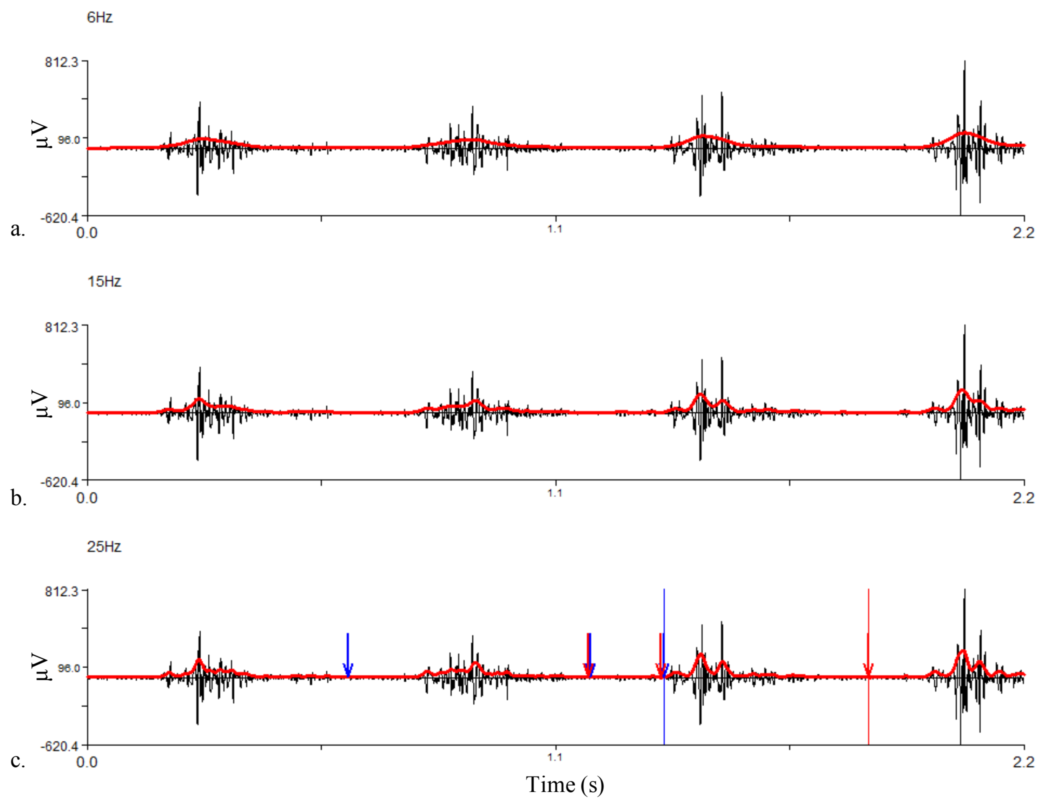


Figure 5.15 Effect of different LPF and threshold parameters on initial detection process in sEMG data collected from the Trapezius (cranial sensor location). Blue and red vertical lines indicate onset and offset events, respectively, which were derived from a first threshold of 1SD. Blue and red arrows indicate onset and offset events, resepectively, which were derived from a first threshold of 2SD. LPF parameters are indicated by bold red lines overlaid on high-pass filtered EMG signals (black). LPF parameters are illustrated in a.) 6Hz b.) 15Hz c.) 25Hz.

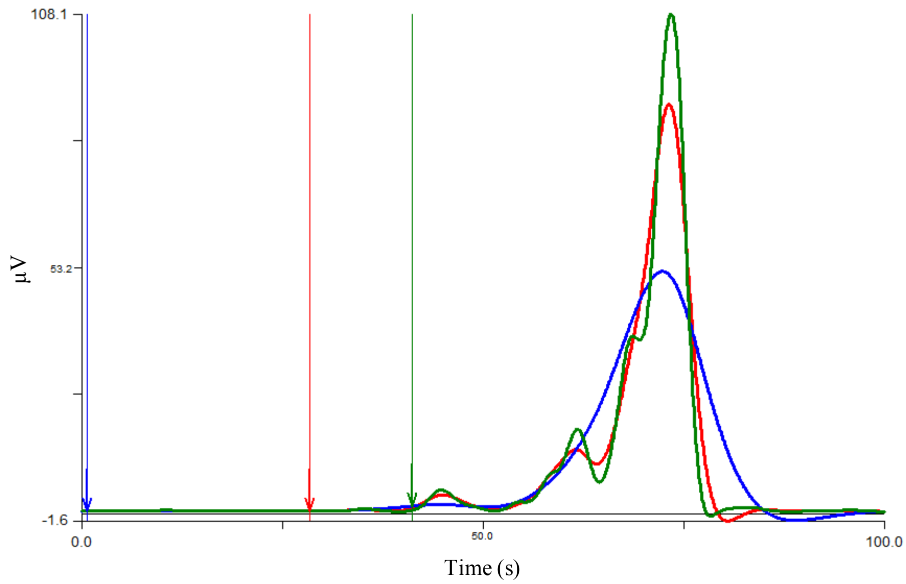


Figure 5.16 Representative enveloped sEMG traces from Biceps Femoris (dorsal sensor location) illustrating the effect of different LPF parameters on onset detection time. LPF cut-off parameters are indicated by: bold blue trace (6 Hz), bold red trace (15 Hz), bold green trace (25 Hz). Correspondingly coloured downward arrows indicate onset events detected using a 2SD threshold for each cut-off frequency.

5.4.3(ii) Optimal threshold parameters: initial detection process

Onset and offset event detection timings were markedly different when threshold values of 1SD and 2SD were applied to low-pass filtered signals at 15 Hz (Figure 5.17) and 25 Hz (Figure 5.18). Type I error, which falsely indicates that the muscle is in active state, was most frequently observed when combinations of 15 Hz/1SD (Figure 5.17b) and 25 Hz/1SD (Figure 5.18b) parameters were applied to signals. Figures 5.17b and 5.18b clearly illustrate the presence of Type I error, which is depicted by prolonged activation intervals. Prolonged activation intervals become especially evident when onset/offset events are visually compared to the clear activation pattern displayed in the non-enveloped sEMG signal (Figures 5.17a and 5.18a).

The 2SD threshold detected a greater number of events when combined with 15 Hz and 25 Hz parameters than the 1SD threshold during the initial detection process (Figures 5.17c and 5.18c). Greater sensitivity of the 2SD threshold resulted in an increased number of detected artefact activation intervals. However, this effect delayed onset detection of the large contractions of interest, providing a more accurate activation interval length. Figure 5.18c illustrates the increased sensitivity and accuracy of activation interval detection when a combination of 25 Hz/2SD parameters was applied to EMG signals.

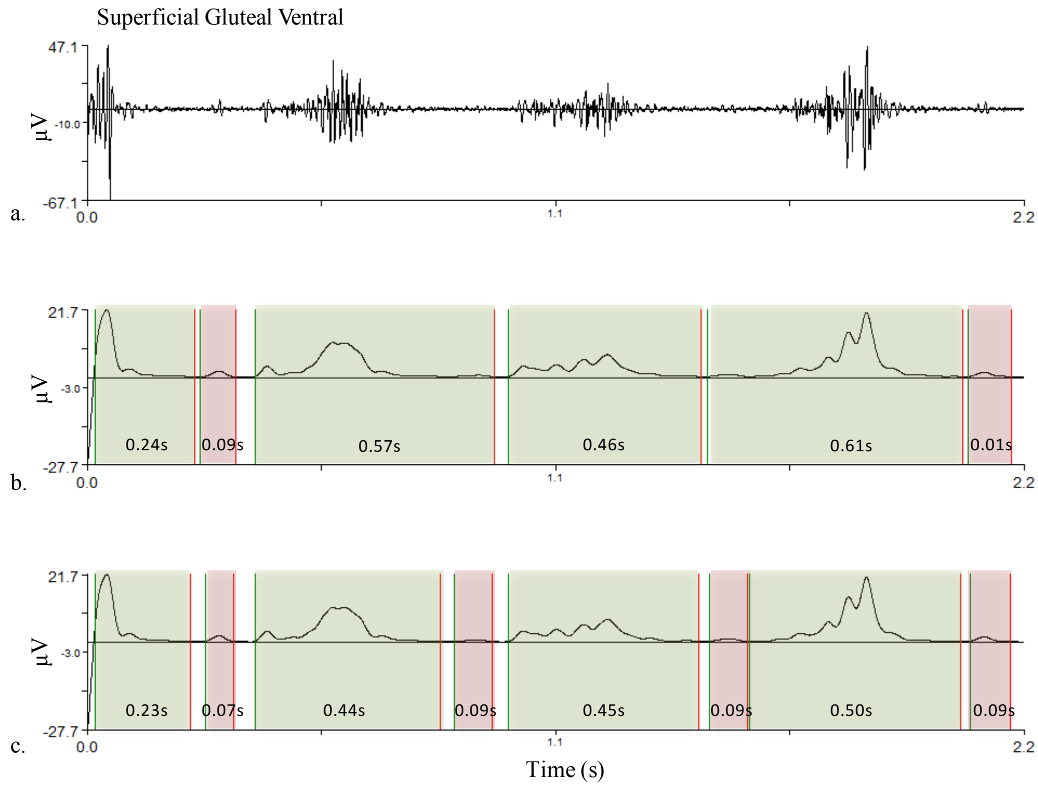


Figure 5.17 Initial detection process using 15 Hz parameter. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 15 Hz cut-off frequency and initial detection thresholds of b.) 1SD and c.) 2SD with a 30 ms time threshold. Green and red vertical lines represent onset and offset events, respectively. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are presented within each shaded area.

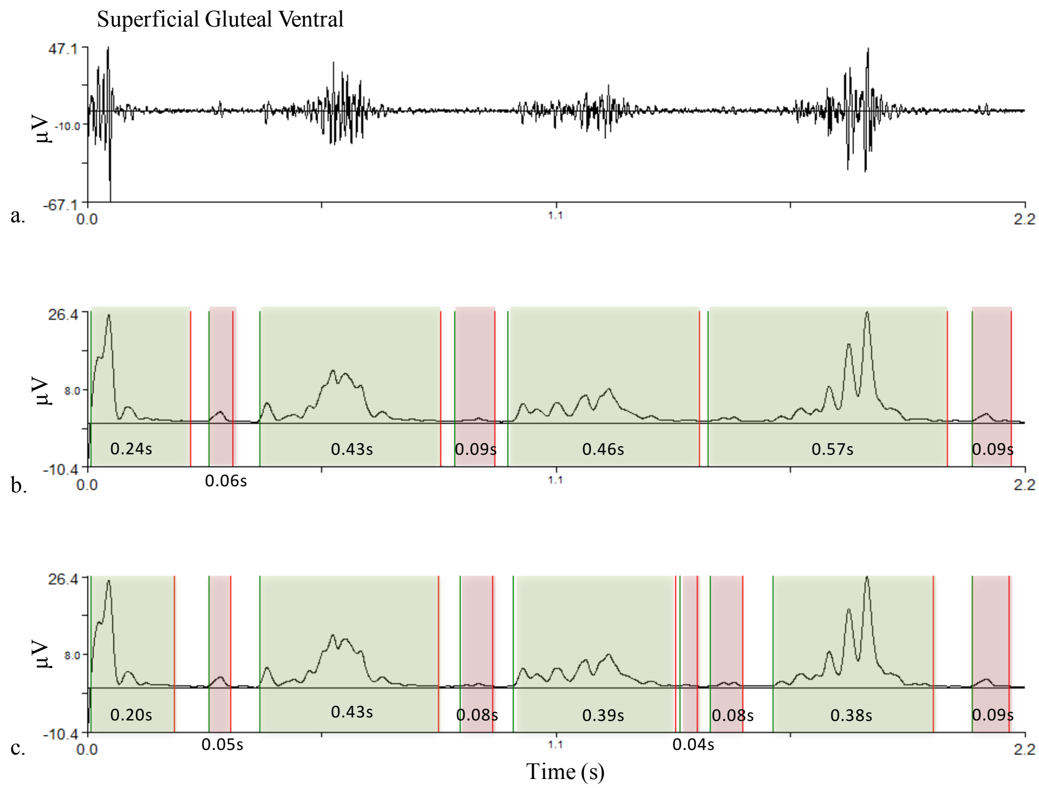


Figure 5.18 Initial detection process using 25 Hz parameter. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 25 Hz cut-off frequency and initial detection thresholds of b.) 1SD and c.) 2SD with a 30 ms time threshold. Green and red vertical lines represent onset and offset events, respectively. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are presented within each shaded area.

5.4.3(iii) Optimal threshold parameters: post processing procedure

Type I error became especially prominent using certain parameter combinations following post processing techniques (Figures 5.19 and 5.20). The merging of false positive events in the 15 Hz/1SD condition resulted in final events, which indicated that the muscle was active throughout most of the trial (Figure 5.19b). Visual examination of the non-enveloped high-pass filtered signal (Figure 5.19a) indicates a distinct pattern of active and inactive states, which confirms that activation intervals detected using the 15 Hz/1SD condition are inaccurate. The 25 Hz/1SD condition (Figure 5.20b) produced similar results, indicating that a threshold of 1SD may not be high enough to accurately detect onset and offset events in highly dynamic trials, regardless of the filtering parameter.

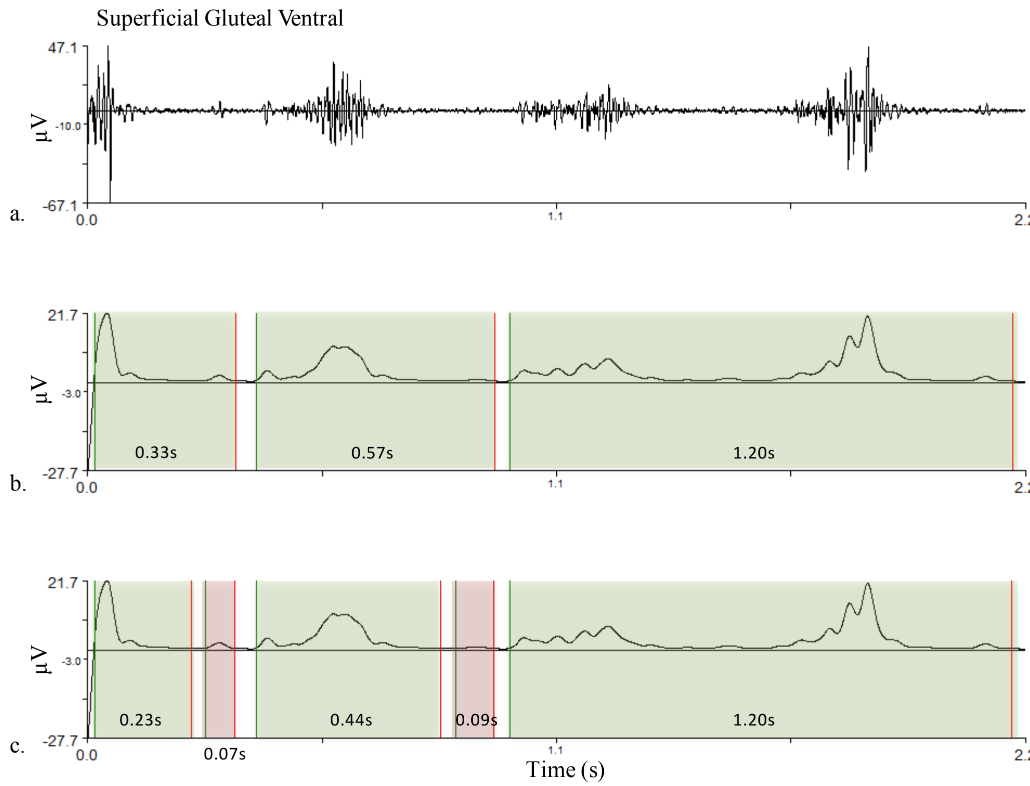


Figure 5.19 Post processing procedure using 15 Hz parameter. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 15 Hz cut-off frequency and post processing detection thresholds of 30 ms between off and on events for initial thresholds of b.) 1SD and c.) 2SD. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are represented in each shaded area.

A combination of 25 Hz/2SD parameters consistently produced the most accurate activation interval identification following post-processing techniques, which are illustrated in Figure 5.20c. Results from this condition consistently detected artefact events between activation intervals of the larger contractions of interest. The ability to accurately distinguish artefact activation intervals from contractions mitigated Type I error. Therefore, merging of false alarms into contractions, which resulted in inaccurate interval times in all other conditions, was minimised using 25 Hz/2SD parameters.

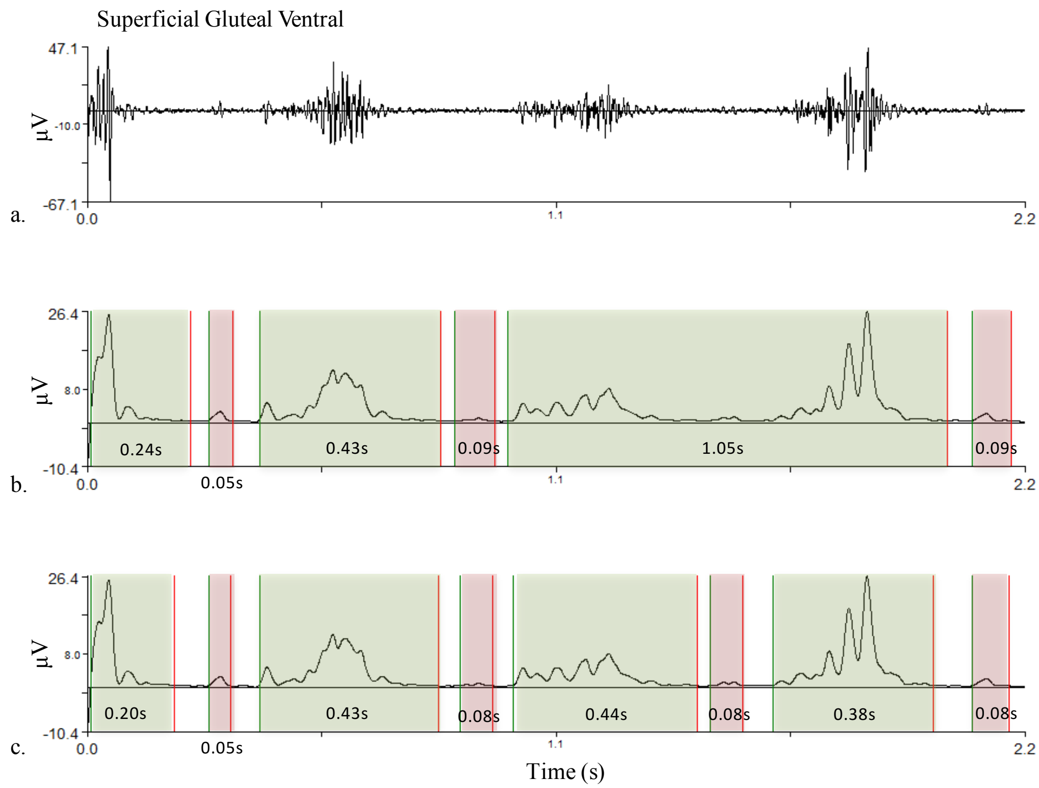


Figure 5.20 Post processing procedure using 25 Hz parameter. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 25 Hz cut-off frequency and post processing detection thresholds of 30 ms between off and on events for initial thresholds of b.) 1SD and c.) 2SD. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are represented in each shaded area.

It was postulated that increasing the first threshold to 3SD would delay onset/offset detection so that artefact interval timings were less than 30 ms, as these would be automatically removed based on the second threshold. Therefore, a first threshold value of 3SD and second threshold value of 30 ms were applied to sEMG data for each sensor location, which were enveloped using the optimal filter parameter of 25 Hz. Events identified in the initial detection process were compared to those detected using the 2SD threshold. This comparison was used to investigate whether a threshold of 3SD would permit automatic removal of artefacts, without affecting activation interval timings of the larger contractions of interest. Differences in onset and offset event timings for 2SD and 3SD threshold parameters are displayed in Table 5.4.

Table 5.5 Mean difference (±SD) and maximum difference between 2SD and 3SD thresholds for onset and offset events from each sensor location. Events presented were detected using the initial detection procedure. A negative difference indicates that events detected using 3SD parameter were identified after 2SD detection. A positive mean difference indicates that events detected using 3SD parameter were identified before 2SD parameter.

	Onset Event		**Offset Event**	
Muscle	**Mean Diff (±SD)**	**Max Diff**	**Mean Diff (±SD)**	**Max Diff**
Splenius	-0.0009 (0.002)	0.004	0.001 (0.002)	0.004
***Trapezius* Cranial (Site 2)**	-0.016 (0.027)	0.047	0.003 (0.003)	0.004
***Trapezius* Caudal (Site 1)**	0	0	0.0022 (0.0031)	0.004
***Triceps Brachii* Cranial (Site 1)**	-0.008 (0.0074)	0.017	0.018 (0.016)	0.039
***Triceps Brachii* Caudal (Site 2)**	-0.003 (0.0024)	0.004	0.002 (0.002)	0.004
***Superficial Gluteal* Dorsal (Site 1)**	-0.008 (0.012)	0.030	0.014 (0.024)	0.082
***Superficial Gluteal* Ventral (Site 2)**	-0.0034 (0.0019)	0.0043	0.012 (0.015)	0.043
***Biceps Femoris* Dorsal (Site 1)**	-0.0014 (0.0022)	0.0043	0.0022 (0.0036)	0.0086
***Biceps Femoris* Ventral (Site 2)**	-0.0035 (0.004)	0.013	0.0073 (0.0089)	0.026

Results from Table 5.4 indicate a minimal difference between 2SD and 3SD event timings. These results also reveal that a first threshold of 3SD consistently delayed the detection of onset events and prematurely detected offset events compared to the 2SD detection parameter. Mean decrease in activation interval timings of contractions was 0.012 ± 0.024 s when a threshold of 3SD was employed compared to intervals detected using 2SD. The mean decrease in interval timings for artefact in all muscles was 0.013 ± 0.016 s when 3SD was employed. Subtle differences in onset/offset detection and interval timings between 2SD and 3SD thresholds are illustrated in Figure 5.21. Figure 5.22 displays an example of events detected using 25 Hz/2SD and 25 Hz/3SD parameters following post-processing techniques. A comparison of 2SD and 3SD thresholds reveals that the 25 Hz/3SD parameter did not decrease artefact interval timings significantly enough for them to be automatically removed using the second threshold (<30 ms). The 25 Hz/3SD parameter did however decrease activation interval timings of the main contractions, which may decrease the accuracy of onset and offset events. Figure 5.23 illustrates the effect of 1SD, 2SD and 3SD thresholds on onset and offset detection timings, further highlighting the effect of 3SD on decreased activation interval time.

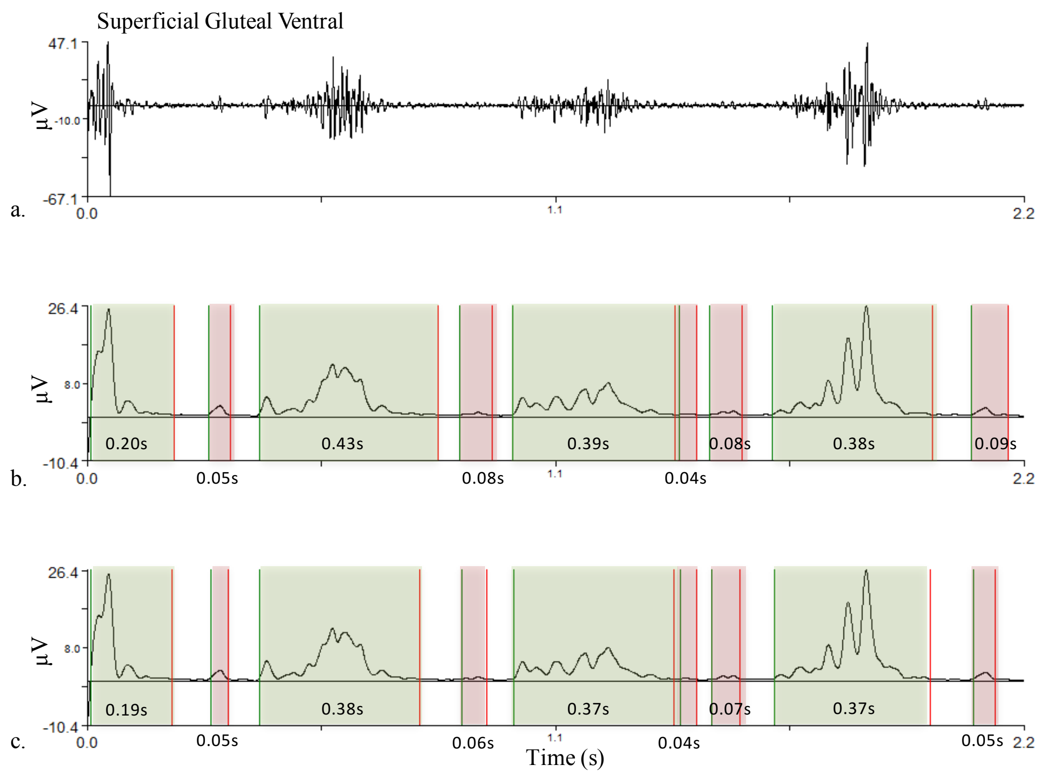


Figure 5.21 Initial detection process illustrating differences between 2SD and 3SD thresholds. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 25 Hz cut-off frequency and initial detection thresholds of b.) 2SD and c.) 3SD with a 30 ms time threshold. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are represented in each shaded area.

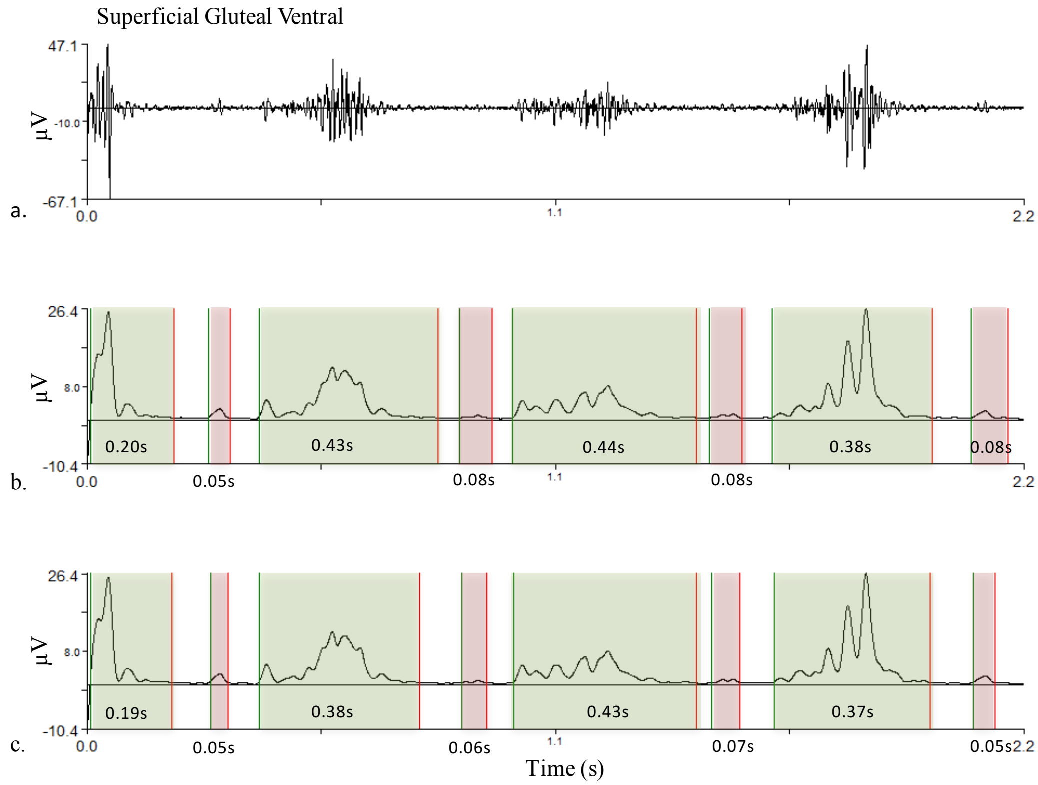


Figure 5.22 Post processing procedure illustrating differences between 2SD and 3SD thresholds. a.) High-pass filtered signal (Butterworth 4th order, 80 Hz cut-off) from Superficial Gluteal (ventral sensor location) prior to application of linear envelope, included for reference. b.) and c.) illustrate the initial detection process using a 25 Hz cut-off frequency and post processing detection thresholds of 30 ms between off and on events for initial thresholds of b.) 2SD and c.) 3SD. Green shaded areas represent areas greater than 0.1s that were considered to be a large contraction. Red shaded areas represent areas of noise or Type 1 error. Muscle activation interval durations are represented in each shaded area.

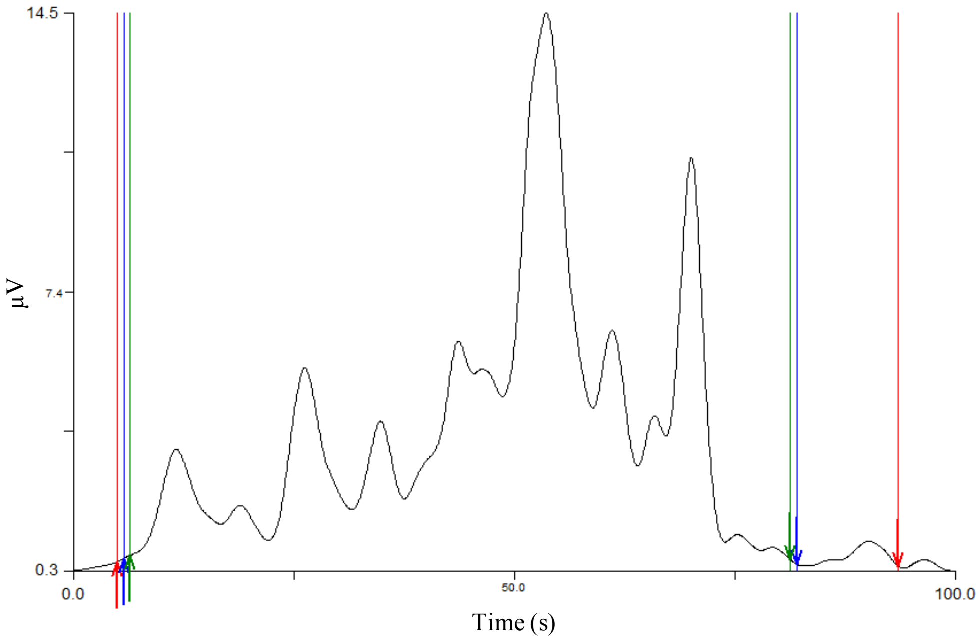


Figure 5.23 Variation in onset/offset detection time determined by different threshold parameters in a low-pass filtered (25 Hz cut-off) sEMG trace from the TB caudal sensor location. Upward arrows indicate onset events and downward arrows indicate offset events determined using thresholds of: 1SD (red), 2SD (blue), 3SD (green).

5.4.4 Discussion

Methods for determining on-off events using pre-determined threshold values have faced criticism. Researchers have stated that threshold values are determined arbitrarily and that activation patterns can only be considered as estimations of activity due to their strong reliance on subjective thresholds (Winter, 1984; Bonato et al., 1998; Benedetti et al., 2012). However, this study has provided objective evidence for the use of the double-threshold method, as a reliable technique for determining muscle activity patterns in equine sEMG data. The double-threshold method allows the user to reject Type 1 error due to the stochastic characteristics of the EMG signal, offering less restriction than the single-threshold method, and was found to be the optimal method for equine sEMG data.

5.4.4(i) Optimal first threshold parameter

An investigation of three thresholds, which are commonly employed in human research, revealed that 2SD was the optimal threshold for equine sEMG data based on its ability to minimise Type I and Type II error. Type I error occurs when the muscle is detected as being in an active state when it is not and is generally associated with a low threshold (Hodges and Bui, 1996). Type II error is denoted by failure to detect EMG onset when it occurs, which is generally associated with conservatively high or low thresholds (Hodges and Bui, 1996). It is known that low threshold values lead to early onset detection and increased false alarms (Hodges and Bui, 1996; Staude et al. 2001). Early onset detection, increased false alarms, and Type I error were observed in this study when a 1SD parameter was employed across all filter parameters. Furthermore, the merging of 1SD false alarms during post processing resulted in events that produced prolonged activation intervals, often grouping two large contractions within the same activation interval (Figures 5.19b, 5.20b).

High threshold values are generally associated with delayed or missed onset detection (Hodges and Bui, 1996; Staude et al., 2001). In this study, the highest threshold of 3SD detected delayed onset and early offset of the large contractions of interest, decreasing the accuracy of events as well as the activation interval. Previous studies have employed threshold parameters of 1SD (Karst and Willet, 1995; Hodges and Bui, 1996; Dixon and Howe, 2007) and 3SD (Di Fabio, 1987; Hodges and Bui, 1996; Edwards et al., 2008; Patil et al., 2011) for human sEMG data. However, these parameters produced undesirable results and were not considered appropriate for the equine sEMG data. An optimal first threshold value of 2SD is in agreement with Hodges and Bui (1996), who recommend this threshold for signals with high background activity. This is in accordance with the inherent high background activity of equine sEMG data collected during highly dynamic movement trials.

5.4.4(ii) Optimal second threshold parameter

A second threshold of 30 ms has been used in several human sEMG studies (Gilleard et al., 1998; Janwantanakul and Gaogasigam, 2005; Edwards et al., 2008; Patil et al., 2011) to denote the time required for the signal to exceed the first threshold. In this study, a second threshold of 30 ms was employed for initial detection and post processing procedures to detect erroneous onset/offset events caused by the inherent stochastic nature of the EMG signal (Bonato et al., 1998). It is generally accepted that muscle activation of 25 – 40 ms has no functional significance on the kinematics and kinetics of gait, (Bogey et al., 1992) suggesting that onset and offset events lasting less than 30 ms be rejected (Bonato et al., 1998). Merlo et al. (2003) reported using a temporal marker of less than 125 ms as the threshold to reject or accept events, as this value was arbitrarily assumed to be the lowest effective muscle activity. However, Hodges and Bui (1996) reported that a threshold value of 50 ms delays onset detection by an average of 33.58ms, while a threshold of 25 ms provided the most accurate onset detection in comparison with reference events. This further justifies the 30 ms threshold proposed in this study and suggests that studies rejecting events based on large timing thresholds should be cautiously considered. Furthermore, to the author's knowledge only one equine study has described a method for determining onset events in equine sEMG data, and specified a first threshold of 30 ms (Harrison et al., 2012).

5.4.4(iii) Optimal low-pass filter parameters

Not only has this study proposed optimal threshold parameters to be used in conjunction with the double-threshold detection method, it has explored optimal LPF parameters for equine sEMG processing. This investigation provides an additional contribution to knowledge, as optimal LPF parameters have yet to be thoroughly investigated in equine research. The benefits associated with the use of an enveloped signal for detection of muscle activity onset/offset have been previously described (Hodges and Bui, 1996) and the accuracy of interpretation of the EMG trace is closely related to the LPF parameters employed (Kleissen, 1990). Greater time lag has been observed when lower cut-off frequencies are employed, with respect to the raw EMG trace, than when higher cut-off frequencies are employed (Kleisen, 1990). In this study, excessive smoothing of data was observed using the 6 Hz parameter, resulting in: a loss of data, signal fluctuation and inaccurate detection of events. This finding is in accordance with Hodges and Bui (1996), who reported errors of 56.44 – 144.87 ms prior to reference events when data were excessively smoothed using a 10 Hz cut-off frequency. In this study, a LPF with a cut-off frequency of 25 Hz proved to be the most accurate and consistent for accurate event detection in equine data. This finding is in accordance with Kleissen (1990), who justified their choice of a 25 Hz filter based on the requirement that rapid fluctuations in the EMG signal intensity were preserved.

Most equine sEMG studies report filtering data using a Butterworth LPF with a cut-off frequency of 10 Hz (Peham et al., 2001a; Licka et al., 2009; Zaneb et al., 2009; Groesel et al., 2010; Zsoldos et al., 2010a, b), which has been justified by referencing Peham et al. (2001b). However, Peham et al (2001b) found significant differences in the SNR between LPF signals at 10 Hz and a signal-adapted filter (SAF), reporting considerable noise reduction when the SAF was applied to equine sEMG data (Peham et al., 2001b). This study may therefore not be an appropriate justification for the LPF parameters used in equine research, as Peham et al (2001b) did not explicitly recommend the use of a LPF. Based on results from this study and from previous research (Kleissen, 1990; Hodges and Bui, 1996) a cut-off frequency of 10 Hz is likely to excessively smooth data, decreasing event detection accuracy by prematurely identifying onset/offset events. Furthermore, a cut-off frequency of 10 Hz will result in a loss of signal data and should not be employed in studies investigating the intricacies of the equine sEMG trace. Therefore, the methods and results described by previous equine sEMG research should be considered with caution. It is strongly advised that future research in this area investigates methods before applying them to equine sEMG data to ensure the accuracy of results.

Cut-off frequencies as high as 500 Hz have been employed in previous research for onset/offset detection (Studenski et al., 1991; Abbinik et al., 1998), which are likely to result in inaccurate, delayed onset detection (Hodges and Bui, 1996). In this study, similar events were detected using cut-off frequencies of 15 Hz and 25 Hz, suggesting that an investigation of higher cut-off frequencies may lead to insufficient data smoothing (Hodges and Bui, 1996) and was therefore not required. The inherently high background activity of equine sEMG data is associated with highly dynamic movements and is an important consideration for the choice of filter parameter. Therefore, every attempt was made to mitigate high background activity using previously described high-pass filtering methods (Section 5.3). However, the 25 Hz parameter was the only cut-off frequency, which permitted event detection in all sensor locations. Type I error was more prevalent in the 15 Hz parameter, especially following post processing techniques, compared to the 25 Hz parameter. For these reasons a LPF with a cut-off frequency of 25 Hz was chosen as the optimal filter parameter for the double detection method.

To the author's knowledge this is the first study to describe a method for determining muscle activity onset and offset events from equine sEMG data. As previously stated, Harrison et al., (2012) is the only known study to include a description of the methods used to determine muscle activity onset/offset in the horse. This study employed a method described by Hortobagyi et al (2009), but failed to provide justification for why this human sEMG method was applied to equine sEMG data. The method described by Hortobagyi et al (2009) employed a LPF with a 40 Hz cut-off frequency to envelope data. Onset and offset events were detected when baseline activity deviated ±13SD from baseline noise for over 30 ms (Hortobagyi et al., 2009). LPF described by Hortobagyi et al (2009) comply with recommendations from Hodges and Bui (1996). However, based on results from the 3SD parameter investigated in this study, a detection threshold of ±13SD would undoubtedly introduce Type II error and delay onset/offset detection substantially in equine sEMG data. Findings from this study suggest that onset/offset results from Harrison et al., (2012) be considered with caution and highlight the importance of investigating human sEMG analysis methods before applying them to equine sEMG data.

5.4.5 Conclusion

This study presented an event detection method for muscle activity onset and offset using equine sEMG data, which was based on double-threshold methods previously described in human research (Bonato et al., 1998; Merlo et al., 2003; Benedetti et al., 2012). An investigation of various LPF and pre-determined threshold parameters revealed that a combination of 25 Hz/ 2SD/ 30ms thresholds provided optimal conditions for detection of muscle onset/offset events. The proposed double-threshold method is suitable for application to sEMG data collected from equine subjects during highly dynamic trials. This study offers a method, which provides an automatic and objective approach to analysing muscle activity intervals in equine subjects and mitigates the subjective and time-consuming processes of previously described methods. It should be noted that a small sample was employed in this study and further research is required to ensure that the methods presented are suitable for use on the wider equine population.

5.5 Exploration of optimal sEMG electrode position for selected superficial muscles

5.5.1 Introduction

It is widely accepted that the location of the sensor over the muscle is the most significant factor for achieving good (SNR) (Basmajian and De Luca, 1985; Richards, in preparation). sEMG signals are also greatly affected by electrode characteristics, subcutaneous tissues and non-homogenous properties of muscle and tissue in the detection area (Basmajian and De Luca, 1985; Roy et al., 1986; Schneider et al., 1991; De Luca, 1997; Saitou et al., 2000; Zaheer et al., 2012). For this reason, standardized sensor locations have been developed for individual muscles in humans (Hermens et al., 2000). However, to the author's knowledge, only one study has investigated sensor placement in horses (Zaneb et al., 2007). Previous equine sEMG studies have provided a description for the method used to identify and standardise sensor location (i.e. Robert et al., 2001b; Schuurman et al., 2003; Hodson-Tole, 2006). However, numerous equine studies do not describe sEMG sensor location or provide an unclear description (i.e. Robert et al., 1999; Zaneb et al., 2009; Crook et al., 2010; Harrison et al., 2012). The exact location of electrodes over a superficial muscle is imperative information and is essential for comparison of findings between studies. Furthermore, without sensor location descriptions, studies lack repeatability, which further limits progression towards standardised protocols for equine sEMG research.

Increasing evidence points to many muscles having functional subdivisions, in most cases this subdivision refers to separate heads (Hermens et al., 2000), which have been accounted for in the Biceps Femoris, Triceps Brachii and Trapezius muscles in this study. However, subdivisions have been described in terms of structurally intermixing of MUs with differing biomechanical functions (Hermens et al., 2000). Regional variations have been shown to occur during muscle activation (Soman et al., 2005; Wakeling et al., 2007; Wakeling, 2009) and optimal activation for a specific dynamic task may involve specific regions of a muscle (Wakeling, 2009). These functional subdivisions imply that certain muscles cannot be represented based on the signals detected from one sensor location (Hermens et al., 2000). The use of standardised electrode placements has therefore been criticized for assuming that measurements from one location are representative of the whole muscle belly (Wakeling, 2009). Based on these findings, analysing the equine muscle as a homogenous unit, especially in the significantly larger muscles of the horse, using one sensor may not provide an accurate depiction of muscle activity (Wakeling, 2009). To the author's knowledge, Wakeling et al. (2007) is the only study to investigate the presence of functional subdivisions in equine musculature. This gap in knowledge further justifies an investigation of optimal sEMG sensor locations, which consistently detect high fidelity sEMG signals.

SNR is generally accepted as the best method for determining the quality of the EMG signal, and is greatly influenced by sensor location (Clancy et al., 2002; De Luca, 2002; Reaz et al., 2006; Richards, in preparation). SNR is defined as the ratio of the energy in the desired EMG signal versus the unwanted noise signal, commonly referred to as baseline noise and movement artefact noise (Reaz et al., 2006; De Luca et al., 2010) (Figure 5.24). The amplitude of the desired EMG signal is highly dependent on the location of the sensor on the muscle of interest, while unwanted noise amplitude is highly dependent on intrinsic noise sources, namely movement artefact and the skin-electrode interface (De Luca, 1997; De Luca et al., 2010). To the author's knowledge, the effect of electrode location on spectral properties has not been considered in equine sEMG studies and could provide evidence for optimal sensor locations in equine biomechanics research. Movement artefact has been previously described in Section 5.3 and is a particular concern for research investigating dynamic movements (De Luca et al., 2010). Sensor locations, which detect minimal baseline noise and movement artefacts, would undoubtedly provide evidence for optimal sensor locations for studies investigating dynamic equine movement.

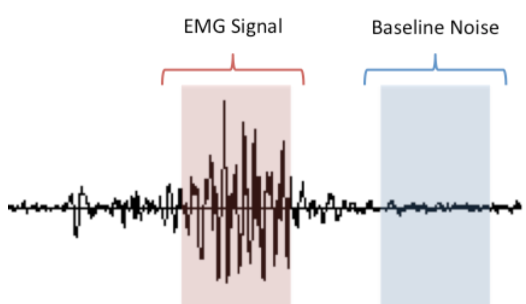


Figure 5.24 sEMG signal and baseline noise components of the sEMG trace.

As previously described in Section 5.2, the recommended position for surface electrodes is on the midline of the muscle belly, between the myotendinous junction and the nearest innervation zone (Basmajian and De Luca, 1985; De Luca, 1997; Hermens et al., 2000; Konrad, 2006). As an alternative second option, electrodes can be placed between the origin and insertion point on the muscle belly (Zaneb et al., 2007). The detrimental influence of innervation zones (IZ) on EMG signals has been previously described and studies have determined IZ distribution for various muscles to inform sensor locations (Roy et al., 1986; Saitou et al., 2000; Rainoldi et al., 2000, 2004). However, to the author's knowledge, no studies have investigated IZ distribution in equine skeletal musculature or discussed their potential impact on results. More research is required in this area to understand the effect of equine muscle structure on sEMG signal detection and sensor locations.

The absence of approved protocols for sEMG sensor placement on equine muscles represents a major gap in knowledge. The validity of results for the main study of the thesis are entirely reliant on representative data for the activity patterns of selected superficial muscles, which can only be successfully obtained through proper placement of sEMG sensors (Basmajian and De Luca, 1985; De Luca, 1997, 2012). The aim of this study was therefore to determine a.) the ideal sensor position for equine muscles, based on previously described locations and b.) whether multiple sensors would be necessary to collect representative data from equine muscles.

5.5.2 Methods

sEMG sensor locations for equine muscles were investigated using locations described in Section 5.2.2(ii) for Trapezius (cranial head), Triceps Brachii (long head), Superficial Gluteal and Biceps Femoris (vertebral head) muscles. sEMG data used in this study were collected during pilot work in accordance with the protocols described in Section 5.2 and Chapter 4. For each muscle, data from three different subjects are presented and were obtained during canter trials. This was done to ensure that any observed patterns were consistent between individuals of varying size, breed, age and training level. Sensor locations were therefore explored in an effort to produce findings, which could be used to standardise electrode-positioning protocol in the wider equine population.

Baseline noise values and muscle activity onset and offset events were determined for each sensor location within each superficial muscle of interest. Onset/ offset event timings and baseline noise were determined using sEMG signals, which had been DC offset removed and high-pass filtered using a zero-lag Butterworth 4^{th} order filter with cut-off frequency of 80 Hz, in accordance with Section 5.3. The high-pass filtered signal permitted clear differentiation between baseline noise and EMG signal during canter trials (Figure 5.25). Figure 5.25 further justifies the use of an 80 Hz cut-off frequency, as described in Section 5.3.

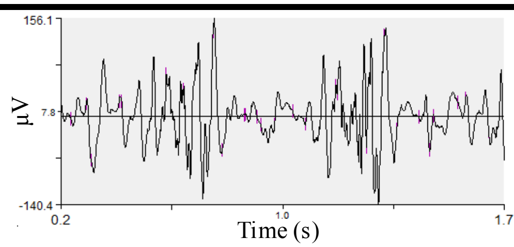
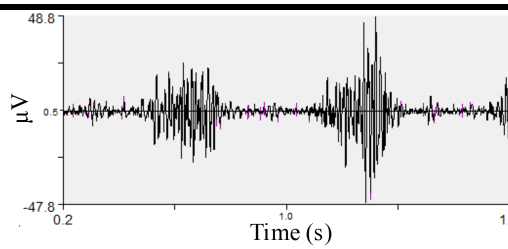
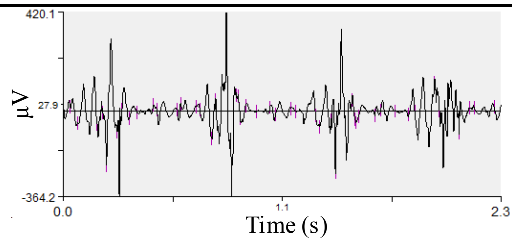
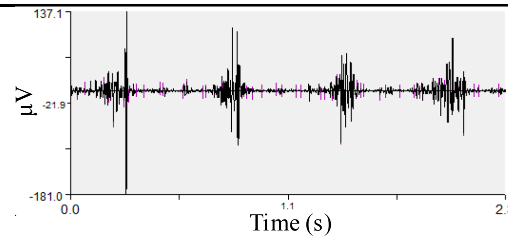
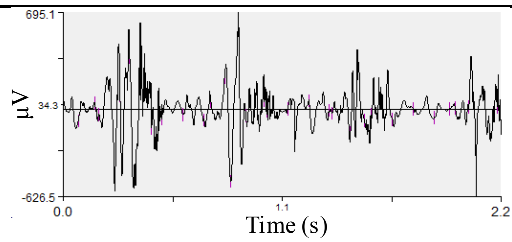
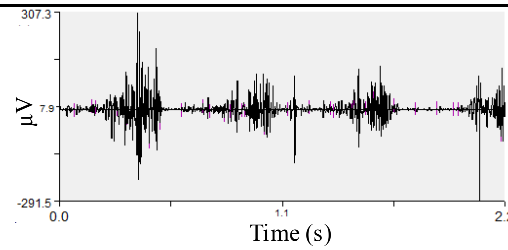
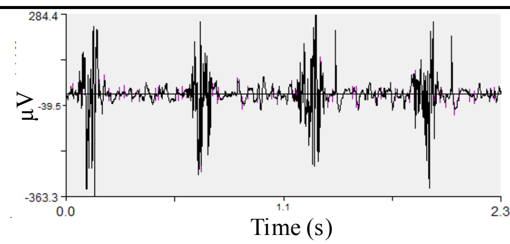
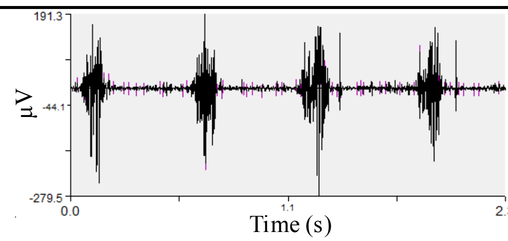
Muscle	Raw EMG Trace	High-Pass Filtered (80Hz cut-off) EMG Trace
Superficial gluteal		
Triceps brachii		
Trapezius		
Biceps femoris		

Figure 5.25 Raw and high-pass filtered (80 Hz cut-off) sEMG traces from selected superficial muscles, illustrating the increased ability to visibly determine baseline noise and EMG signal from high-pass filtered signals.

Muscle activity onset and offset events were determined in accordance with the double-threshold method described in Section 5.4. The number of onset/offset event detections and event timings were used to compare muscle activity patterns from both sensor locations from each muscle of interest. Differences in event timings were calculated as the average difference in onset/offset event detection time for each location across all three subjects for each muscle. Maximum timing difference within the three subjects for each muscle was also calculated.

Baseline noise values from both sensor locations within each muscle of interest were calculated to determine which location was least affected by low frequency noise contamination. Visual identification of a quiescent period during each trial was used to create two events, which denoted a baseline noise subset. Events denoting baseline noise subsets were identical for each sensor location to ensure that baseline noise values were calculated from the same number of data points, permitting direct comparison between locations. Baseline noise values were calculated as the mean value of the full-wave rectified sEMG signal (DC offset removed, Butterworth 4th order high-pass filter, cut-off frequency 80 Hz) between events denoting the baseline noise subset.

5.5.3 Results

In this section, descriptive statistics from all three subjects are presented for each muscle of interest. However, figures presented for each muscle are only representative of one subject. Figures for the remaining two subjects are included in Appendix D.

5.5.3(i) Superficial gluteal

Selected sEMG traces from dorsal (Site 1) and ventral (Site 2) Superficial Gluteal sensor locations are illustrated in Figure 5.26. Visual inspection of both locations suggests a similar muscle activity pattern. Activity patterns were further investigated through a comparison of muscle onset and offset illustrated in Figure 5.28 Across all subjects, the average difference between onset event timings for each location was 0.038 ± 0.031 s, with a maximum difference of 0.082 s. The average difference for offset event timings for each location was 0.113 ± 0.069 s, with a maximum difference of 0.241s. Type I error was observed once in the ventral location of Subject 2, where two activity bursts were grouped into the same activation interval (Figure 5.28b). Baseline noise values were very similar for both locations across all subjects (Figure 5.27), however values were consistently higher in the ventral location (Table 5.5).

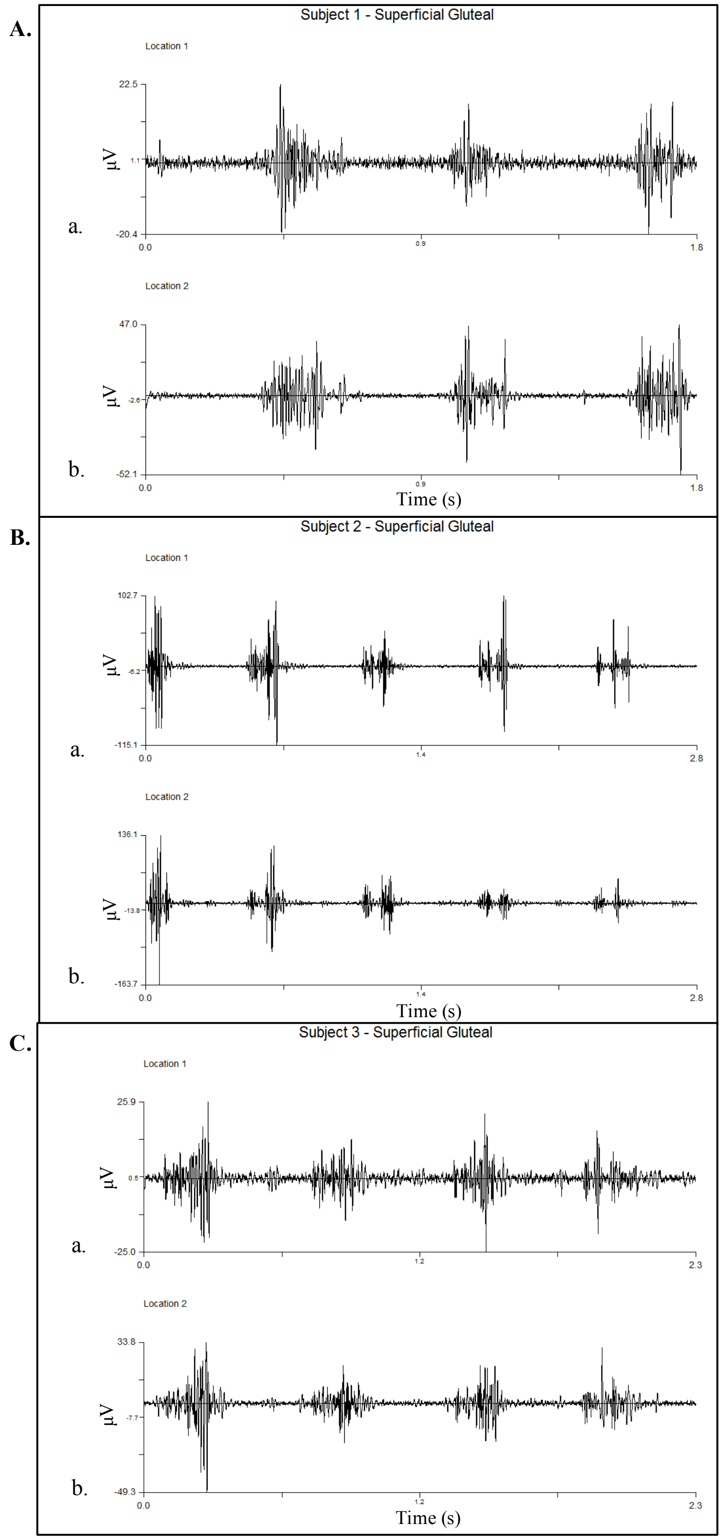


Figure 5.26. sEMG signals from electrodes positioned on a.) Site 1 (dorsal) and b.) Site 2 (ventral) of the Superficial Gluteal muscle. Signals presented are DC offset removed and high-pass filtered with a cut-off frequency of 80 Hz and were obtained from the three subjects during canter.

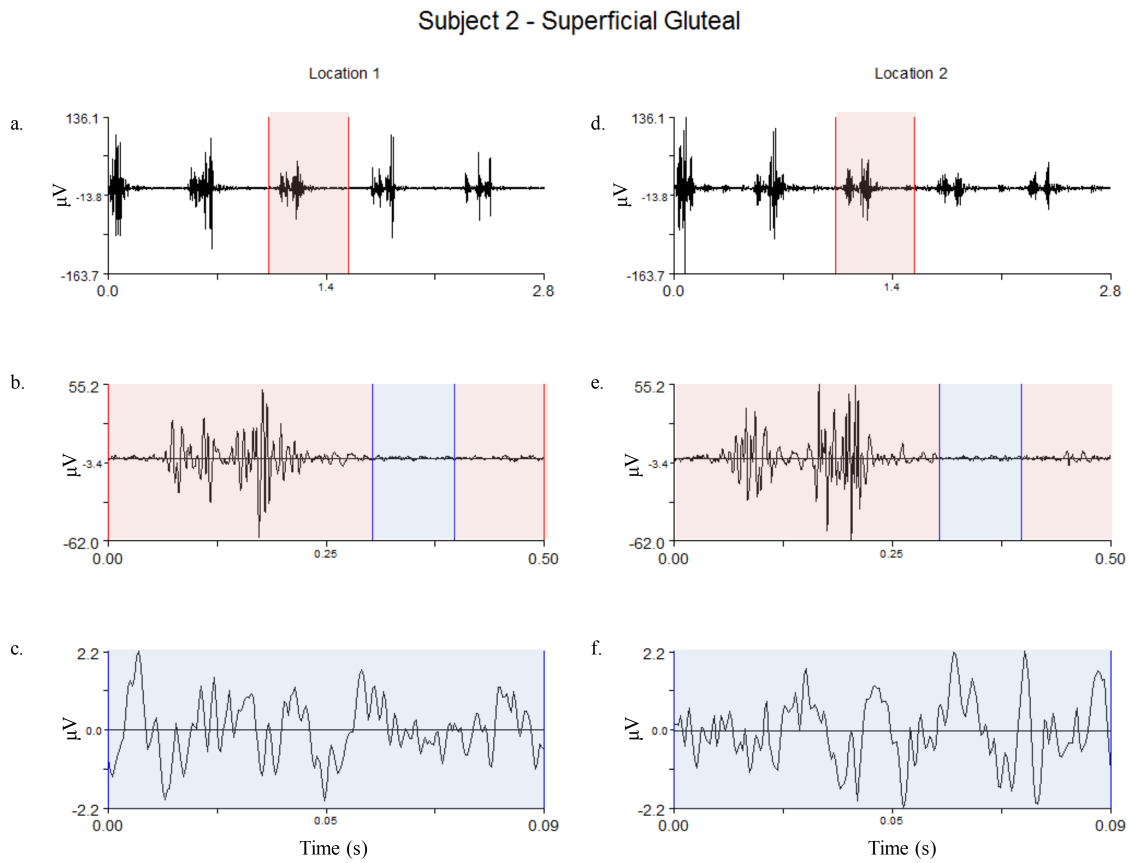


Figure 5.27 Time domain and spectral characteristics of baseline noise and sEMG signals from Superficial Gluteal from electrode Site 1 (a, b, c) and Site 2 (d, e, f) in subject 2. Signals presented are high-pass filtered with an 80 Hz cut-off frequency. Blue shaded areas represent selected areas of baseline noise, with blue vertical lines representing the beginning and end of the baseline noise subset.

Table 5.6 Mean ± SD values for baseline noise (µV) from Superficial Gluteal sensor locations.

	Site 1 (Dorsal)	Site 2 (Ventral)
Subject 1	0.61 ± 0.42	0.82 ± 0.76
Subject 2	0.65 ± 0.48	0.73 ± 0.54
Subject 3	0.67 ± 0.51	0.73 ± 0.59

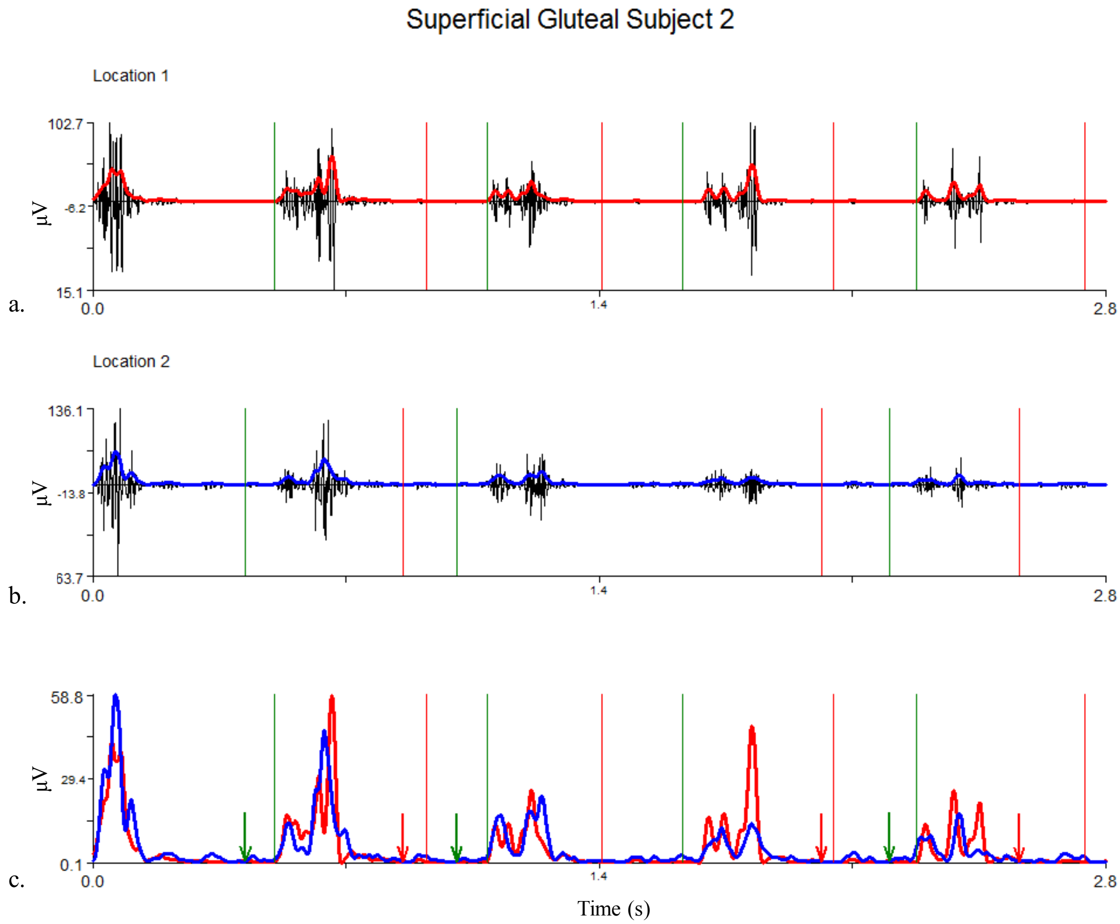


Figure 5.28 Onset and offset events for Superficial Gluteal sensor locations from subject 2.

a.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 1 (dorsal) and low-pass filtered trace (cut-off frequency 25 Hz) (red bold).

b.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 2 (ventral) and low-pass filtered trace (cut-off frequency 25 Hz) (blue bold). Green and red vertical lines represent onset and offset events, respectively for graphs a.) and b.).

c.) Overlay of low-pass filtered sEMG traces (cut-off frequency 25 Hz) for Site 1 (red bold) and Site 2 (blue bold). Green and red vertical lines represent onset and offset events, respectively for Site 1. Green and red arrows represent onset and offset events, respectively for Site 2.

5.5.3(ii) Triceps brachii

Selected sEMG traces from cranial (Site 1) and caudal (Site 2) Triceps brachii (long head) sensor locations are illustrated in Figure 5.29. Visual inspection of both locations indicates a similar muscle activity pattern, apart from the Site 2 in subject 3, where signal quality has been compromised by external noise sources. A comparison of muscle onset and offset events are illustrated in Figure 5.31. Onset/offset events from each location indicate a very similar muscle activity pattern in both locations. Across all subjects, the average difference between onset event timings for each location was 0.028 ± 0.021 s, with a maximum difference of 0.056 s. The average difference for offset event timings for each location was 0.065 ± 0.059 s, with a maximum difference of 0.164 s. Type I error was only observed in the caudal (Site 2) location in subject 3 (see Appendix D). Figure 5.30 illustrates baseline noise values from both sensor locations in subject 2. Similar levels of baseline noise were observed in Subjects 1 and 2 (Table 5.6). Subject 3 exhibited the greatest baseline noise values for both locations, which is likely due to the external factors contaminating the signal. Baseline noise was consistently higher in the caudal (Site 2) location across all subjects.

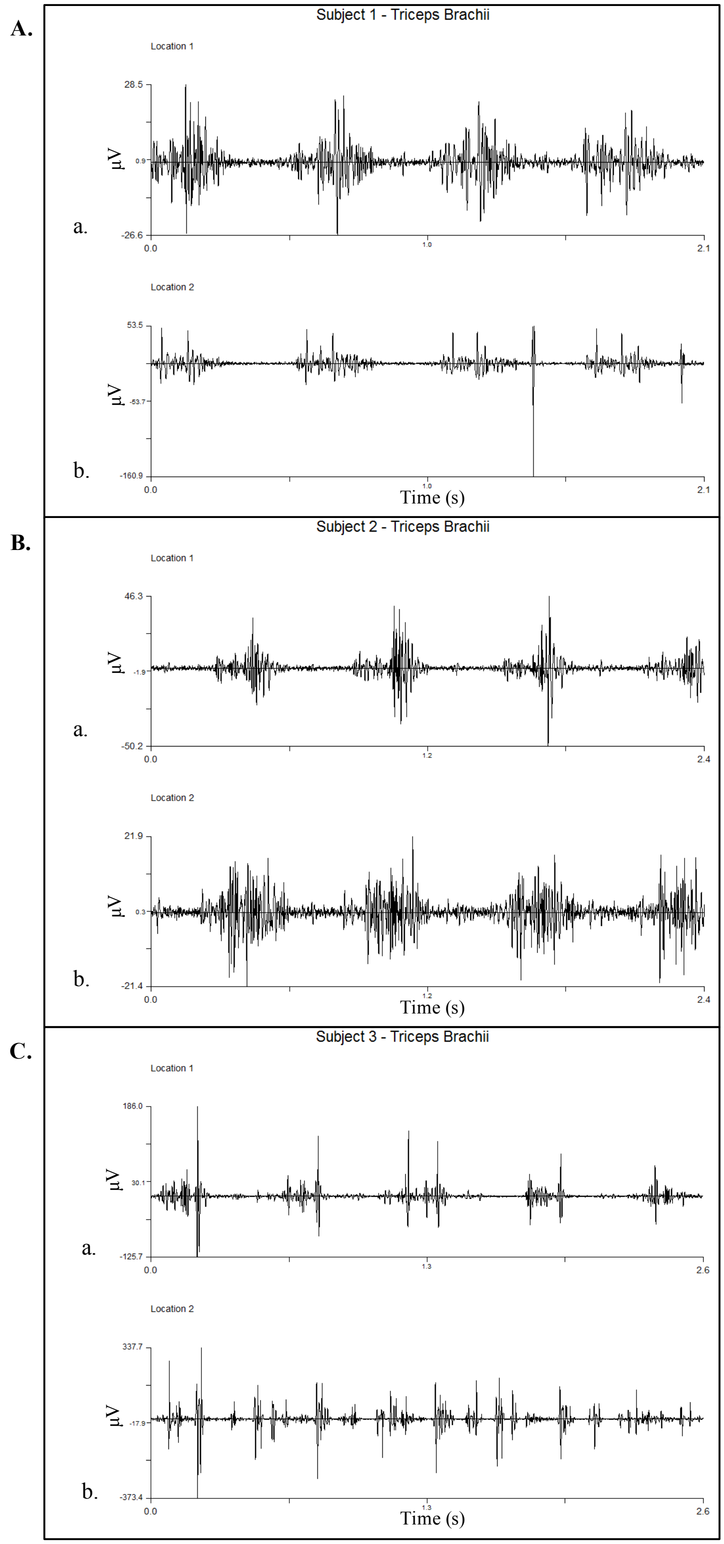


Figure 5.29 sEMG signals from electrodes positioned on a.) Site 1 (cranial) and b.) Site 2 (caudal) of the Triceps Brachii (long head) muscle. Signals presented are DC offset removed and high-pass filtered with a cut-off frequency of 80 Hz and were obtained from the three subjects during canter.

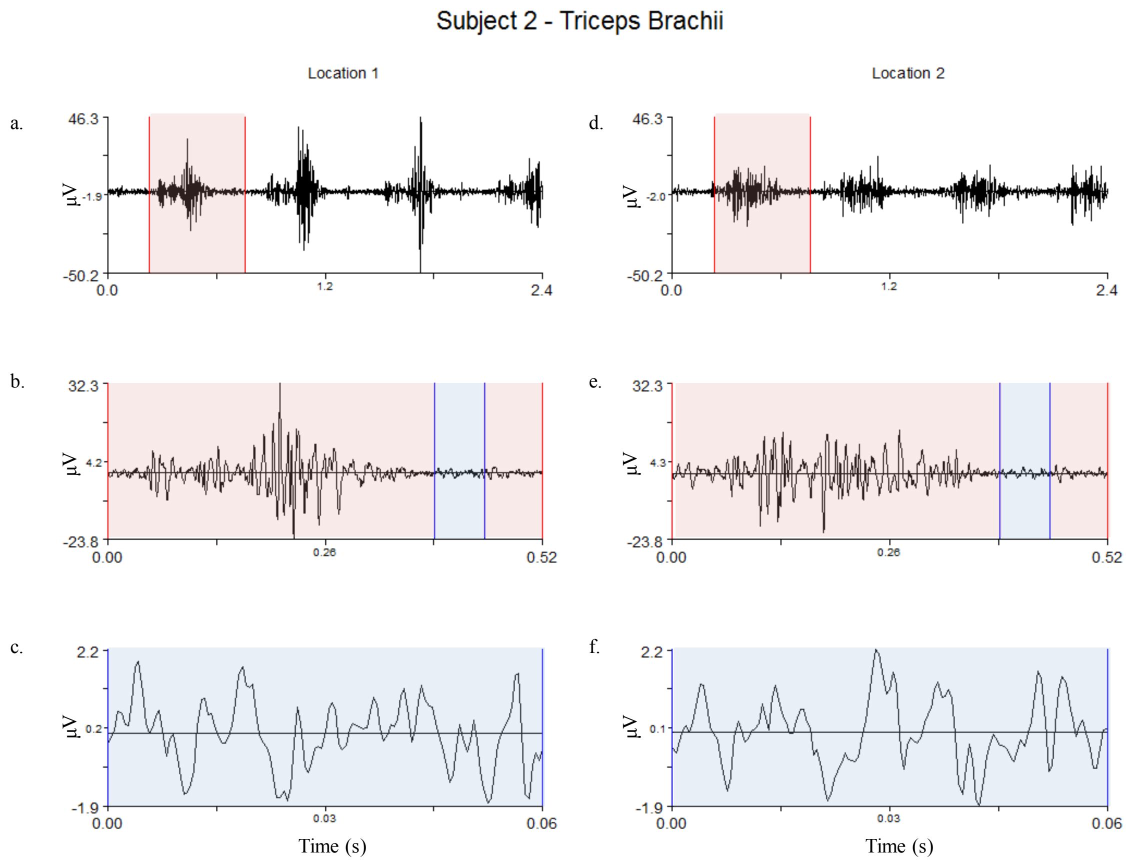


Figure 5.30 Time domain and spectral characteristics of baseline noise and sEMG signals from Triceps Brachii from electrode Site 1 (a, b, c) and Site 2 (d, e, f) in subject 2. Signals presented are high-pass filtered with an 80 Hz cut-off frequency. Blue shaded areas represent selected areas of baseline noise, with blue vertical lines representing the beginning and end of the baseline noise subset.

Table 5.7 Mean ± SD values for baseline noise (µV) from Triceps Brachii sensor locations

	Site 1 (Cranial)	Site 2 (Caudal)
Subject 1	0.41 ± 0.30	0.54 ± 0.40
Subject 2	0.65 ± 0.53	0.68 ± 0.53
Subject 3	1.37 ± 0.95	2.24 ± 2.17

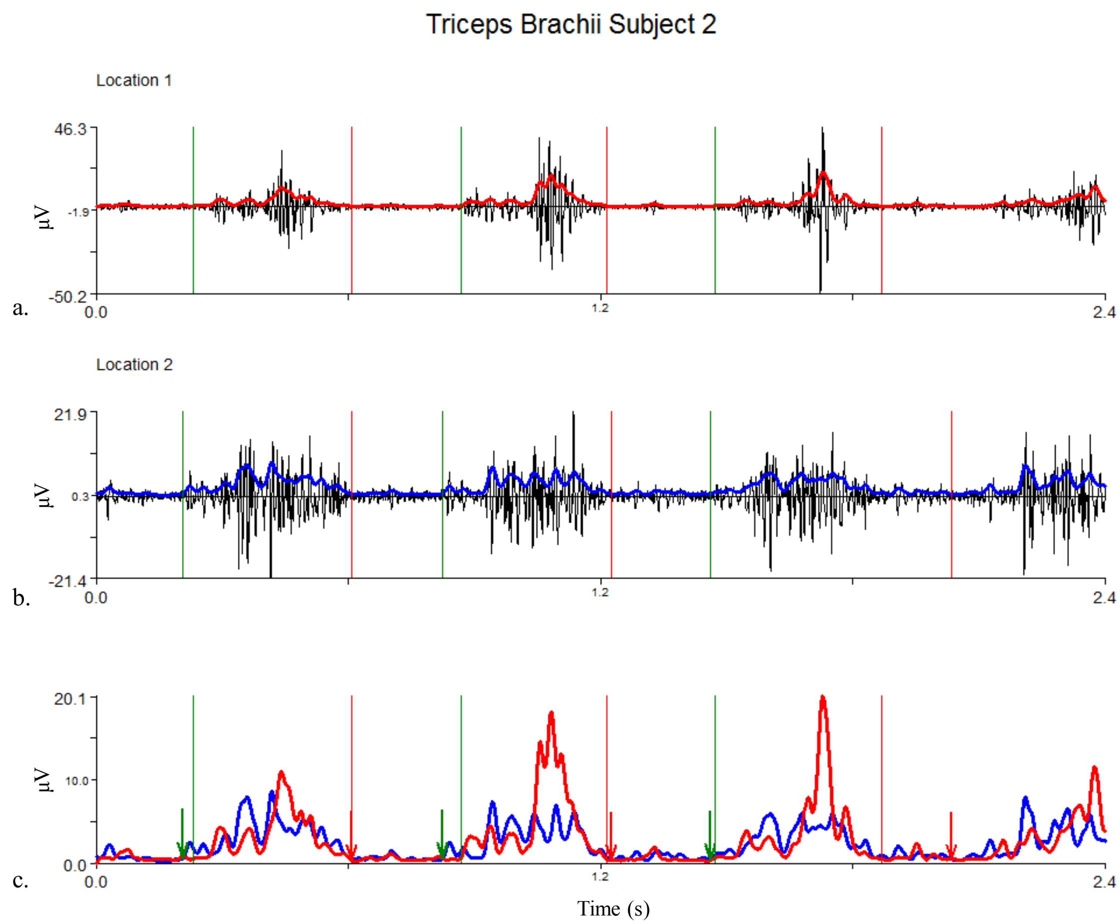


Figure 5.31 Onset and offset events for Triceps Brachii sensor locations from subject 2.

a.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 1 (cranial) and low-pass filtered trace (cut-off frequency 25 Hz) (red bold).

b.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 2 (caudal) and low-pass filtered trace (cut-off frequency 25 Hz) (blue bold). Green and red vertical lines represent onset and offset events, respectively for graphs a.) and b.).

c.) Overlay of low-pass filtered sEMG traces (cut-off frequency 25 Hz) for Site 1 (red bold) and Site 2 (blue bold). Green and red vertical lines represent onset and offset events, respectively for Site 1. Green and red arrows represent onset and offset events, respectively for Site 2.

5.5.3(iii) Trapezius

Selected sEMG traces from cranial (Site 1) and caudal (Site 2) Trapezius (cervical head) sensor locations are illustrated in Figure 5.32. Visual inspection of both locations revealed a similar muscle activity pattern. A comparison of muscle onset and offset events are illustrated in Figure 5.34 and revealed a fairly similar muscle activity pattern from both sensor locations in Subject 1. However, both sensor locations in Subjects 2 and 3 exhibited very different onset/offset events, which are illustrated in Figure 5.35. Across all subjects, the average difference between onset event timings for each location was 0.042 ± 0.041 s, with a maximum difference of 0.078 s. The average difference for offset event timings for each location was 0.097 ± 0.165 s, with a maximum difference of 0.453 s. Type I error was observed in the cranial (Site 1) location in subjects 2 and 3 and in the caudal (Site 2) location in subject 3 (Figure 5.35). Figure 5.33 illustrates baseline noise values from both sensor locations in subject 1. Similar levels of baseline noise were observed in subjects 1 and 2 (Table 5.7). Differences in baseline noise values for both sensor locations were observed across all subjects. Baseline noise values were higher in the caudal (Site 2) location for 2/3 subjects.

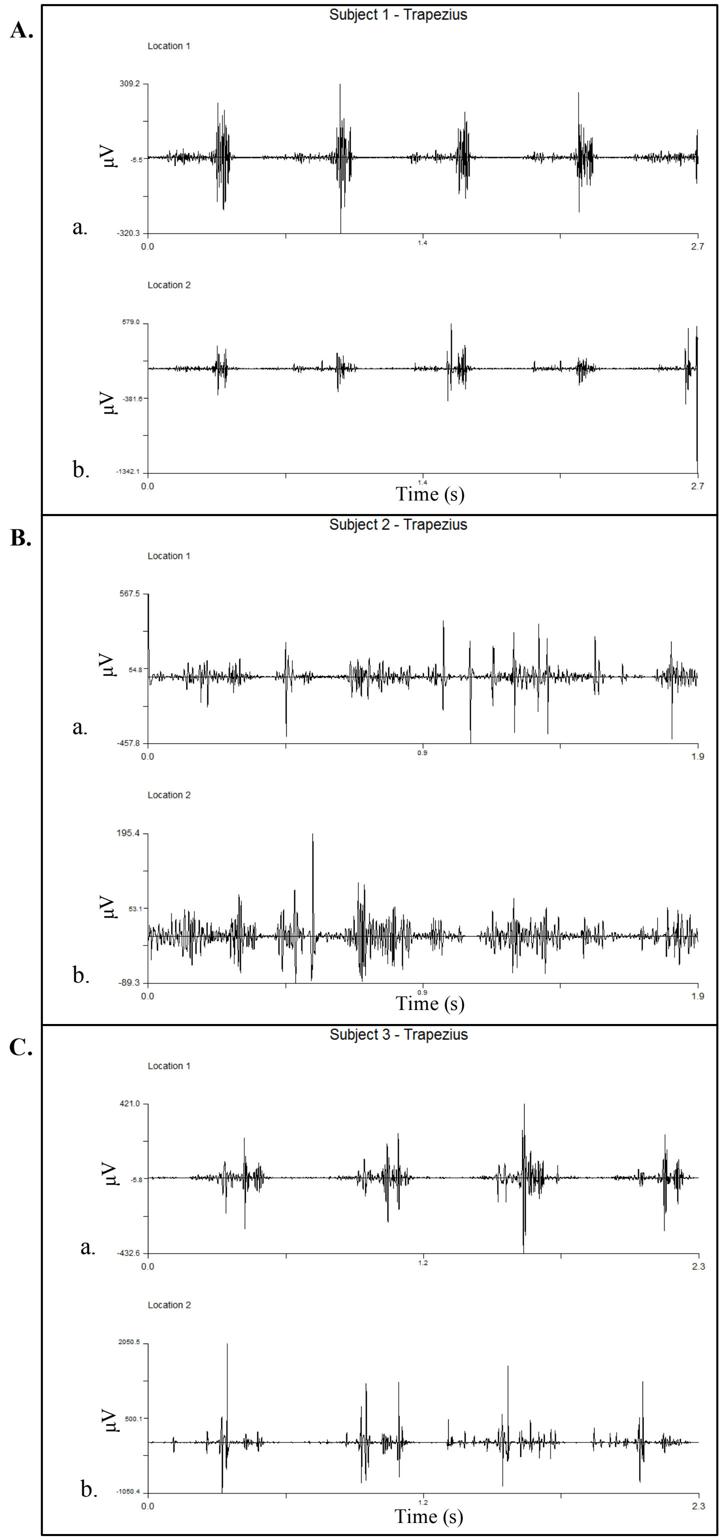


Figure 5.32 sEMG signals from electrodes positioned on a.) Site 1 (cranial) and b.) Site 2 (caudal) of the Trapezius (cervical head) muscle. Signals presented are DC offset removed and high-pass filtered with a cut-off frequency of 80 Hz and were obtained from the three subjects during canter.

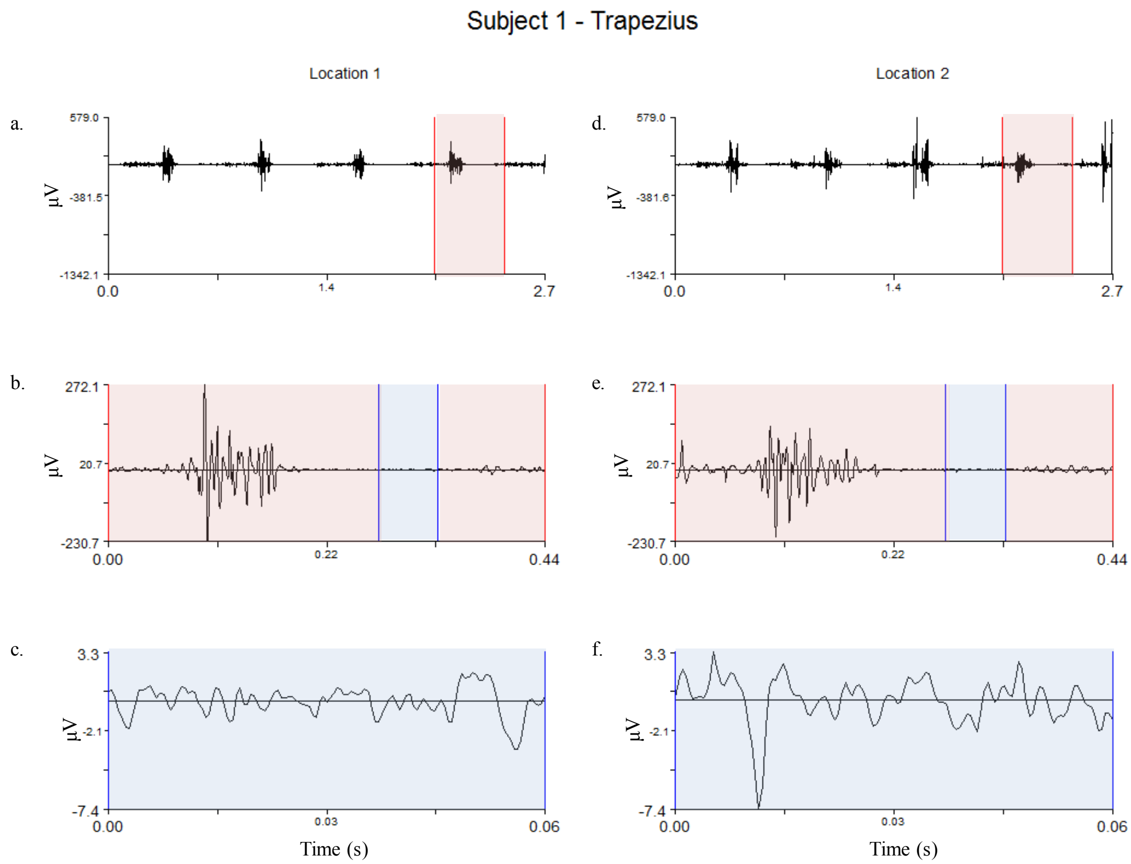


Figure 5.33 Time domain and spectral characteristics of baseline noise and sEMG signals from Trapezius from cranial (a, b, c) and caudal (d, e, f) electrode sites in subject 1. Signals presented are high-pass filtered with an 80 Hz cut-off frequency. Blue shaded areas represent selected areas of baseline noise, with blue vertical lines representing the beginning and end of the baseline noise subset.

Table 5.8 Mean ± SD values for baseline noise (μV) from Trapezius sensor locations

	Site 1 (Cranial)	Site 2 (Caudal)
Subject 1	0.74 ± 0.65	1.12 ± 1.05
Subject 2	1.20 ± 0.87	0.88 ± 0.72
Subject 3	1.43 ± 1.59	2.10 ± 1.72

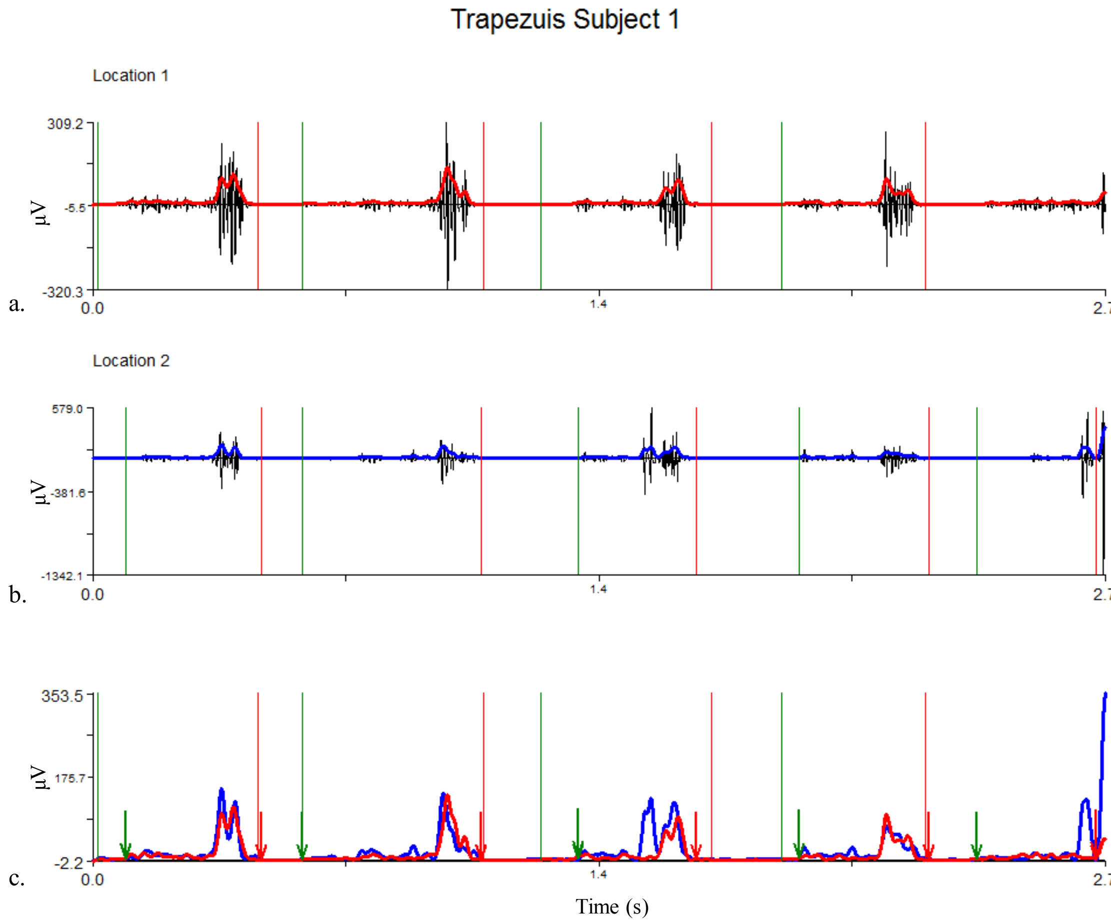


Figure 5.34. Onset and offset events for Trapezius sensor locations from subject 1.

a.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 1 (cranial) and low-pass filtered trace (cut-off frequency 25 Hz) (red bold).

b.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 2 (caudal) and low-pass filtered trace (cut-off frequency 25 Hz) (blue bold). Green and red vertical lines represent onset and offset events, respectively for graphs a.) and b.).

c.) Overlay of low-pass filtered sEMG traces (cut-off frequency 25 Hz) for Site 1 (red bold) and Site 2 (blue bold). Green and red vertical lines represent onset and offset events, respectively for Site 1. Green and red arrows represent onset and offset events, respectively for Site 2.

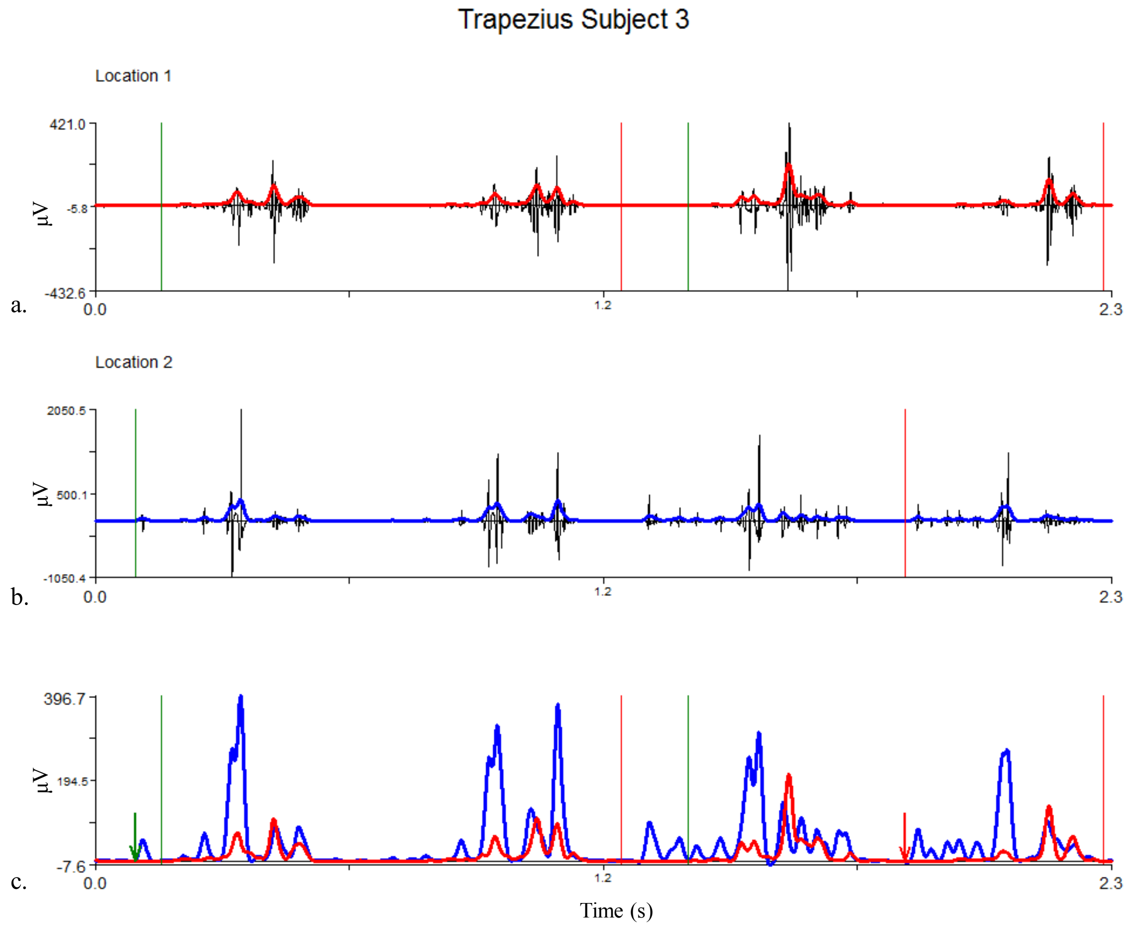


Figure 5.35 Onset and offset events for Trapezius sensor locations from subject 3, illustrating the extreme differences in onset and offset event detection.

a.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 1 (cranial) and low-pass filtered trace (cut-off frequency 25 Hz) (red bold).

b.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 2 (caudal) and low-pass filtered trace (cut-off frequency 25 Hz) (blue bold). Green and red vertical lines represent onset and offset events, respectively for graphs a.) and b.).

c.) Overlay of low-pass filtered sEMG traces (cut-off frequency 25 Hz) for Site 1 (red bold) and Site 2 (blue bold). Green and red vertical lines represent onset and offset events, respectively for Site 1. Green and red arrows represent onset and offset events, respectively for Site 2.

5.5.3(iv) Biceps Femoris

Selected sEMG traces from dorsal (Site 1) and ventral (Site 2) Biceps Femoris (vertebral head) sensor locations are illustrated in Figure 5.36. Visual inspection of both locations revealed a very similar muscle activity pattern, except in subject 3 where the ventral signal was compromised by external noise sources. Muscle onset/ offset events are presented in Figure 5.38, which illustrates differences in onset/offset events between sensor locations. Across all subjects, the average difference between onset event timings for each location was 0.080 ± 0.053 s, with a maximum difference of 0.168 s. The average difference for offset event timings for each location was 0.187 ± 0.231 s, with a maximum difference of 0.754 s. Type I error was observed in the ventral (Site 2) location in subjects 1 and 3, but was not observed in the dorsal (Site 1) location across all subjects (Figure). Figure 5.37 illustrates baseline noise values from both sensor locations in subject 1. Varying levels of baseline noise were observed across all subjects for both sensor locations (Table 5.8), but were consistently higher in the ventral location across subjects.

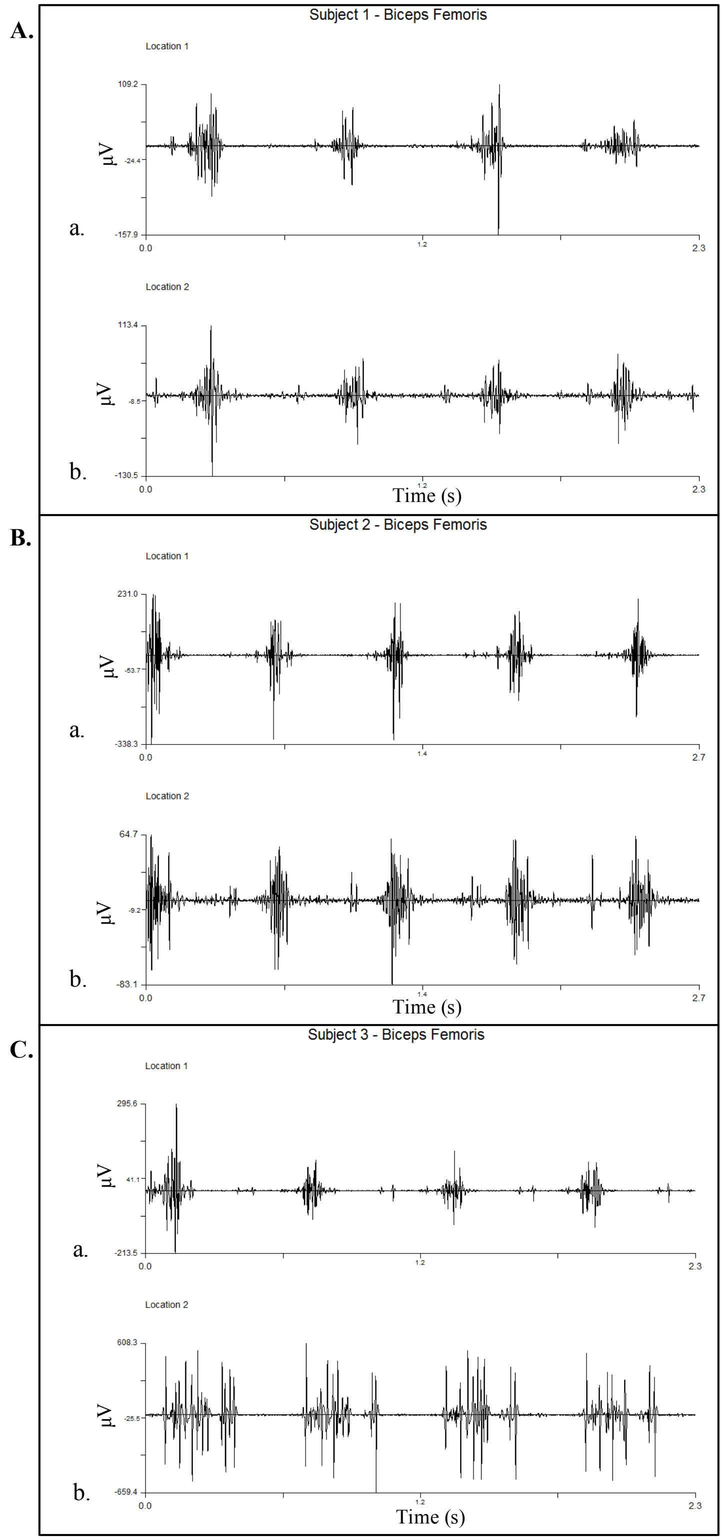


Figure 5.36 sEMG signals from electrodes positioned on a.) Site 1 (dorsal) and b.) Site 2 (ventral) of the Biceps Femoris (vertebral head) muscle. Signals presented are DC offset removed and high-pass filtered with a cut-off frequency of 80 Hz and were obtained from the three subjects during canter.

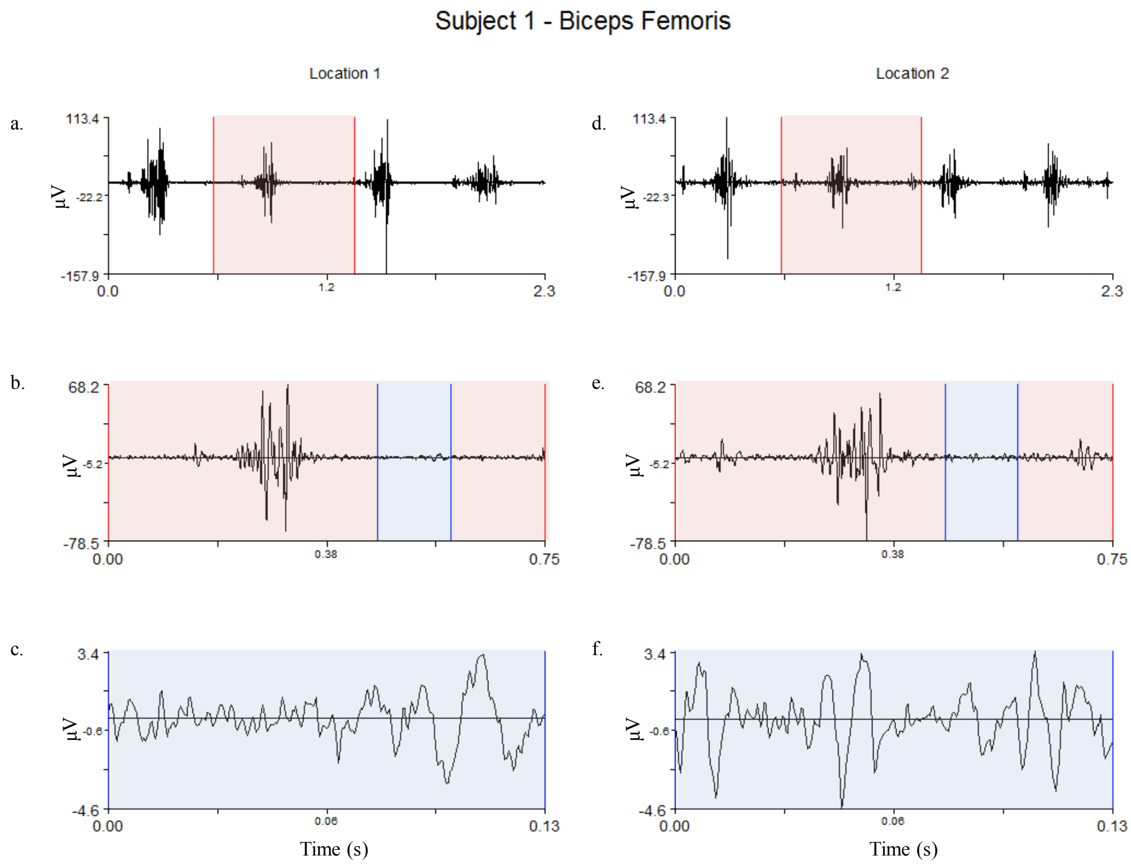


Figure 5.37 Time domain and spectral characteristics of baseline noise and sEMG signals from Biceps Femoris from electrode Site 1 (dorsal) (a, b, c) and Site 2 (ventral) (d, e, f) in subject 1. Signals presented are high-pass filtered with an 80 Hz cut-off frequency. Blue shaded areas represent selected areas of baseline noise, with blue vertical lines representing the beginning and end of the baseline noise subset.

Table 5.9 Mean ± SD values for baseline noise (µV) from Biceps Femoris sensor locations

	Site 1 (Dorsal)	Site 2 (Ventral)
Subject 1	0.82 ± 0.76	1.08 ± 0.96
Subject 2	0.41 ± 0.28	1.07 ± 1.05
Subject 3	0.60 ± 0.64	2.08 ± 2.25

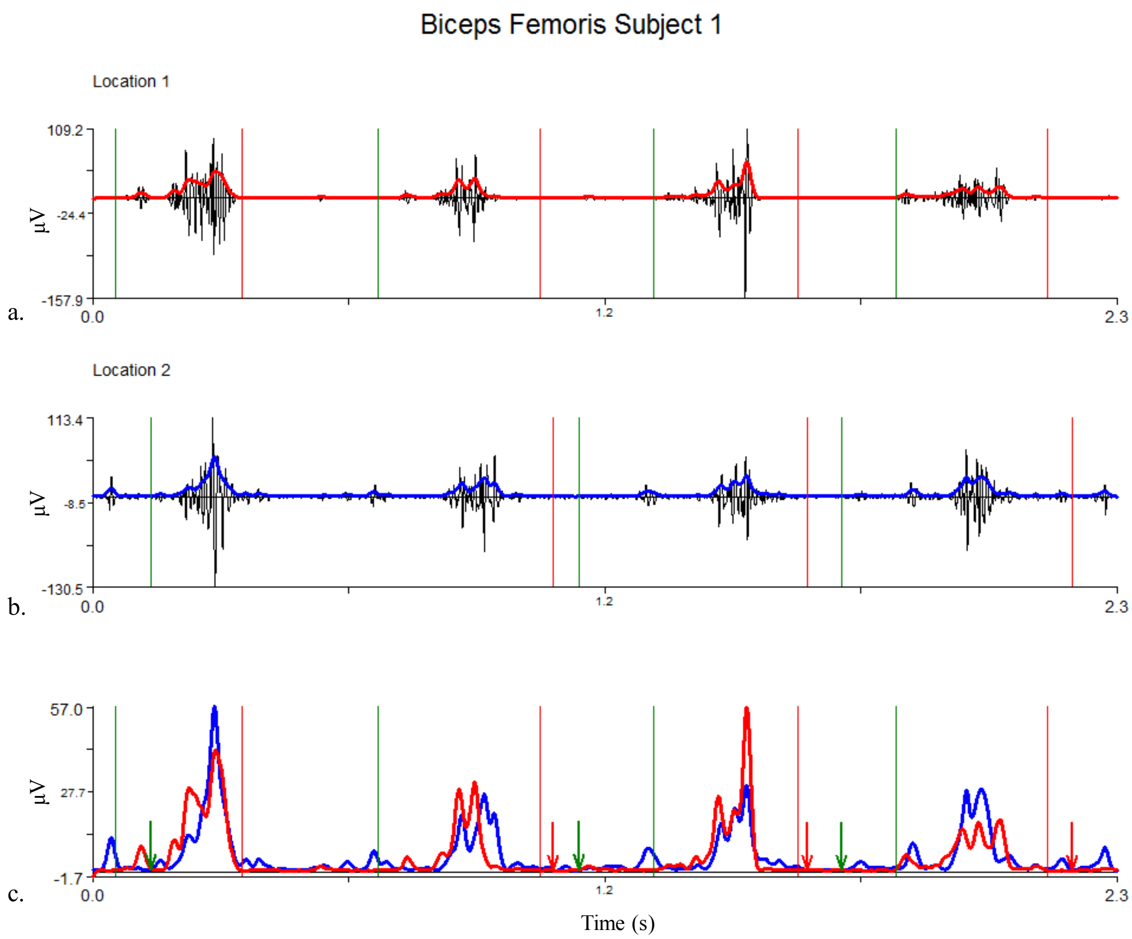


Figure 5.38 Onset and offset events for Biceps Femoris sensor locations from subject 1.

a.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 1 (dorsal) and low-pass filtered trace (cut-off frequency 25 Hz) (red bold).

b.) Overlay of 80 Hz high-pass filtered sEMG trace (black) for Site 2 (ventral) and low-pass filtered trace (cut-off frequency 25 Hz) (blue bold). Green and red vertical lines represent onset and offset events, respectively for graphs a.) and b.).

c.) Overlay of low-pass filtered sEMG traces (cut-off frequency 25 Hz) for Site 1 (red bold) and Site 2 (blue bold). Green and red vertical lines represent onset and offset events, respectively for Site 1. Green and red arrows represent onset and offset events, respectively for Site 2.

5.5.4 Discussion

5.5.4(i) Superficial Gluteal

Although visual inspection of both Superficial Gluteal sensor locations indicated similar muscle activity patterns from both locations, differences in onset/ offset event timings imply that signals are not identical due to differing signal characteristics. Differences in event timings are likely due to consistently higher baseline noise values exhibited at the ventral location (Figure 5.27, Table 5.6), which decreases the accuracy of the detection method (Hodges and Bui, 1996). Type I error was observed once in subject 2 in signals from the ventral location, resulting in two activity bursts being grouped into the same activation interval (Figure 5.28b). This is also indicative of increased background activity that would decrease the sensitivity of the detector threshold (Hodges and Bui, 1996). Subjects 1 and 3 exhibited similar onset/offset events (Appendix D), however timing differences as high as 0.082 s and 0.241 s, verify that these sensor locations cannot be used interchangeably. Again, these differences are likely a consequence of consistently higher baseline noise in the ventral location.

Baseline noise values from the dorsal location were remarkably similar across all subjects, indicating high within-location reproducibility (Hogrel et al., 1998). This similarity in baseline noise is an especially significant finding considering the physical differences between the three subjects investigated for this muscle. Although previous authors have ruled out cross talk as a major concern in equine EMG research due to the significantly larger muscles (Robert et al., 1999; Licka et al., 2004; Hodson-Tole, 2006), it is possible that signals from the ventral location are prone to cross talk contamination from the adjacent Biceps Femoris (vertebral head) and Tensor Fascia Lata muscles. Along with the Gluteus Medius, the Biceps Femoris (vertebral head) represents the largest muscle in the equine pelvic limb with an approximate mass and volume of 6112 g and 5766 cm^3 (Payne et al., 2005). The Superficial Gluteal is much smaller by comparison with approximate values of 646 g and 1316 cm^3 reported by Payne et al. (2005). The large triangular area of the Tensor Fascia Lata inserts onto the patella where it merges with the ventral portion of the Superficial Gluteal (Pattillo, 2007). Furthermore, the large caudal head of the Biceps Femoris partially covers the insertion point of the Superficial Gluteal (Pattillo, 2007). It would therefore be highly probable that the ventral sensor location is prone to detecting signals from muscles adjacent to the one of interest. These findings imply that results from studies, such as Robert et al., (1999), which do not describe specific sensor locations and rule out the possibility of cross talk for investigating Gluteus Medius, Tensor Fascia Lata and Superficial Gluteal, be considered with caution. Baseline noise and muscle activity patterns indicate that the dorsal location, originally proposed by Zaneb et al., (2007), represents a sensor location where high quality EMG signals from the Superficial Gluteal are detected.

5.5.4(ii) Biceps Femoris (vertebral head)

Muscle activity patterns from both Biceps Femoris sensor locations appeared very similar. However, maximum differences of 0.168 s and 0.754 s for onset and offset events, respectively, indicated that dorsal and ventral sensor locations detected very different muscle activity patters. Type 1 error was observed in signals detected from the ventral location in 2 of 3 subjects, which was understandable due to poor sensor adherence and subsequent decreased signal quality in subject 3. However, the presence of Type I error in the ventral location is again, the result of consistently higher baseline noise and a greater presence of movement artefact at this location, which decreases the sensitivity of the detection method (Hodges and Bui, 1996). Movement artefact in the ventral location was likely due to both increased shortening/stretching of overlying tissues and increased force impulses due to its more distal location (Wilson et al., 2001). The dorsal location therefore provided a more pragmatic location for adhesion, which was demonstrated through decreased movement artefact noise and consistently lower baseline noise values in all subjects. Type I error was not noted in any subjects for signals detected from the dorsal location.

The biarticular ventral head of the Biceps Femoris forms part of the hamstring group and is the largest muscle in the equine pelvic limb (Payne et al., 2005). The Biceps Femoris is positioned very superficially and is covered only by fascia and skin, which permits the detection of high fidelity EMG signals from this muscle. The middle and caudal heads of the muscle arise from the ischial tuberosity, where all three heads divide into different directions (Pattillo, 2007). The division of these heads have been equated to three different muscles due to their different neuromuscular components in the cat (English and Weeks, 1987). To the author's knowledge, no studies have explicitly investigated the functional differences in the separate muscle bellies of the Biceps Femoris, however Payne et al. (2005) have described anatomical differences, which would support findings from research in cats. Differences in EMG signals detected from both sensor locations may therefore be due to possible regional variations in the equine Biceps Femoris. The ventral location of the separate muscle bellies comprising this muscle may provide an explanation for why the more ventral sensor location, described by Zaneb et al. (2007), detected signals with higher baseline noise values and greater movement artifact. Findings from this study therefore suggest that the dorsal sensor location, originally proposed by Schuurman et al. (2003), permits detection of high fidelity signals from the vertebral head of the equine Biceps Femoris muscle.

5.5.4(iii) Triceps Brachii (long head)

The Triceps Brachii is a large muscle composed of three heads, which insert together on the olecranon (Watson and Wilson, 2007). The long head is the largest thoracic limb muscle and is bi-articular, working to flex the shoulder and extend the elbow (Tokuriki et al., 1989; Ryan et al., 1992; Hodson-Tole, 2006; Clayton et al., 2013). A maximum horizontal distance of 5 cm separated cranial and caudal Triceps Brachii sensor locations. However, even this small distance was enough to produce slight average differences of 0.028 s and 0.065 s for onset and offset events, respectively. The Triceps Brachii exhibited the lowest average and maximum timing differences for activation interval events in both sensor locations. Baseline noise values for both locations in subjects 1 and 2 were also very similar (Appendix D), indicating that similar EMG signals are detected from both locations. Similarities in baseline noise may account for similarities observed in the onset/ offset event timings in these subjects. However, the caudal location consistently displayed a less abrupt onset, which is likely responsible for slight differences observed in event timings. Type I error was only observed in the caudal location of Subject 3 (Appendix D), which was unsurprising due to the increased levels of background noise and the presence of motion artefacts that decrease detector sensitivity and result increased false positive detections. Watson and Wilson (2007) reported few aponeuroses and very little pennation in the equine Triceps Brachii, with muscle fibres that tended to run along the length of the muscle belly. This may suggest that spectral differences in signals from both sensor locations were due to time domain differences, which may be related to generation and propagation of action potentials along the parallel muscle fibres (von Tscharner et al., 2014). Regardless, findings from this study suggest that the cranial location, originally proposed by Hodson-Tole (2006), permits detection of high fidelity EMG signals from the Triceps Brachii. This location is also pragmatically superior for data collection in the ridden horse, as the cranial location is less likely to come into contact with the rider's foot or stirrup.

5.5.4(iv) Trapezius (cervical head)

The cervical head of the Trapezius muscle is separated from the thoracic head by an aponeurosis and acts to elevate the scapula and facilitate limb protraction (Payne et al., 2004). By comparison, it is a small extrinsic muscle of the thoracic limb, with medium length fascicles that insert into the dorsal aspect of the scapula in a vertical (middle fascicles) and cranio-caudal orientation (cranial and caudal fascicles) (Payne et al., 2004). To the author's knowledge, no previous studies have provided a description for sensor locations used to detect EMG signals from the equine Trapezius muscle. Locations in this study were therefore established by locating the muscle belly between the origin and insertion points of this muscle. The origin of the cervical head is the nuchal ligament from C2-T3 (Pattillo, 2007). The Trapezius is triangular and expands out to insert onto the entire surface of the scapular spine (Pattillo, 2007). Cranial sensors were placed ¾ of the length of the neck at approximately the 6^{th} cervical vertebrae, which coincides with the middle of the muscles origin on the nuchal ligament. They were placed 10 cm ventral to the top of the neck to minimise potential for crosstalk from the adjacent Splenius muscle.

This muscle proved to be the most difficult to collect EMG signals from during dynamic ridden movements. This was mainly due to motion artefact from shortening/ lengthening of superficial tissues and from external interference with the rider's hands and reins. As a result, this muscle detected high levels of baseline noise in both locations across all subjects. Although baseline noise values varied considerably across all subjects and locations, the cranial location detected lower noise levels than the caudal location in 2 of 3 subjects. Muscle activity patterns differed considerably in signals from both sensor locations, with maximum event timing differences of 0.453s reported for offset events and Type I error occurring in signals from 2 of 3 subjects. Type I error and differences in event timings were predominantly due to variations in baseline noise, and an increased presence of motion artefact in the caudal location. The choice of sensor location for this muscle was not as straightforward as the other muscles investigated due to variations in results from both cranial and caudal sensor locations. Cranial and caudal locations were separated by a maximum distance of 5 cm, representing a small portion of the muscle belly. Faria et al., (2002) investigated the effect of sensor locations on crosstalk over a comparable portion of human muscle (7cm), reporting that differences in crosstalk signals are not apparent in small regions of the muscle belly. As a result, Faria et al. (2012) suggest that selection of electrode placement should be based on reduction of movement artefact rather than crosstalk minimisation. Therefore, the cranial location is recommended as a sensor location for the equine Trapezius muscle. The choice of this location is similar to the Triceps Brachii, in that it detected the lowest baseline noise values in the majority of subjects and is a more pragmatic location due to its increased distance from the rider's hands, which are correctly held more caudally above the withers.

5.5.5 Conclusion

This study has provided suggestions for sensor locations, capable of detecting high fidelity EMG signals from selected superficial equine muscles. Limitations associated with this study included a small sample size and an investigation of only two locations per muscle. Recommendations for sensor locations therefore refer to the superior location of the two selected locations, which were compared. Results from this study must therefore be viewed as preliminary guidelines that will evolve and adapt as knowledge in this field advances. Future studies must be conducted to quantify IZ using high-density EMG sensors, as has been done in human research (Masuda et al., 1985; Saitou et al., 2000) and the role of regional muscle variation in equine musculature. This information will allow equine researchers to better determine optimal sensor locations based on anatomical evidence. Although a range of equine subjects were investigated in this study, intra and inter-subject sEMG has is associated with high variability (Winter and Yack, 1987; De Luca, 1997; Araújo et al., 2000). Therefore, due to the small sample size employed in this study, results may not be widely generalizable to the wider equine population and future work is required to explore optimal sensor location on a larger sample size. Although these limitations must be considered when interpreting results from this study, these preliminary results represent the first step towards standardisation of measurement protocols for equine sEMG research.

5.6 Chapter Conclusion

Advances in knowledge and progression towards standardisation of sEMG protocol in human research has led to better understanding of the physiological processes, signal processing and methods of application (Hermens et al., 2000). Unfortunately, advances equine sEMG research have occurred at a much slower rate than that of human research and areas requiring further research have been highlighted throughout this chapter. Although some research has been conducted to develop methods for equine sEMG data, the majority of research in this field has employed data analysis techniques, which have not explicitly been investigated for use on sEMG data from equine subjects. This chapter has provided a starting point for equine researchers to build upon in an effort to develop standardised data acquisition and signal processing methods for equine sEMG research. It is hoped that further research will be conducted in this field on a larger sample, to ensure that findings are applicable to the wider equine population. The methods explored and described in Sections 5.2 – 5.5 have provided an original contribution to knowledge through careful consideration of questions posed by De Luca (1997).

Chapter 6. Development and optimisation of methods for kinematic data analysis

This Chapter describes the development of methods for the analysis of kinematic data, which would be used in the main study of the thesis. Three studies are presented in this chapter, which detail the development of optimal methods for kinematic: filtering (Section 6.1), gait event detection (Section 6.2) and measurement of desirable movement traits as described by industry professionals (Section 6.3).

6.1 Development of optimal method for signal filtering of kinematic data

6.1.1 Introduction

Kinematic analysis techniques typically use skin markers to denote underlying skeletal landmarks of interest (Bogert et al., 1990; van Weeren et al., 1992). However, biological errors, associated with tissue movement over skeletal landmarks, are inherent when skin mounted markers are used. Soft tissue artefact noise is undesirable in kinematic signals, as it can significantly impair the accuracy of measured joint angles (Cappozzo, 1991, 1996; Sha et al., 2004; Leardini et al., 2005; Akbarshahi et al., 2010). This type of noise contamination generally occurs within a higher frequency range than the true kinematic signal and is typically attenuated using a low-pass filter (LPF) (Sinclair et al., 2013). Low-pass filtering attenuates frequencies higher than the selected cut-off frequency and passes frequencies, which are lower allowing them to remain in the waveform (Derrick, 2004; Kirtley, 2006; Sinclair et al., 2013). Identifying the optimal cut-off frequency is therefore an essential consideration for kinematic signal processing, as appropriate low-pass filtering requires a compromise between signal distortion and the amount of noise permitted to pass (Winter, 2009).

Residual analysis is commonly used for objectively determining the optimal cut-off frequency value for a LPF (Winter, 2009). This method investigates the difference between filtered and raw data over a range of pre-determined cut-off frequencies (Cooper, 1995). “Residual” therefore refers to the signal content that remains when filtered data is subtracted from the raw data and the optimal cut-off frequency is selected using the inflection point of the residual curve (Cooper, 1995; Sinclair et al., 2013). This technique suggests the frequency where signal distortion is equal to residual noise, which is the optimal balance for attenuating skin displacement noise (Winter, 2009) Figure 6.1 illustrates a residual analysis, as described by Sinclair et al., (2013), where line A represents the best estimate of the noise residual. The X intercept at 0Hz represents the root mean square (RMS) value of the noise (Winter, 2009). The optimal cut-off frequency is then determined by projecting a horizontal line (B) from X to intersect the residual plot at Y, where the optimal cut-off is selected on the x axis (Winter, 2009; Sinclair et al., 2013).

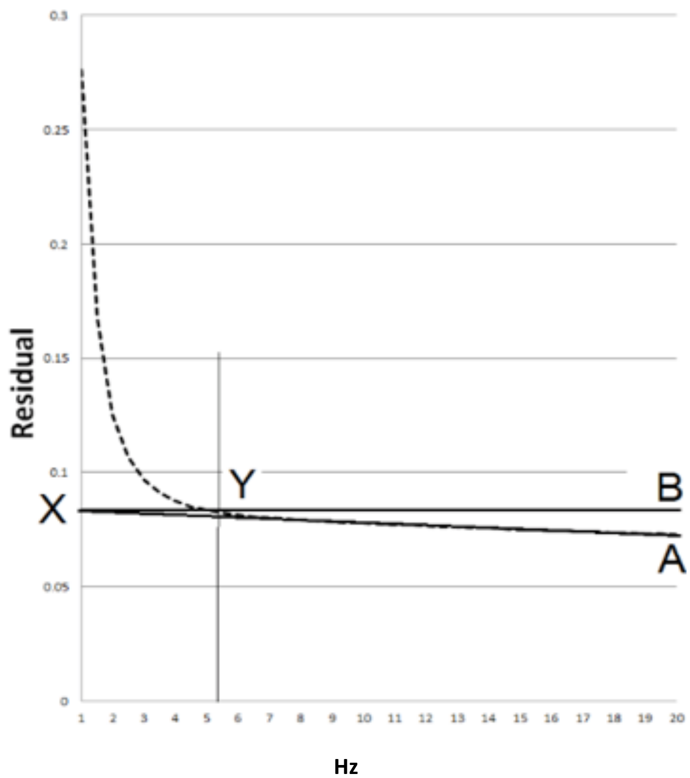


Figure 6.1 Plot of the residual between a filtered and raw signal as a function of the filter cut-off frequency (included with permission from Dr. Jonathan Sinclair).

The importance of skin displacement correction in equine gait analysis has been previously described, as this factor can limit measurement of true joint angles (Fredericson, 1972 cited by van Weeren and Barneveld, 1986; Bogert et al., 1990; van Weeren et al., 1988, 1990b, 1992). Correction factors for equine skin displacement have been described, where algorithms are applied to skin marker data to calculate the position of the underlying bone (Bogert et al., 1990; van Weeren et al., 1992). However, these correction factors are: subject, task, and location specific and have only been investigated using data from walk and trot (van Weeren et al., 1990a, 1992). The most important factors influencing skin displacement are differences in inertial forces and vibrations between gaits (van Weeren et al., 1990b, 1992) and as no studies have described correction factors for canter and jump data, this technique was not deemed appropriate for use in the thesis. A zero-lag Butterworth 4^{th} order LPF, in line with recommendations from Robertson and Dowling (2003), is commonly employed in equine biomechanics research for attenuating noise contamination and was therefore considered the optimal method for use in the thesis.

Previous kinematic research, investigating equine jump technique, has reported using 4th order Butterworth digital filters with cut-off frequencies ranging from 4 – 8 Hz (Clayton et al., 1995; Powers and Harrison, 2000; Santamaria et al., 2004a, b, 2005; Bobbert and Santamaria, 2005). To the author's knowledge, Powers and Harrison (2000) is the only study to utilise residual analysis to determine optimal cut-off frequencies in equine gait analysis. This study reported cut-off frequencies of 5 and 6 Hz for markers associated with carpal and tarsal angles, respectively (Powers and Harrison, 2000). However, Powers and Harrison (2000) did not conduct residual analysis on all marker positions required for the main study of this thesis, warranting a validation study to ensure that optimal cut-off frequencies are applicable to proximal and distal markers of interest in this work. The wide range of frequency cut-offs reported in the literature further warrants an investigation into optimal cut-off frequencies to ensure that low-pass filter parameters are suitable for the data set employed in the main study of the thesis.

The aim of this study was to objectively determine the optimal cut-off frequency for smoothing kinematic data collected during canter and jump trials in equine subjects.

6.1.2 Methods

Kinematic pilot data collected from four non-elite equine subjects (age: 7.3 ± 2.6 years, height: 155.0 ± 8.2 cm, breed: ISH, WB, Welsh Cross, sex: 2 mares, 2 geldings) during testing at Myerscough College (Bilsborrow, Preston, UK) (Chapter 4) and one elite horse (age: 13 years, height: 164 cm, breed: WB, sex: gelding) were used for this study. Data collection procedures are outlined in Chapter 4. Data were examined for each movement of interest in the main study of the thesis (canter and jump). The use of elite and non-elite data ensured that the optimal cut-off frequency would be suitable for data obtained from horses of all calibres in the main study of the thesis.

Optimal cut-off frequency was examined using residual analysis on raw data from a selection of distal and proximal markers placed on the FL and HL. Data from three FL markers placed on the: proximal end of the scapular spine (Prox Scap), lateral styloid process of the radius (LSR) and the centre of rotation of the distal interphalangeal joint (Fore DIPJ) were examined using residual analysis techniques. HL markers examined in this study included: greater trochanter (Gr Troch), lateral malleolus of the talus (Talus) and the centre of rotation of the hind DIP joint (Hind DIPJ).

One canter and one jump trial were randomly selected from each of the five subjects for investigation. Residual analysis was conducted on marker coordinates in X (cranio-caudal) and Z (vertical) directions obtained during the entire jump or canter trial. Raw data from each of the six markers, for each canter and jump trial investigated, were separately exported to text files from QTM software and imported into Microsoft Excel. A residual analysis was conducted for each marker in Microsoft Excel, using a purpose-built spreadsheet based on equations by Winter (2009). Figure 6.2 illustrates an example residual plot for Prox Scap data during a jump trial from the elite subject.

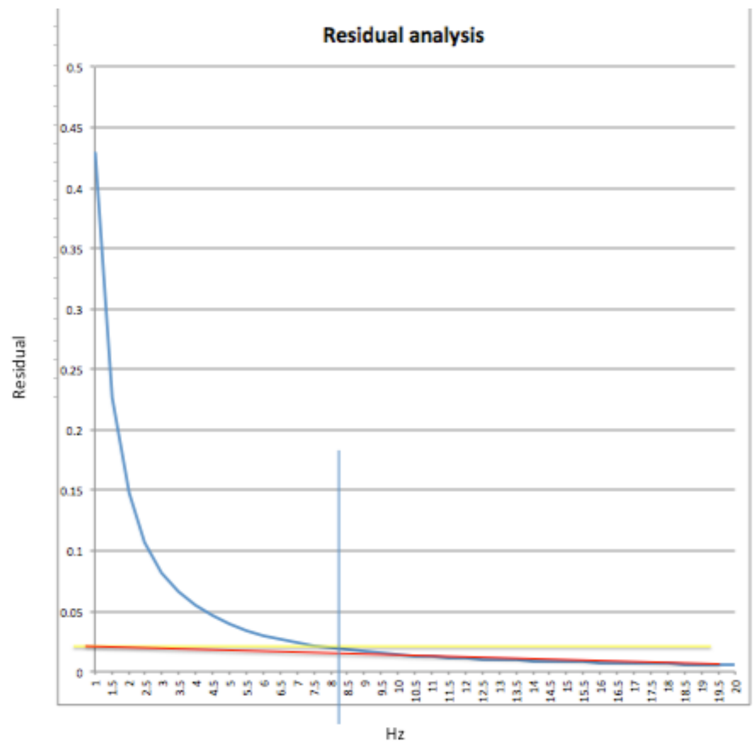


Figure 6.2 Example residual analysis plot of data from Proximal Scapula marker in the X direction during a jump trial from an elite subject.

6.1.3 Results

Residual analysis revealed an optimal cut-off frequency range of 5 – 12 Hz. Optimal cut-off frequencies from each marker for canter and jump trials in all subjects are illustrated in Tables 6.1 and 6.2, respectively. Average cut-off frequencies of 8.73 ± 1.14 Hz and 8.47 ± 1.31 Hz were found for X and Z directions, respectively in all markers across canter trials. For jump trials, average cut-off frequencies of 9.03 ± 1.00 Hz and 7.73 ± 1.05 Hz were found for all markers in X and Z directions, respectively. Residual analysis revealed maximum cut-off frequencies of 11 Hz and 12 Hz for canter and jump trials, respectively. The highest overall average cut-off frequency values were found in the X direction of distal HL markers for both canter and jump trials. For canter, an average cut-off frequency of 9.60 Hz was found for the Hind DIPJ and Talus. In jump trials, average cut-off frequencies of 9.40 and 9.60 Hz were found for the Hind DIPJ and Talus respectively. The highest cut-off frequency of 12 Hz was observed in the X direction of the Fore DIPJ marker during a jump trial.

Table 6.1 Overall min-max ranges for optimal cut-off frequency values (Hz) for selected anatomical markers across all subjects during canter trials.

Marker	Prox Scap		LSR		Fore DIPJ		Gr Troch		Talus		Hind DIPJ	
Direction	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z
Optimal cut-off frequency	8 - 9	5 - 9	8 -11	7 - 10	5 - 9	7 - 10	8 - 9	6 - 9	9 - 10	7 - 10	9 - 10	8 - 10

Table 6.2 Overall min-max ranges for optimal cut-off frequency values (Hz) for selected anatomical markers across all subjects during jump trials.

Marker	Prox Scap		LSR		Fore DIPJ		Gr Troch		Talus		Hind DIPJ	
Direction	X	Z	X	Z	X	Z	X	Z	X	Z	X	Z
Optimal cut-off frequency	8 - 9	5 - 8	8 - 10	7 – 9	7 - 12	8 - 9	8 - 9	7 - 9	9 - 10	6 - 9	9 - 10	6 - 9

6.1.4 Discussion

The maximum cut-off frequency found in the data tested was 12 Hz, and as such this was chosen as the appropriate cut-off frequency for equine jump and canter movements. Although proximally positioned markers are associated with a different frequency content than distally positioned markers, the application of a single cut-off frequency for all markers is commonplace in kinematic research (Sinclair et al., 2013). Residual analysis ensures that frequency is determined based on an equal balance between signal distortion and the amount of noise let through (Winter, 2009). Therefore, the maximum cut-off frequency was chosen to represent optimal cut-off frequency for all markers, to ensure that signal noise and attenuation of the true signal are minimised.

Residual analysis is commonly used in human kinematic research and has been shown to reliably provide optimal frequency cut-off for quantification of displacement and velocity measurements in human lower limb kinematics (Sinclair et al., 2013). As previously stated, most equine jump kinematic studies do not provide justification for cut-off frequencies used to smooth kinematic data (i.e. Santamaria et al., 2004a, b, 2005; Bobbert and Santamaria, 2005), with only one known study reporting the use of residual analysis (Powers and Harrison, 2000). Powers and Harrison (2000) determined optimal cut-off frequencies of 5 and 6 Hz for carpal and tarsal angle markers, respectively, using residual analysis. However, findings from this study suggest that the optimal cut-off frequencies proposed by Powers and Harrison (2000) may be too low. These lower cut-off frequencies may be due to the fact that Powers and Harrison (2000) obtained data from loose jumping horses, which may account for differences in noise frequency content observed in data collected from ridden horses in this study. Findings from this study indicate that previous equine studies applying cut-off frequencies in the range of 6 – 8 Hz to data obtained from the ridden horse (Santamaria et al., 2004a, b, 2005; Bobbert and Santamaria, 2005) are also likely to be too low and risk attenuating the true kinematic signal. The differences in signal filtering protocols reported in equine literature highlight the need for future work to objectively determine appropriate cut-off frequencies prior to data analysis using validated algorithms, such as residual analysis. This has been supported in human research, where variation between studies led Angeloni et al (1994) to suggest that cut-off frequencies must be determined based on the frequency content of the specific data set, rather than general rules of thumb.

6.1.5 Conclusion

In this study, an optimal cut-off frequency of 12 Hz was objectively determined using residual analysis. Data from proximal and distal FL and HL markers, obtained during canter and jump trials, were used to determine this cut-off frequency. Data from elite and non-elite horses were investigated, therefore a cut-off frequency of 12 Hz can be consistently applied to both canter and jump trials for all horses in the main study of the thesis. Differences in optimal cut-off frequency values reported in this study and in previous equine kinematic research were found. These differences suggest that future work employ an objective criterion for determining optimal cut-off frequency to ensure that a suitable balance between noise attenuation and true kinematic signal preservation is maintained.

6.2 Determination of Kinematic Gait Events During the Jump Stride

This study references the work of Holt et al. (2017), which was submitted over the course of this PhD project and has been accepted by the Equine Veterinary Journal with revisions. The author of the thesis is listed as second author and was heavily involved in data analysis and editing of the paper by Holt et al. (2017).

6.2.1 Introduction

A standardised method for identifying jump stride gait events (GE) does not exist. As a result, the majority of kinematic jump studies have provided vague descriptions of the method used to identify hoof impact and lift off events, with the majority relying on visual identification of GE (i.e. Clayton et al., 1995). To the author's knowledge, Hobbs et al. (2010) is the only study that has described a validated approach for identifying hoof impact at jump landing using kinematic data. A comparison of GE, detected using 3D kinematic data and "gold standard" GRF data (Schamhardt and Merkins, 1994), revealed that the hoof impact event consistently occurred after vertical velocity minima and vertical acceleration maxima of a palmar hoof marker, but before the point where rate of vertical displacement began to decrease (Hobbs et al., 2010). Unfortunately, the method proposed by Hobbs et al. (2010) was only validated for hoof impact detection during landing and no other studies have validated GE detection methods for the remaining phases of the jump stride.

Interestingly, some kinematic studies from the 1980's and early 90's provide detailed descriptions of the kinematic methods used to determine GE during the jump stride (Leach and Ormrod, 1984; Deuel and Park, 1991; Moore et al., 1995). The hoof impact event has generally been identified visually, as the first frame where extension of the MCPJ/ MTPJ occurs (Deuel and Park, 1991; Moore et al., 1995). The hoof lift off event has generally been identified as the frame where the MCPJ/ MTPJ reaches a palmar angle of 180 degrees at the end of stance phase (Leach and Ormrod, 1984; Deuel and Park, 1991; Moore et al., 1995). Alternative GE detection methods for the HL during approach and take-off phases, which rely on proximal joint kinematics, have also been described (Moore et al., 1995) and are based on HL loading patterns described by Hjertén et al. (1994). Carpal joint kinematics have also been used for identifying FL on and off events during take-off (Leach and Ormrod, 1984; Moore et al., 1995). The precision for identifying hoof on and off using these proximal joint detection methods has been estimated at ±0.010 seconds (Moore et al., 1995). However, none of the aforementioned methods have been validated using "gold standard" GRF data, which provides the most accurate detection method for ground contact (Schamhardt and Merkins, 1994). Furthermore, methods have not been investigated using modern 3D kinematic tracking software, which warrants further investigation, as these programs are less prone to digitising errors and can account for movements outside of the sagittal plane (Richards et al., 2008a; Clayton and Schamhardt, 2013, see Section 2.6.1).

Recently, Holt et al. (2017) have described a method for kinematic GE detection, which can be applied to data from the ridden horse during walk, trot and canter. To the author's knowledge, no other studies have described GE detection methods for kinematic data collected from canter under field conditions. The method described by Holt et al. (2017) was therefore considered to be the most appropriate for identifying GE from kinematic canter data throughout the thesis. However, it was not known which method would provide the most accurate GE detection for kinematic jump data. Throughout the thesis, many of the calculations used for analysis of kinematic and EMG data are dependent on temporal domains, which are defined using GE (Section 7.3). This highlights the importance of GE detection for accurate data analysis in the thesis. The aim of this study was therefore to determine the most accurate GE detection method for identifying hoof impact and lift off events during the jump stride. Obtaining GRF data from jumping trials was beyond the scope of this study Therefore, GE detection methods described in previous equine jump studies and by Holt et al. (2017), were applied to kinematic jump data and were compared to determine which method was best suited for GE detection.

6.2.3 Methods

6.2.3(i) Data Collection

Kinematic pilot data collected from pilot work (Chapter 4) were used in this study to investigate GE detection methods.

6.2.3(ii) Data Processing

Data were digitised and processed in accordance with Section 4.5.6(ii) and were analysed in V3D (C-motion Inc., USA). All data were low-pass filtered at 12Hz in accordance with Section 6.1.

6.2.3(iii) Gait Event Detection

Kinematic gait events were calculated in V3D using data from jump trials over a 1.0m vertical fence. Gait events were calculated in accordance with methods described by: Holt et al. (2017), Leach and Ormrod (1984), Deuel and Park (1991, 1993) Moore et al., (1995) and Hobbs et al., (2010). GE detection methods are summarised in Table 6.3.

Table 6.3 Description of GE detection methods and method for calculating gait events using Visual 3D.

Method	Author (s)	Target marker or joint angle used	Specified Jump Phase	Description of detection method	Method for calculating event in Visual 3D.
A	Holt et al. (2017)	-	-	See Holt et al., (2017) (Appendix E)	See Holt et al., (2017) (Appendix E)
B	(Leach and Ormrod, 1984; Deuel and Park, 1991, 1993; Moore et al., 1995)	MCPJ, MTPJ	Landing and Departure	**FL "hoof on" event:** defined as first frame where visual extension of the MCPJ occurred **FL and HL "hoof off" event:** defined as frame after limb contact where MCPJ and MTPJ reached a palmar angle of 180°	A threshold of 0° used to define events. Hoof-on and hoof off events identified as the first frame where MCPJ/MTPJ time-angle curve (X direction) crossed 0° on ascent and descent, respectively.
C	(Leach and Ormrod, 1984; Moore et al., 1995)	Carpal joint	Approach and Take off	**FL "hoof on" event**: Defined as frame where carpal joint reached an angle of 180° plus 0.055s, based on timespan reported by Deuel and Park (1991) **FL "hoof off" event:** Defined as first frame following observable carpal flexion	A threshold of 0° used to define events. Hoof-on identified as the frame where the carpal joint time-angle curve crossed 0° on ascent, plus 0.055s. Hoof off identified as the first frame where the carpal joint time-angle curve (X direction) crossed 0° on descent.
D	(Hobbs et al., 2010)	DIPJ Marker	Landing	**FL "hoof on" landing event:** Defined as frame midway between vertical velocity minima and acceleration maxima of DIPJ marker	First and second derivative of DIPJ marker target path (Z direction) calculated to obtain vertical velocity and acceleration, respectively. Vertical acceleration maxima (Acc Max) event identified using "global_maximum" command. Vertical velocity minima (Vel Min) identified as "global_minimum" command. Hoof on event determined as the frame midway (50%) between Acc Max and Vel Min events using "event_between" pipeline command
E	(Moore et al., 1995)	Tarsal joint	Approach and Take off	**HL "hoof on" event:** Defined as the frame just prior to rapid increase in tarsal angular velocity. **HL "hoof off" event:** Defined as the frame where tarsal joint reached maximum extension prior to upward vertical displacement	Joint angular velocity of tarsal joint calculated in accordance with Section 6.3.2(i). Hoof on identified using "global_minimum" command for angular velocity signal (X direction). Hoof off identified using "global minimum" command for tarsal joint time-angle curve (X direction).

6.2.3(iv) Data Analysis

Hoof on and hoof off GE timings derived from methods A – E were exported from V3D into Microsoft Excel for analysis. The difference between GE detection times were calculated for all methods for FL and HL during each jump phase. Stance duration values were calculated using corresponding hoof on and off GE detected using each method in accordance with Section 6.3.2(i). The difference between stance duration values were also calculated for all methods. Mean ± SD difference values for stance duration and GE detection time were compared to determine which method was best suited for data analysis in the thesis. Joint angles associated with detection methods, as outlined in Table 6.3 were calculated at each GE detection time using the "metric signal value at event" command in V3D. Mean ± SD joint angle values were used to examine the accuracy of the detection method based on joint angles reported in literature.

6.2.4 Results

A total of 87 stance phases (43 FL, 44 HL) were analysed across each limb and jump phase. The calibration area was not large enough to consistently obtain stance phases from approach and departure strides. Approach and departure stride GE were therefore removed from analysis, as conclusive findings could not be reported from the small data set. Mean ± SD difference values for GE detection time at take-off and landing in the FL and HL are summarised in Tables 6.4 and 6.5, respectively. Mean ± SD difference values for FL and HL stance duration at take-off and landing are presented in Table 6.6. For Tables 6.4 – 6.6, the mean ± SD value in each cell is the result of subtracting the method specified in the corresponding column from the method specified in the corresponding row. For example: in Table 6.4, difference values presented in the row representing method A during take-off were calculated as: (method A – method B) and (method A - method C). Negative mean difference values for GE detection timings indicate that the method indicated in the row occurred prior to the method of comparison in the corresponding column, and vice versa for positive values. For stance duration, negative values indicate shorter duration and positive values indicate longer duration than the method of comparison (corresponding column). Lower mean ± SD values indicate greater similarity between methods for GE detection.

In the FL, methods A and B consistently exhibited the greatest similarity for hoof on event detection during take-off and landing, with method A detecting events slightly later than method B. For FL hoof off event detection, methods A and B also exhibited the greatest similarity during landing, however method A detected events prior to method B. Interestingly, methods B and C were remarkably similar for detecting FL hoof off at take-off, with methods A and B showing the second lowest mean difference value. Apart from FL hoof off detection at take-off, method C consistently exhibited the greatest mean difference values for detecting FL hoof on and off events, revealing its dissimilarity to other methods. Method C consistently detected FL hoof on events later, and hoof off events prior to all methods it was compared to at take-off and landing. Methods A and C exhibited similar mean difference values when compared to method D for FL hoof on detection at landing.

Table 6.4 Mean (±SD) difference values for GE detection times between all FL detection methods outlined in Table 6.3 during take-off and landing. Mean (±SD) difference values in each cell calculated as the method specified in the corresponding column minus the method specified in the corresponding row. Patterned cells indicate where differences were not calculated. "-" indicates where methods were not applicable to the specified gait event or jump phase. All values are in ms.

		Hoof on			Hoof off	
Jump Phase	**Method**	**B**	**C**	**D**	**B**	**C**
Take off	**A**	26.55 (16.16)	-133.07 (19.44)	-	-13.45 (9.17)	35.92 (12.46)
	B		-154.38 (26.13)	-		0.05 (0.01)
Landing	**A**	22.09 (16.59)	-141.75 (39.22)	-35.56 (38.18)	-9.88 (2.37)	34.21 (6.76)
	B		-159.26 (43.45)			43.37 (7.12)
	D	57.65 (38.40)	-32.33 (38.68)		-	-

In the HL, methods A and B exhibited mean difference values of <1ms for hoof on and off event detection during take-off and landing, with method A detecting events slightly later than B. Comparison of methods B and E revealed the highest mean difference values for detecting HL GE during take-off and landing. Mean ± SD differences for GE detection timings in the FL and HL are reflected in mean ± SD differences between stance durations (Table 6.6). GE detected using methods A and B resulted in the greatest similarity between mean stance duration values in the FL and HL at take-off and landing. In the FL, method A resulted in stance durations that were slightly shorter than method B. In the HL, stance durations showed a mean difference of <1ms, when calculated from GE detected using methods A and B. Again, method C resulted in the greatest mean difference in FL stance duration values, being considerably shorter than all methods it was compared to. In the HL, the highest mean difference in stance duration values were found between methods B and E. Mean ± SD joint angles, calculated from each GE detection, are presented in Table 6.7 and are discussed further in Section 6.2.5.

Table 6.5 Mean (±SD) difference values for gait event detection times between all HL detection methods outlined in Table 6.3 during take-off and landing. Mean (±SD) difference values in each cell calculated as the method specified in the corresponding column minus the method specified in the corresponding row. Patterned cells indicate where differences were not calculated. All values are in ms.

		Hoof on		Hoof off	
Jump Phase	**Method**	**B**	**E**	**B**	**E**
Take off	**A**	0.34 (1.72)	5.21 (8.52)	0.34 (2.76)	37.00 (35.18)
	B		-16.68 (98.05)		41.79 (9.13)
Landing	**A**	0.21 (0.94)	2.87 (4.44)	0.41 (1.30)	20.59 (31.10)
	B		3.90 (9.13)		65.48 (80.29)

Table 6.6 Mean (±SD) difference values for FL and HL stance duration calculated from applicable methods outlined in Table 6.3 during take-off and landing. Mean (±SD) difference values in each cell calculated as the method specified in the corresponding column minus the method specified in the corresponding row. Patterned cells indicate where differences were not calculated. All values are in ms.

		Forelimb		Hindlimb	
Jump Phase	**Method**	**B**	**C**	**B**	**E**
Take off	**A**	-38.45 (19.67)	168.98 (24.66)	0.00 (3.05)	31.79 (35.79)
	B		200.83 (33.56)		76.51 (135.88)
Landing	**A**	-31.97 (17.00)	179.08 (44.16)	0.21 (1.66)	17.72 (30.65)
	B		202.63 (47.44)		61.58 (78.53)

Table 6.7 Mean (±SD) joint angles (º) associated with methods outlined in Table 6.3 during take-off and landing. Mean (±SD) joint angle (º) values were calculated at gait event detection times for the corresponding method, as outlined in Table 6.3.

	Take off		Landing	
Joint Angle	**Hoof on**	**Hoof off**	**Hoof on**	**Hoof off**
FL MCPJ (Method B)	1.02 (0.78)	-1.91 (1.83)	1.14 (0.97)	-3.93 (2.32)
HL MCPJ (Method B)	1.37 (0.88)	-1.87 (1.30)	1.65 (0.83)	-2.50 (2.28)
Carpus (Method C)	6.03 (3.15)	-0.66 (0.56)	6.38 (4.50)	-1.05 (0.57)
Tarsus (Method E)	40.62 (5.51)	4.89 (3.93)	37.84 (7.09)	1.99 (2.75)

6.2.5 Discussion

6.2.5(i) Gait events detected from Holt et al. (2017) (Method A)

The method described by Holt et al. (2017), was not explicitly recommended for GE detection during the jump stride. However, in this study, method A exhibited the lowest overall mean difference values for GE detection time and stance duration when compared to all other methods. The similarities between method A and detection methods, which have been described explicitly for GE detection during jumping, indicate that this method may be suitable for use in the thesis to identify GE from kinematic jump data. The suitability of method A for GE detection during jump will be discussed further in preceding sections in relation to the other detection methods explored in this study.

6.2.5(ii) Gait events detected using MCPJ kinematics (Method B)

Method B is the most commonly reported method for GE detection in kinematic studies investigating the equine jump (Leach and Ormrod, 1984; Deuel and Park, 1991; Moore et al., 1995; Clayton et al., 1995; Santamaria et al., 2002). This is likely due to the general acceptance that angle-time graphs for the MCPJ/ MTPJ reflect the limb-loading pattern (Riemersma, 1988a, b; Hodson et al., 2001; McGuigan and Wilson, 2003). Although Method B has been described in a number of studies as a GE detection method, Schamhardt and Merkins (1994) concluded that MCPJ/ MTPJ kinematics alone do not provide a consistent indicator for defining hoof on or hoof off at walk and trot. Schamhardt and Merkins (1994) reported that MCPJ/ MTPJ angles reached 0 degrees up to 88ms prior to hoof on events and 20ms after hoof off events, which were determined using GRF data at walk, with the trot showing similar patterns. These findings are comparable to Ratzlaff et al., (1993), who used an instrumented shoe to investigate the relationship between forces and distal limb kinematics at gallop. Based on their findings, Ratzlaff et al. (1993) and Schamhardt and Merkins (1994) explicitly caution against using MCPJ/MTPJ kinematics to identify hoof on and hoof off, as angles of 0 degrees were consistently found to occur prior to actual hoof impact (Schamhardt and Merkins, 1994) and after actual hoof lift off (Ratzlaff et al., 1993).

Schamhardt and Merkins (1994) reported average MCPJ angles 0f 16.5 and 14.6 degrees at initial ground contact during walk and trot, respectively. These values are in accordance with previous studies (Back et al., 1995a; Clayton et al., 1998, Hodson et al., 2000). To the author's knowledge, only Bobbert and Sanatmaria (2005) have presented MCPJ angle data during jumping, which were approximately 14 and 26 degrees in the TrF and LdF, respectively at the beginning of stance at take-off. At hoof lift off, MCPJ angles of 18-20 degrees have been reported during gallop (Ratzlaff et al., 1993), with smaller angles (increased flexion) reported at slower gaits (Back et al., 1995a). Unsurprisingly, mean MCPJ angles reported in this study, which were derived from detection method B, coincide with an angle of 0 degrees and were therefore much smaller than joint angles reported in literature (Table 6.7). Events detected using method B showed the greatest overall similarity to those detected using method A (Holt et al., 2017) (Table 6.4). Interestingly, mean MCPJ angles calculated for hoof on and hoof off events of detected using method A (Table 6.7), were similar to those reported in previous research (Ratzlaff et al., 1993; Schamhardt and Merkins, 1994; Bobbert and Santamaria, 2005). Furthermore, hoof on and off events detected using method A consistently occurred later than, and prior to, Method B events, respectively. These findings suggest that method A may detect events closer to actual hoof impact and lift off than method B.

In the HL, detection methods exhibited greater overall similarity for GE detection time and stance duration than in the FL. Back et al. (1997) reported 13.9 and 14.3 degrees of extension at impact in the LdH and TrH, respectively during canter. To the author's knowledge, no studies have reported MTPJ angles for hoof lift-off during canter or jump. However, MTPJ angles of 6.4 degrees of flexion have been reported at hoof lift-off during trot (Back et al., 1995d). Similar to the FL, MTPJ angles derived from events detected using method B were much smaller than those described in literature (Table 6.7). In the HL, methods A and B also exhibited the greatest similarity between GE detection timings, which is unsurprising since method A also relies partly on alignment of third metatarsal and hind pastern (P1) segments for event detection (Figure 6.3). Methods A and B appear to detect the HL hoof on event just prior to hoof impact, when the MTPJ is fully extended in preparation for initial ground contact (Back et al., 1995d; Hodson et al., 2001) and may explain why greater extension angles have been reported in literature (Back et al., 1995d, 1997). MTPJ angles in

Table 6.7 indicate that method B may also detect the hoof off event just prior actual hoof lift off, as the transition from extension to flexion occurs just prior to the end of stance phase (Back et al., 1995d). However, GE detection just prior to actual impact and lift-off events is arguably beneficial, as it ensures that actual events are not "missed".

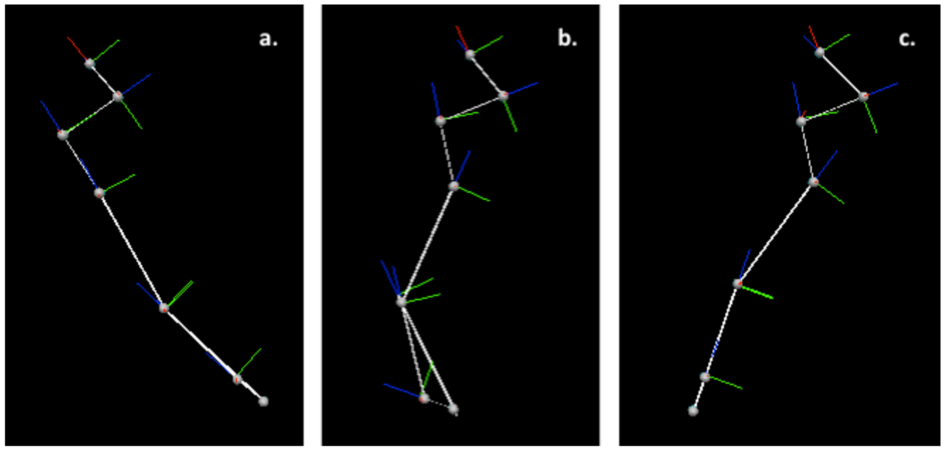


Figure 6.3 Visual representation of the alignment of the HL sagittal plane angle and third metatarsal segments, as described by Holt et al. (2017) during a.) hoof on, b.) mid stance and c.) hoof off events.

6.2.5(iii) Gait events detected using carpal joint kinematics (Method C)

Moore et al (1995) specifically recommend method C for use during approach and take-off, based on findings by Deuel and Park (1991), who reported carpal angles of 180 degrees an average of 55ms prior to hoof impact at take-off. However, Moore et al. (1995) do not clarify whether 55ms was used in each trial or whether some degree of judgement was used to determine if this timespan was appropriate for accurate FL hoof on detection. As a result, it was assumed that 55ms was to be applied to all files following carpal extension of 180 degrees. Method C exhibited the greatest overall difference values for GE detection time and stance duration when compared to other FL event detection methods.

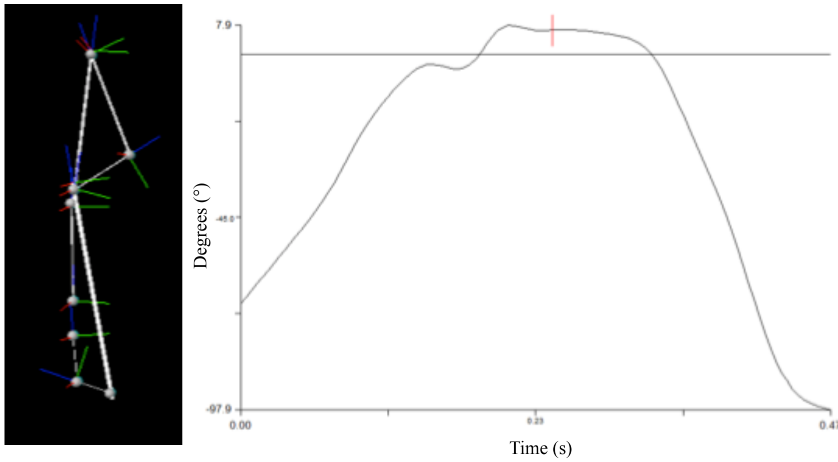


Figure 6.4 A typical time-angle curve for the carpal joint during take-off. The red vertical line represents a typical FL hoof on event detected using method C. Visual representation of the hoof on event is illustrated by a corresponding snapshot of the model to the left of the time-angle curve.

Average carpal angles derived from method C hoof on events (Table 6.7) are in accordance with previous studies, which have reported carpal extension angles of 4.7 degrees during mid stance at walk (Back et al., 1995a) and 4.4±2.8 and 6.7±3.6 degrees in LdF and TrF, respectively during stance phase at canter (Back et al., 1997). Previous studies have also reported that carpal extension begins prior to hoof impact, with maximal extension occurring during stance phase (Ratzlaff et al., 1993; Duel, 1994; Back et al., 1995a). These findings, along with carpal angles reported in Table 6.7, suggest that method C identifies FL hoof on events too late, resulting in events that occur during stance phase rather than at actual hoof impact. Delayed FL hoof on event detection is illustrated in Figure 6.4.

Interestingly, hoof off detection timings from method C showed greater similarity to other detection methods, with method C and B showing the greatest similarity for hoof off detection at take-off. Method C hoof off detection relies on the assumption that carpal flexion is initiated at hoof lift off, which previous studies have proven to be a false (Ratzlaff et al., 1993; Deuel, 1994; Back et al., 1995a). Ratzlaff et al. (1993) explicitly advise against using the carpal flexion to identify hoof off, based on their finding that flexion is initiated during stance phase when weight is shifted from the heel to toe. This may explain why hoof off events detected using method C were consistently detected prior to all other methods of comparison. Delayed hoof on and early hoof off detections are also reflected in stance durations derived from method C, which were shorter than all methods of comparison. Findings from this study and from previous research indicate that method C is not appropriate for GE detection for jumping and would therefore not be used in the thesis.

6.2.5(iv) Gait events detected from Hobbs et al. (2010) (Method D)

In this study, the detection method described by Hobbs et al. (2010), for FL hoof impact at landing, was the only method to be validated using GRF data. Comparison of methods with method D was therefore considered to provide the truest depiction of accuracy for hoof impact detection at jump landing. Methods A and C exhibited the greatest similarity to method D. In accordance with Section 6.5.5(ii), method C consistently exhibited delayed hoof on detection compared to method D, indicating that method C was likely to "miss" the actual hoof impact event. However, method A consistently detected events prior to method D, which is illustrated in Figure 6.5. Figure 6.5 shows a typical time-angle curve for the FL sagittal plane angle described by Holt et al. (2017) (method A) and illustrates hoof on events detected using methods A and D. Events in Figure 6.5 are separated by 0.035s, which equates to 7 frames. However, qualitative assessment of kinematic data revealed that method D consistently detected a more accurate hoof on event at jump landing, whereas method A events generally detected hoof on prematurely.

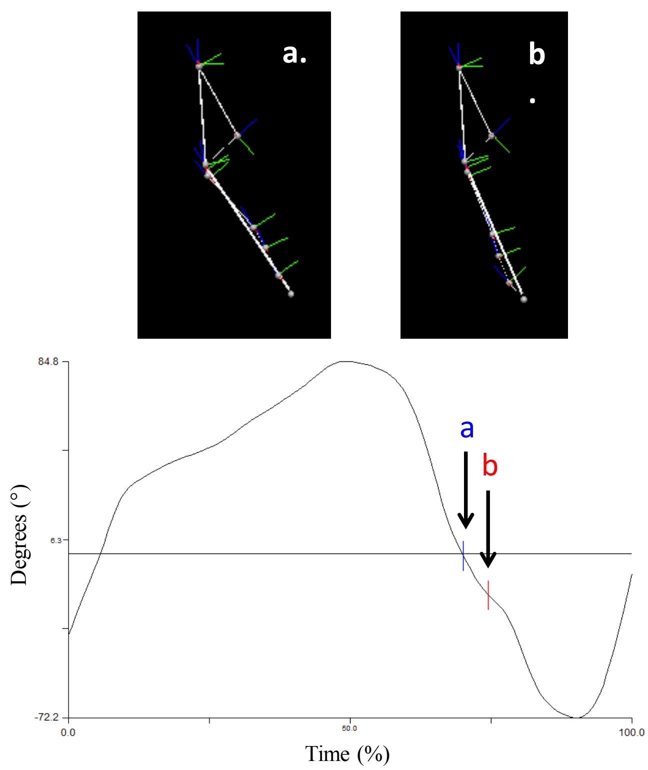


Figure 6.5 A typical time-angle curve of the FL sagittal plane angle described by Holt et al. (2017) at jump landing. Representative hoof on events derived from method A and method D are illustrated by blue (a) and red (b) vertical lines, respectively on the time-angle curve. Visual representations of method A (a) and method D (b) hoof on events are presented by corresponding screenshots of the model above the time-angle curve.

Although Figure 6.5 depicts typical timing differences between hoof on events from method A and D, greater timing differences were found in files where horses exhibited early unfolding (extension) of the tucked FL during jump suspension, which is illustrated in Figure 6.6. Extension of the FL in preparation for landing resulted in the FL sagittal plane angle, described by Holt et al. (2017), reaching 0 degrees prior to hoof impact. This was only seen in certain trials, but may be the result of grouping gait events that were derived from LdF and TrF, which exhibit different kinematics during jump landing (Clayton and Barlow, 1991; Meershoek et al., 2001, see Section 2.6.2(i)). Kinematic differences may also be the result of inherent jump techniques exhibited by individual horses (Santamaria et al., 2002; 2004a, b). Gait events detected using method D were not affected by early FL extension, suggesting that it is more appropriate for accurate identification of hoof on at landing.

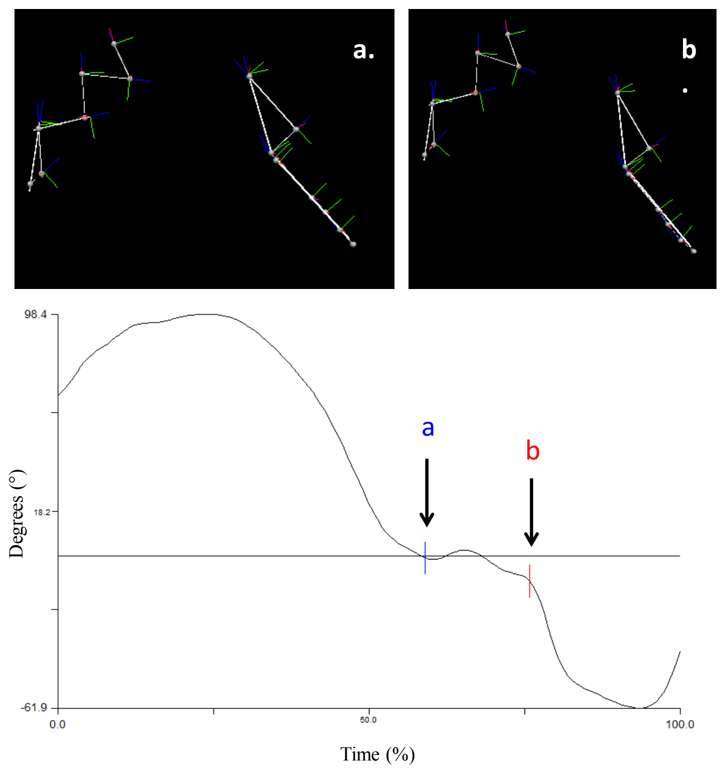


Figure 6.6 A time-angle curve of the FL sagittal plane angle, described by Holt et al. (2017), in a horse that exhibited early extension of the FL joints at jump landing. Representative hoof on events derived from method A and method D are illustrated by a.) blue and b.) red vertical lines, respectively. Visual representations of method A (a) and method D (b) hoof on events are presented by corresponding screenshots of the model above the time-angle curve.

6.2.5(v) Gait events detected using tarsal joint angles (Method E)

The method described by Moore et al. (1995) (method E) for hoof on event detection is based on the rapid increase in tarsal angular velocity observed at the beginning of stance phase (Hjertén et al., 1994; Back et al., 1995d). In this study, average tarsal angles for hoof on events from method E (Table 6.7) are in accordance with Bogert et al (1994), who reported tarsal flexion of 40 degrees during the first part of take-off in ridden horses executing a 1.50m fence. Bobbert and Santamaria (2005) presented similar tarsal angles at take-off over a 1.15m fence. The explanation provided by Moore et al. (1995) for HL hoof off is in accordance with previous studies, which have described maximal extension of the tarsal joint just prior to the end of stance phase (Back et al., 1995d). Back et al. (1995d) reported average tarsal angles of 6.2 degrees of extension at the end of stance phase at trot, with similar values reported by Dutto et al. (2004) for ridden horses executing a small (0.65m) fence. These findings are in accordance with tarsal angles reported in this study for hoof off events, which were derived using method E (Table 6.7). Similarities between tarsal joint angles reported for method E and in previous research, suggests that method E may provide an accurate GE detection method for the HL during jump.

Two periods of tarsal extension were observed at take-off and landing. Certain horses exhibited a larger initial joint extension through in the time-angle curve, and as a result, the software prematurely identified hoof off during stance phase. These findings are illustrated in Figure 6.7 and indicate that method E was not entirely robust in horses that exhibited greater tarsal extension during stance. Method E showed the greatest similarity to method A for hoof on and off GE detection, with method E consistently detecting events prior to A (Table 6.5). However, method A demonstrated consistent identification of hoof off and was not affected by horses that exhibited increased tarsal extension during stance phase (Figure 6.7). Method A was therefore less likely to prematurely identify hoof off events at take-off and landing. For hoof on, tarsal angles of 36.77 ± 6.89 and 34.71 ± 6.33 were found during take-off and landing, respectively for GE detected using method A, which are similar to those reported for method E (Table 6.7) and in previous studies (Bogert et al., 1994). These findings demonstrate the similarities between method A and E, but indicate that method A may be more reliable for identifying hoof off during take-off and landing.

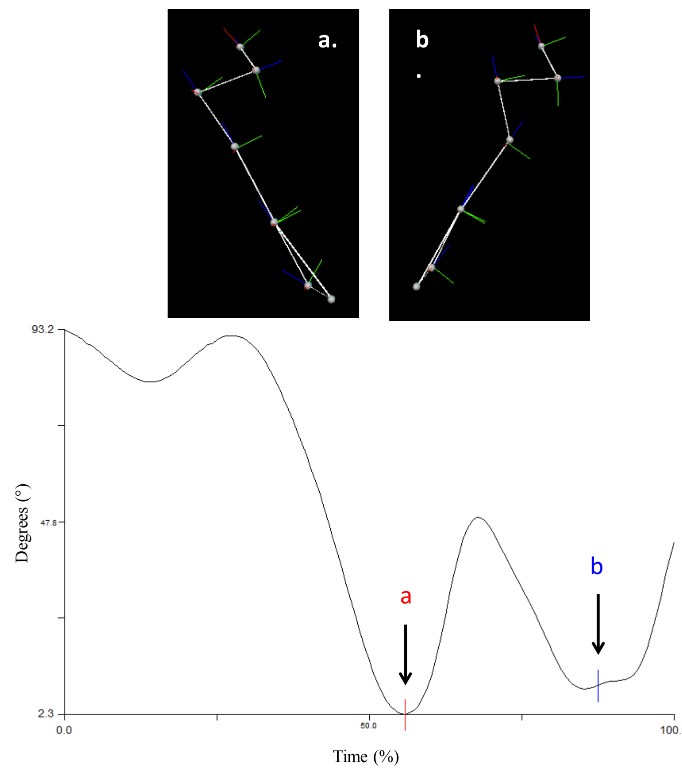


Figure 6.7 A time-angle curve for the tarsal joint at take-off in a horse exhibiting greater extension during stance phase than at hoof lift off. Representative hoof off events derived from method E and method A are illustrated by red (a) and blue (b) vertical lines, respectively on the time-angle curve. Visual representations of both method E (a) and method A (b) hoof on events are presented by corresponding snapshots of the model above the time-angle curve.

6.2.6 Conclusion

To the authors knowledge this is the only study to explore the accuracy of GE detection methods during the jump stride. This study has highlighted similarities between various GE detection methods, as well as the inherent inaccuracies associated with certain methods described in previous research. Findings from this study revealed that the method described by Holt et al. (2017) (method A) exhibited the greatest overall similarity to GE detection methods, which had previously been used in studies examining the kinematic jump technique. An investigation using GRF data to validate GE detection methods was beyond the constraints of this study and represents an area for future research. However, in the absence of GRF data, joint angles provided a means of investigating the accuracy of GE detection methods. Joint angles derived from GE detected using the method described by Holt et al. (2017) (method A), exhibited the greatest overall similarity to those reported in previous literature for hoof impact and lift off events. The method described by Hobbs et al. (2010) (method D) exhibited better accuracy for detecting FL hoof impact at landing than Holt et al. (2017) (method A), which was affected by early FL extension prior to landing.

However, this was only observed in certain files and, as a result, method A was found to be the most robust method for GE detection in the FL and HL during jump take-off and landing phases. The method described by Holt et al. (2017), would therefore be universally applied to kinematic data throughout the thesis for GE detection during canter and jump trials.

6.3 Development of Kinematic Measurement Techniques for the Quantitative Evaluation of "Quality" Movement as Defined by Equine Industry Professionals

6.3.1 Introduction

As previously stated in Chapter 1, the integration of equestrian opinions and preferences into scientific studies would enhance knowledge transfer, allowing research to produce findings that are more relevant to the equine industry professional. As outlined in Section 3.2.1, the ability to biomechanically define and measure preferred movement traits, as outlined by industry professionals, would be necessary to incorporate the equestrian definition of "quality" movement into the main study of the thesis. The aim of this study was to develop kinematic measurement techniques, which encompassed the definition of "quality" movement, as defined by equine industry professionals. In this study, "quality" movement traits, as defined in Chapter 3, were used to inform kinematic data analysis techniques for the main study of the thesis. The objectives of this study were to:

1. Determine specific movement traits, which industry professionals desire when evaluating "quality" canter and jump technique;
2. Determine whether equestrian terminology for specific movement traits can be translated into biomechanical measurements;
3. Determine whether biomechanical measurements can be quantified from kinematic data.

6.3.2 Methods

Data from the questionnaire study (Chapter 3) were assessed to determine the most prevalent movement traits described by industry professionals. Results from content analysis (Sections 3.4.3(ii), 3.4.5(ii)), which ranked the top coding categories for responses to open-end questions, were used to determine the most prevalent codes used to define desirable movement. Within each code, specific movement traits were described, as outlined in Section 3.4.3(i) (Table 3.1). Once the most prevalent coding categories were established for canter and jump, specific movement traits from each category were investigated to determine whether they could be quantified using kinematic data. An initial literature review was conducted to define rider terminology, which was used to describe movement traits. Definitions from: the FEI, breeding groups and frequently referenced equestrian groups (i.e. GNEF) were examined to determine the true meaning of each movement trait. A second review of equine biomechanics literature was then conducted to examine how specific movement traits could be defined biomechanically and to investigate how previous studies have measured these traits kinematically. Kinematic data from canter and jump were then used to develop optimal kinematic measurement techniques based on findings from the literature review.

6.3.2(i) Kinematic data analysis

Kinematic data collected from pilot work (Chapter 4) were used in this study to develop kinematic measurement techniques. Data were digitised and processed in accordance with Section 4.5.6(ii) and were analysed in Visual 3D. All data were low-pass filtered in accordance with Section 6.1. Kinematic gait events were calculated for each file in accordance with Section 6.2. Linear and temporal kinematics for canter and jump conditions were calculated using FL and HL gait events. Stance and stride duration were calculated using the "Metric_Time_Between_Events" command in the V3D pipeline. Stance duration was calculated as the time between hoof on and hoof off events in both the FL and HL. Stride duration was calculated as the time between successive HL hoof on events. Stride length was calculated in Microsoft Excel as the difference between x-coordinates of the hind DIPJ marker in the LCS during successive hind hoof on events. Duty factor was calculated in accordance with Biewener (1983) as the temporal proportion of stride duration where HL is in contact with the ground (% stance). First derivative values of x-coordinate data from the croup marker in the LCS were averaged over one stride to calculate stride velocity.

For each horse, joint angular velocity was calculated based on the segment model, using the "Compulte_Model_Based_Data" command. Joint angular velocity was calculated to describe the angular velocity of the distal segment relative to the proximal (reference) segment. Positive angular velocity corresponds to joint flexion (distal segment rotates towards palmar aspect of proximal segment) and negative corresponds to extension. A FL and HL segment were created to explore protraction and retraction angles. It is generally accepted that the elbow and hip joints drive pro and retraction in the FL and HL, respectively (Dutto et al., 2006; Clayton et al., 2011). The "distal FL segment" was therefore constructed using the lateral epicondyle of the humerus and fore DIPJ markers as proximal and distal ends, respectively. The "HL segment" was constructed using the tuber coxae and hind DIPJ markers as proximal and distal ends, respectively. Pro/retraction was calculated in the sagittal plane within the LCS (Y axis).

6.3.3 Results and Discussion

6.3.3(i) Preferred movement traits for "quality" canter

The prevalent movement themes chosen for further kinematic investigation of quality canter were: impulsion, collection, joint articulation and rhythm. These four traits represented the 1st, 3rd, 4th and 7th most frequently described themes from industry professionals, respectively (see Table 3.4). *Functional conformation*, *relaxation* and *connection* represented the 2nd, 5th and 6th most frequently described movement themes, respectively, but were not selected for kinematic analysis. Kinematic investigation of functional conformation would not serve to fulfil the objectives of the main study of the thesis, as the traits associated this theme did not directly describe dynamic movement or muscle activity (i.e. length of back).

For relaxation, respondents described traits such as: supple, loose, elastic and free moving. Relaxation is also referred to as looseness or suppleness, and describes the horse's physical and mental ability to work without tension (Belton and GNEF, 1997). Relaxation is achieved when the horse works through its back with its muscles free from tension and is expressed through: a rhythmically swinging back, snorting and a soft, but closed mouth (Belton and GNEF, 1997). To the author's knowledge, Back et al., (1994) is the only study to biomechanically describe suppleness, reporting that judged scores for this trait were significantly correlated with maximum fetlock extension. However, this study was conducted in the trotting horse and no references could be found for the kinematic evaluation of relaxation during canter. Therefore, relaxation was considered to be a largely qualitative trait and would not be included for kinematic analysis.

Specific traits such as: round through neck and back and ability to lift the back under the saddle were described for connection. Connection precedes impulsion and collection in the training scale and is exhibited when the horse is able to work forward from the rider's leg and seat aids into a steady contact with the hands (Belton and GNEF, 1997). The horse must work through from behind with a driving hind leg and is considered to "go onto the contact" when it is moving forward into the bridle (Belton and GNEF, 1997). Previous studies have evaluated the effect of different "head and neck positions" (HNP) achieved through various degrees of contact, on kinetics (Weishaupt et al., 2006a; Waldern et al., 2009) kinematics (Rhodin et al., 2005, 2009; Álvarez et al., 2006) and muscular activity (Kienapfel, 2015). In this study, collection of kinematic data and sEMG data from the thoracic spine and from relevant musculature, such as the Longissimus dorsi*,* were restricted due to the position of the rider and saddle. A kinematic analysis of connection was therefore beyond the scope of this study.

The following Sections (6.3.3(ii)-(v)) describe the prevalent movement themes chosen for further kinematic investigation of “quality” canter. Descriptions of movement traits are based on definitions developed through a review of equestrian literature. Broad movement themes and the most prevalent specific traits, which comprised each theme, are presented in Table 6.8.

6.3.3(ii) Impulsion

The FEI’s definition of impulsion is described in Section 3.4.3(i). Impulsion is not achieved solely through increased speed, but through controlled muscular power in the hindquarters (FEI, 2016). The horse must push off the ground energetically with the HL, enabling increased HL protraction underneath the horse’s body (engagement) (Belton and GNEF, 1997; FEI, 2016). Impulsion results in increased articulation of the hind leg, where the hock exhibits a smooth, continuous forward and upwards action (Belton and GNEF, 1997; FEI, 2016). The collective marks awarded for impulsion by dressage judges, as outlined by the FEI, include: the desire to move forward, energy and elasticity, suppleness of back, and engagement of hindquarters (Hawson et al., 2010). The specific traits described in the questionnaire for impulsion (Table 6.8), conform well to the definitions given by the FEI and the GNEF.

6.3.3(iii) Collection

Collection is the main goal of all gymnastic training and is accomplished when the collective weight of the horse and rider is transferred more evenly across all four limbs (Belton and GNEF, 1997; FEI, 2016). The horse’s natural FL/ HL weight distribution ratio is approximately 60:40 (Hoyt et al., 2000; Witte et al., 2004; Ross, 2010; Baxter and Stashak, 2011; Malikides et al., 2013; Hobbs et al., 2014), with the weight of the rider increasing this to approximately 70:30 (Belton and GNEF, 1997; Malikides et al., 2013). A more equal load-carrying capacity is therefore achieved by transferring more weight to the hindquarters by lowering and engaging the hindquarters through increased flexion of the stifle and hock joints (Holmström et al., 1995; Belton and GNEF, 1997; Holmström and Drevemo, 1997). The forehand and neck are subsequently lifted, giving an “uphill” appearance, which permits greater mobility and expression of the FL (Belton and GNEF, 1997; FEI, 2016). Figure 6.8 provides a visual depiction of the collection.

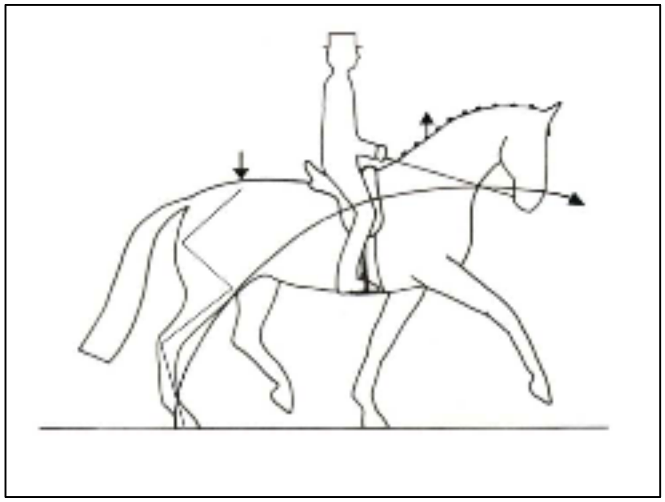


Figure 6.8 Visual representation of the collection, which also illustrates engagement of the hindlimb (Fédération Equestre Internationale, 2016).

6.3.3(iv) Joint Articulation

Industry professionals provided various descriptions of joint articulation, which were desirable traits of "quality" canter in jumping horses. As previously mentioned in Sections 6.3.3(ii) and 6.3.3(iii), increased stifle and hock flexion are requirements for the engagement observed during impulsion and collection (Holmström et al., 1995; Belton and GNEF, 1997; Holmström and Drevemo, 1997). Questionnaire results revealed that hock flexion was one of the most prevalent traits described for joint articulation, with no specific mention of the stifle joint. Increased FL mobility and lifting of the forehand are also related to the collection (Belton and GNEF, 1997; FEI, 2016). For the FL, equine professionals described a preference for "good use of shoulder" and FL "reach" when evaluating "quality" of canter.

6.3.3(v) Rhythm

Rhythm represents the first stage of the training scale and is a prerequisite for all proceeding stages of training. It is defined as the regularity of steps and strides in each gait (Belton and GNEF, 1997). The canter is a three-beat gait and should therefore exhibit regular strides of equal distance and duration (Belton and GNEF, 1997; FEI, 2016). Industry professionals described a preference for long canter strides of equal length, but also stated that adjustability was an important factor to consider.

6.3.3(vi) Optimal methods for kinematic measurement of preferred movement traits for "quality" canter

A review of relevant equine biomechanics literature highlighted possible kinematic measurement techniques for the preferred movement traits of canter (Sections 6.3.3(ii)-(v)). In comparison with walk and trot, fewer studies have kinematically investigated the canter. As a result, a review of the literature included studies, which had investigated preferred movement traits at trot and walk. Descriptions of kinematic measurement techniques developed for the main study of the thesis are presented in Table 6.8.

Linear and temporal kinematics (Section 6.3.2(i)) were used to calculate stride duration and stride length, which were used to investigate canter rhythm, in accordance with (Clayton, 1994b). Back et al. (1994) revealed that horses judged as having superior gait quality at trot exhibited a longer HL swing duration, than horses with poor gait quality. Increased stance and swing duration, and subsequent increases in stride length, have also been described as an indicator of the strength or impulsion in horses that exhibit good gait quality at trot (Back et al., 1994). Duty factor was therefore calculated in accordance with Biewener (1983) to quantify power under the broad theme of impulsion (Table 6.8).

Previous studies have used HL and FL pro/retraction angles to kinematically explore quality of movement at trot (Back et al., 1994; Holmström et al., 1993, 1994, 1995). Back et al. (1995) observed increased maximal HL protraction in horses that displayed good engagement, However, Holmström et al., (1995) reported no significant differences in HL protraction between collected and working gaits. HL pro/retraction were frequently reported by industry professionals and were therefore used to quantify movement traits for impulsion and collection, as outlined in Table 6.8. Maximum protraction of the FL was used to kinematically examine FL "reach" and "stretch", as described by industry professionals for joint articulation. Industry professionals appeared to place separate emphasis on protraction of the FL, through "freedom of movement at the elbow" and "use of the shoulder". Previous studies have described the importance of elbow flexion, as a factor for determining superior FL movement (Holmström et al., 1993, 1994, 1995). Therefore, elbow and shoulder ROM were calculated to explore these traits kinematically.

The equestrian definition of collection is described in Section 6.3.3(iii). From a biomechanical perspective, collection is characterised by increased stance duration (Holmström et al., 1995; Holmström and Drevemo, 1997; Clayton, 1994b), a caudal shift of the CM due to increased HL vertical impulse and joint flexion (Roepstorff et al., 2002; Weishaupt et al., 2006a, 2009) and subsequent elevation of the forehand (Holmström and Drevemo, 1997; Barrey, 2013; Dyson, 2016). Industry professionals described "elevation" and "uphill tendency" of the forehand as desirable traits for canter collection. These traits were kinematically examined by measuring the vertical displacement of the most proximal forehand marker (proximal scapula) during each stride cycle. Previous studies have estimated caudal shift of the CM based on the ratio of vertical impulse in the FL and HL (Roepstorff et al. 2002; Weishaupt et al., 2006a, 2009) However, to the author's knowledge, no studies have explicitly observed a caudal shift of the CM during collected gaits. Hobbs and Clayton (2013) observed continuous forward movement of the CM and a sinusoidal pattern for CM vertical velocity at trot, with the highest point occurring just prior to suspension phase. Although industry professionals did not explicitly describe increased elevation of CM as a desirable, vertical displacement of the CM was investigated based on findings from Hobbs and Clayton (2013) due to its frequent use in the biomechanical definition of the term.

"Tracking up" or "over tracking" are terms used by equestrians to describe a free-moving and forward stride, where the HL impacts the ground at the same, or further ahead of, the location of ipsilateral FL impact (Bryant, 2012; Micklem, 2012). Over tracking and tracking up were reported as desirable movements for impulsion and are the result of HL propulsion and engagement. Previous studies have quantified the degree of over tracking as the linear distance between footfalls of ipsilateral limbs (Colborne et al., 1995; Galisteo et al., 1997; Cano et al., 1999; Sole et al., 2013, 2014). This calculation was therefore included for kinematic analysis of impulsion.

Table 6.8 Kinematic measurement techniques for desired movement traits of quality canter, as described by industry professionals. Maximum and minimum events described were determined using "Metric_minimum" and "Metric_maximum" V3D pipeline commands within one stride or stance phase, as described for each technique.

Broad Theme	Specific Movement Trait	Kinematic Definition	Kinematic Measurement Technique
Impulsion	Powerful	Duty factor (% stride)	See Section 6.3.2(i)
	Active [hindlimb]	Hock angular velocity (°/s) [stance phase]	Min (extension) and max (flexion) hock angular velocity values for stance phase
		Pro/retraction ROM (°)	See Section 6.3.2(i) Difference between max HL protraction and retraction values from one stride.
	Forward moving	Average stride velocity (m/s)	See Section 6.3.2(i)
	"Tracking up/ overtracking"	Max HL protraction (°)	See Section 6.3.2(i)
		Linear distance between footfalls of ipsilateral limbs	Difference between ipsilateral FL and HL x-coordinate values for DIPJ marker at midstance event within LCS.
Collection	Hocks underneath body	Max HL protraction (°)	See Section 6.3.2(i)
	Stepping underneath body	See "Tracking up" under Impulsion theme	See "Tracking up" under Impulsion theme
	Elevation, uphill	Vertical displacement of proximal scapula marker and CM marker (m)	Max z-coordinates of proximal scapula and CM markers within the LCS from one stride. Max values normalised to z-coordinates from static trial.
Joint articulation	Hock flexion [stance phase]	Max hock flexion at stance phase (°)	Max hock joint flexion angle in sagittal plane during stance phase.
	Use of shoulder	Shoulder angle ROM (°)	Difference between max and min shoulder joint angle in sagittal plane for one stride.
	Forelimb "reach and stretch"	Maximum FL protraction (°)	See Section 6.3.2(i)
	Elbow ROM	Elbow angle ROM (°)	Difference between max and min elbow joint angle in sagittal plane for one stride.
Rhythm	Even, Equal Stride	Stride length (m)	See Section 6.3.2(i)
	3 Time, True Step	Stride duration (s)	See Section 6.3.2(i)

6.3.3(vii) Preferred movement traits for "quality" jump technique

The prevalent movement themes chosen for kinematic investigation of quality jump technique were: joint articulation, impulsion, reflex and engagement. These four traits represented the 2nd, 3rd, 4th and 9th most frequently described themes from industry professionals (see Table 3.5). The most frequently described movement trait for jump technique was "bascule", which is directly defined as a structure or device, in which one end is counterbalanced by the other (i.e. a seesaw) (Merriam-Webster, 2016). In equestrian terms, bascule generally describes the horse's ability to lower the neck and flex the thoracic spine during jump suspension (Denoix, 2014). This cervical-thoracic flexion creates a desirable rounded arc during flight. However, bascule was not selected for kinematic investigation in this study due to limitations associated with collecting kinematic and sEMG data from the thoracic spine (see Section 6.3.3(i)). Balance, relaxation, aesthetics and scope themes preceded engagement in relation to their importance when evaluating quality jump technique. However, these themes were not selected for kinematic analysis for reasons described below.

Balance represents a principal goal of dressage training (Weishaupt et al., 2006a), as a well-balanced horse is essential for advanced movements in dressage or jumping and for decreased musculoskeletal injury risk (Waldern et al., 2009). However, balance is a broad term, which is generally associated with shifting the CM caudally so that the horse carries more weight on its HL (Holmström and Drevemo, 1997). Kinematic studies have linked prolonged stance duration and positive diagonal advanced placement to good balance at trot (Holmström et al., 1995). However, in questionnaire responses, industry professionals described balance during jumping as "equal FL loading" and the horse's ability to move away from the fence in a "balanced manner" at landing. Kinematic data were only collected from the right side of the horse; therefore, equal loading of the forelimb at landing could not be measured. Balance was therefore not included for kinematic analysis, however aspects of balance (i.e. stance duration) were investigated under other movement themes (i.e. impulsion).

Relaxation was not investigated further for the reasons described in Section 6.3.3(i). For the aesthetics theme, respondents described specific traits such as: neat, tidy and clean. These terms were generally linked to symmetry of FL "tuck" during take-off and jump suspension phases. Similar to balance, kinematic data from one side of the horse did not allow for a quantitative investigation of symmetry. Furthermore, traits such as "clean" and "tidy" were considered to be largely subjective and difficult to quantify. Therefore, aesthetic traits were not included for kinematic analysis.

Scope is defined in Section 3.4.6(v) and can be kinematically quantified as vertical displacement of CM during jump suspension (Powers and Harrison, 2000; Santamaría et al., 2004a, b, 2005; Bobbert et al., 2005). However, industry professionals reported conflicting descriptions for scope, with some preferring "a long jump suspension with plenty of fence clearance as a sign of a strong horse" and others preferring a quick jump suspension and horses that did not "hang" in the air. The latter description favoured horses without excessive fence clearance in order to decrease injury risk at landing and time faults. Kinematic research has highlighted the relationship between scope and impulsion, as push-off by the HL at take-off acts a main determinant for the trajectory of the jump (Bogert et al., 1994; Barrey and Galloux, 1997). This relationship is discussed in detail in Section 6.3.3(xii). Engagement preceded scope in relation to its importance when evaluating movement, but plays an important role in power production at take-off (See Section 6.3.3(xii)). It was therefore decided that scope would be explored under the impulsion theme (Table 6.9) to investigate movement traits associated with engagement.

The following sections describe the prevalent movement themes chosen for further kinematic investigation of "quality" jump technique. Broad movement themes and the most prevalent specific traits, which comprised each theme, are presented in Table 6.9.

6.3.3(viii) Joint articulation

Most traits in this theme were associated with the horse's ability to articulate the FL joints into a "tucked" position during take-off and jump suspension. Respondents frequently used the broad term "good use of shoulder" when describing good FL action at take-off, which appeared to be related to shoulder joint flexion and lifting of the scapula. The terms "throwing away behind", "opening out behind" and "not cramped behind", were described as desirable traits for the HL. "Opening up behind" is an equestrian term, which is used to describe the release of the HL during the second half of jump suspension, so that the hip, stifle and hock joints are extended and the limb is "straightened out behind" (Micklem, 2012). "Cramping behind" is used to describe a poor jump technique, in which the horse does not extend the HL joints and is more susceptible to knocking rails (Micklem, 2012).

6.3.3(ix) Impulsion

The traits used to describe impulsion in relation to quality jump technique were similar to those described for quality canter (Section 6.3.3(ii)). However, respondents placed greater emphasis on the horse's ability to generate a powerful push-off during take-off phase.

6.3.3(x) Reflex

Traits comprising the reflex theme were almost entirely related to the horse's ability to articulate and "snap up" the FL joints into the "tucked" position during take-off. The speed at which the horse is able to lift its FL and HL off the ground at take-off was also described. These trait descriptions are in accordance with performance testing criteria for WB breeding organisations (i.e. KWPN), which evaluate speed/ quickness at take-off and reflex when evaluating jump technique (Bobbert et al., 2005; Ducro et al., 2007; KWPN North America, 2016).

6.3.3(xi) Engagement

Engagement was encompassed under the collection theme for canter, as it is essential for achieving collection during flatwork (Belton and GNEF, 1997; FEI, 2016; see Section 6.3.3(iii)). Questionnaire results revealed that respondents frequently described traits, which were explicitly related to engagement of the hindquarters and this trait was therefore treated as a stand-alone theme for evaluating jump technique. The most prevalent descriptive traits for engagement placed emphasis on the horse's ability to increase flexion of the HL joints (i.e. "sit" or "rock" back onto hocks) to shift its weight caudally during the take-off phase, in preparation for push-off.

6.3.3(xii) Optimal methods for kinematic measurement of preferred traits for "quality" jump technique

As previously stated, numerous studies have kinematically examined the equine jump technique. These studies provided examples of kinematic measurement techniques for movement themes outlined in Sections 6.3.3(viii)-(xi). Descriptions of kinematic measurement techniques developed for the main study of the thesis are presented in Table 6.9.

The linear distance between the jump pole and the lowest point of the limb has previously been used to examine FL and HL clearance technique (Lewczuk et al., 2005; Lewczuk and Ducro, 2012; Lewczuk, 2013; de Godi et al., 2014, 2016). However, this measurement does not provide an indication of the amount of limb shortening, which occurs due to increased joint flexion during take-off and jump suspension. Other studies have used absolute joint angles of the FL and HL to explore limb clearance technique. These studies have shown that increased joint flexion is an important kinematic trait to consider when examining jump technique (Powers and Harrison, 2000; Bobbert et al., 2005; Santamaría et al., 2006; 2005; 2004a). Although elbow flexion was not frequently described in questionnaire results, Bobbert et al (2005) found that increased elbow flexion was indicative of superior jump technique. It was therefore decided that absolute joint angles for the shoulder, elbow and carpus would be used to investigate FL joint articulation and limb clearance technique for the main study of the thesis. Scapula inclination was also measured in accordance with Holmström et al. (1993, 1994, 1995), to investigate "lifting of the shoulder". Industry professionals described a preference for "lifting the forelimb/ forearm" at take-off; therefore, radius inclination was also included in kinematic analysis.

The length of FL and HL segments has also been employed to evaluate the degree of limb clearance during jump suspension (Santamaría et al., 2006, 2005, 2004a, b; Bobbert et al., 2005). Shortening of these segments during jump suspension provides a kinematic indication of the degree of "tucking" action. De Godoi et al (2016) state that the vertical distance between the humeroradial joint and the fore MCPJ represent the flexion grade of the FL, with smaller distances being desirable to avoid knocking rails. Length of the "distal FL segment" (Section 6.3.2(i)) was therefore included in kinematic analysis to further investigate FL clearance technique.

Previous studies have examined HL clearance technique during jump suspension as the linear distance between the greater trochanter and MTPJ markers (Bobbert et al., 2005; Santamaría et al., 2004a, b, 2006) or between femorotibial and MTPJ markers (de Godoi et al., 2014, 2016). Bobbert et al. (2005) found distinct differences for HL retroflexion in good and poor jumpers, indicating that it was an important variable for evaluating HL clearance technique. Both, HL segment length and HL retroflexion calculations could therefore be used to provide a kinematic measure for "opening up behind" (Section 6.3.3(viii)) (de Godoi et al., 2016) and were included for kinematic analysis. HL retroflexion has been calculated as the angle between the back and HL segments (Bobbert et al., 2005; Santamaría et al., 2006; 2005). However, in this study, kinematic data for the back segment were not available, so HL retraction during jump suspension was used to calculate HL retroflexion.

As previously stated (Section 2.6.2(ii)), the mechanical energy required to execute the jump is produced during HL stance phase at take-off (Schamhardt et al., 1993; Bogert et al., 1994; Barrey and Galloux, 1997; Dutto et al., 2004; Bobbert and Santamaría, 2005). The impulse of the HL GRF during take-off, governs the magnitude and initial velocity of the CM, which in turn determines the ballistic flight of the CM during jump suspension (Barrey and Galloux, 1997). Previous studies have found that maximum vertical displacement of the CM during jump suspension is positively correlated with vertical velocity of the CM during take-off (Bobbert et al., 2005; Powers, 2005; Santamaría et al., 2004a, b; 2005). Santamaría et al., (2004a) calculated the integral of CM vertical acceleration using HL stance duration at take-off, which revealed that horses with greater vertical displacement of CM were able to generate greater vertical push-off forces over a shorter HL stance duration. As with canter (Section 6.3.3(vi)), power generation and strength during jumping can therefore be linked to stance duration, which was employed to kinematically evaluate impulsion during jumping (Table 6.9). As discussed in Section 6.3.3(vii), vertical displacement of the CM was also investigated under the impulsion theme due to the link between power production (impulsion) and CM trajectory (scope) during jump suspension (Barrey and Galloux, 1997; Powers and Harrison, 2000).

Angular velocity of the shoulder, carpus and elbow joints were used to measure the horse's reflex to "tuck" the FL during take-off. Clayton (1989) highlight joint angular velocity as an important consideration for kinematic examination of the take-off phase. Previous studies have presented data for angular velocity of the trunk (Bogert et al., 1994) and CM (Galloux and Barrey, 1997) during jumping. However, to the author's knowledge, no studies have reported joint angular velocity during jumping. During collected movements at trot, increased angular velocity of the HL joints is associated with superior movement and has been attributed to increased storage of elastic strain energy through increased joint flexion at stance phase (Holmström and Drevemo, 1997). Angular velocity data for FL joint flexion at take-off may therefore provide insight into the horse's reflexes.

Movement traits comprising the engagement theme for jump technique were similar to those comprising the collection theme for quality canter (See Table 6.8). This is unsurprising, as engagement is a key component to achieving collection during flatwork (Belton and GNEF, 1997; FEI, 2016). "Elevation" and "ability to place the HL underneath the body" were therefore calculated using the same kinematic measurement techniques as canter (Table 6.8). As previously stated in Section 6.3.3(iii) increased flexion of the HL joints are required for engagement of the HL. During jump take-off, flexion of the hip, stifle and hock joints contribute to the absorption (hip and hock) and production (stifle) of mechanical power by extensor musculature (Clayton, 1989; Bogert et al., 1994; Dutto et al., 2004; Bobbert et al., 2005) In the second half of HL stance, concentric contractions extend the hip, stifle and hock joints, which generate power (positive work) used to propel the horse into the air (Clayton, 1989; Bogert et al., 1994; Dutto et al., 2004; Bobbert et al., 2005). Industry professionals described a preference for increased hock flexion at take-off, which was therefore employed for kinematic analysis.

Table 6.9 Kinematic measurement techniques for desired movement traits of quality jump technique, as described by industry professionals. All variables were calculated within the jump stride, unless otherwise stated. Maximum and minimum events described were determined using "Metric_minimum" and "Metric_maximum" V3D pipeline commands within one stride (consecutive HL hoof on events) or stance phase, as described for each technique.

Broad Theme	Specific Movement Trait	Kinematic Definition	Kinematic Measurement Technique
Joint articulation	Use of shoulder, elevation	Maximum shoulder flexion (°)	Max shoulder joint flexion angle in sagittal plane following FL hoof off event at take-off.
		Scapula inclination (°)	Max sagittal plane angle for scapula segment within LCS (Y axis) following FL hoof off event at take-off.
	FL "Tuck"	Maximum shortening of distal FL segment (m)	Resultant signal calculated for distal FL segment by subtracting coordinates from proximal (lateral epicondyle of humerus) and distal (fore DIPJ) ends. Max shortening calculated as minimum resultant signal value following FL hoof off event at take-off. Normalised to segment length in static file.
		Maximum carpus flexion (°)	Max carpal joint flexion angle in sagittal plane following FL hoof off event at take-off.
		Maximum elbow flexion (°)	Max elbow joint flexion angle in sagittal plane following FL hoof off event at take-off.
		Maximum radius inclination (°)	Max sagittal plane angle for radius segment within LCS (Y axis) following FL hoof off event at take-off.
	HL "Tuck" [jump suspension]	Maximum shortening of HL segment (m)	"FL Tuck" measurement technique applied to HL segment. Max shortening calculated as minimum resultant signal value following HL hoof off event at take-off. Normalised to segment length in static file.
	"Open behind", "throwing away HL"	Maximum HL retraction (°) during jump suspension	See Section 6.3.2(i). Max value determined following HL hoof off event at take-off.
Impulsion	Power [push at take-off]	HL stance duration at A1 stride and take off (s)	See Section 6.3.2(i)
		Duty factor (% stride)	See Section 6.3.2(i) Measured at A1 and jump stride

		Vertical displacement of CM (m) [jump suspension]	Max z-coordinates of CM marker within the LCS during jump suspension (following HL lift off event). Max values normalised to z-coordinates from static trial.
	Strength	HL stance duration at A1 stride and take off (s)	See Section 6.3.2(i)
	Forward	A1 and jump stride velocity (m/s)	See Section 6.3.2(i)
Reflex	"Snap up" [forelimb at take-off]	Angular velocity for elbow, carpus and shoulder joints (°/s)	Max positive (flexion) angular velocity values for shoulder, elbow and carpal joints following FL hoof off event at take off
	Quick FL off ground [take-off]	FL stance duration (s)	See Section 6.3.2(i). Measured at take-off and phase.
Engaged	Take weight behind, "sit" and "rock" onto hocks [take off]	Maximum hock flexion during take-off (°)	Max hock joint flexion angle in sagittal plane during HL stance phase at take-off.
	Elevation and lifting [FL] at take-off, "back off" fence	Vertical displacement of proximal scapula and CM marker (m)	Max z-coordinates of proximal scapula and CM marker within the LCS during take-off (HL stance phase). Max values normalised to z-coordinates from static trial.
	HL underneath body	Linear distance between footfalls of ipsilateral limbs	See Table 6.8 for "tracking up/ overtracking".

6.3.4 Conclusion

Previous kinematic studies investigating the equine jump technique have relied on biomechanical models (Powers and Harrison, 2000) or studbook assessment criteria (Lewczuk and Ducro, 2012; Lewczuk, 2013) to identify selection of kinematic variables for data analysis. To the author's knowledge, this is the only study to establish kinematic measurements based on movement traits, which were defined and identified by industry professionals as being relevant to the evaluation of quality movement. In this study, kinematic measurement techniques were developed based on the translation of equestrian terminology and tacit knowledge into biomechanical terms, which could be quantified. The integration of rider preferences and opinions into the main study of the thesis will ensure that muscle activity and kinematic data are analysed in relation to movement traits, which are relevant and applicable to industry practice.

Chapter 7. Methods for the Main Study of the Thesis

This chapter describes the data collection and analysis techniques employed for the main study of the thesis. Kinematic and sEMG data were collected from elite and non-elite horses over four separate data collection sessions. The succeeding sections describe each data collection session in relation to its respective sample group. Data analysis techniques (Section 7.3) were employed for both elite and non-elite data.

7.1 Data collection protocols for the elite group

Data from elite horses were collected over two separate data collection sessions, each of which are detailed in this section. Data collection session one was conducted at a private yard in Newbury, Berkshire, in July 2015. Session two was conducted at a private yard in Preston, Lancashire in August 2015.

7.1.1 Animals

Seven horses (age: 10.4 ± 2.6 years, height: 164.9 ± 4.4 cm, breed: WB, sex: 3 mares, 4 geldings) were employed for this study. All horses were in work at the time of data collection and had SJ competition experience ranging from BS Foxhunter to 3* eventing and 1.60m International SJ classes. Three professional riders rode the horses, each with competition experience at Foxhunter level and above.

7.1.2 Animal Preparation

Horses were warmed up in accordance with Section 4.5.2(i). Kinematic marker and sEMG sensor application were conducted in accordance with Sections 4.5.2(ii) and 5.2.2, respectively. For elite horses, sEMG sensors were only applied to ideal sensor locations outlined in Section 5.5. This was done to minimise the number of clipped areas on horses competing at high-level events, where appearance is an important aspect of competition. Figure 7.1 shows an elite horse following kinematic marker and sEMG sensor application.

Figure 7.1 An example of an elite horse used for data collection.

7.1.3 Jump arrangement and equipment set up

The Qualisys Oqus (Qualisys AB, Göteborg, Sweden) camera system and Delsys Trigno (Delsys Inc., Boston, USA) kit were set up in accordance with Section 4.5.3 for elite data collection sessions. Both sessions were conducted in outdoor riding arenas, therefore the active filtering setting was applied to all cameras, as described in Section 4.3.1. An extended calibration was performed in accordance with Sections 4.3.2(i) and 4.5.3. Figure 7.2 illustrates jump arrangement and equipment set up from one elite data collection session.

Figure 7.2 Equipment and jump set up for elite data collection session two.

7.1.4 Procedure

The data collection procedure was conducted in accordance with Section 4.5.5. After six successful jumping trials over the 1.0m vertical, larger fences were constructed and data were collected over these fences. However, this progression was dependant on: the rider's discretion, the horse's fitness, level of fatigue and whether the retro-reflective markers and sEMG sensors were still adhering to the horse. The maximum height of fences used for additional jump trials was based on the maximum height each horse had successfully competed at. As a result, data were collected from three horses over a 1.0m square oxer with a spread of approx. 80cm (Figure 7.3). Two horses completed larger ascending oxers with a maximum back rail height of 1.40m (Figure 7.4).

Figure 7.3 An elite horse from session two completing an extra jump trial over a 1.0m square oxer.

Figure 7.4 An elite horse from session two completing an extra jump trial over a 1.40m ascending oxer.

7.2 Data collection protocols for the non-elite group

Data from non-elite horses were collected over two separate data collection sessions, each of which are detailed in this section. Both sessions were conducted in April 2015. Session one was conducted at Craven College (Skipton, North Yorkshire) and session two was conducted at Hargate Hill Equestrian Centre (Glossop, Derbyshire).

7.2.1 Animals

Eight horses (age: 9.6 ± 1.6 years, height: 155.2 ± 6.1 cm, sex: 5 geldings, 3 mares) of varying breeds (ISH, TB, Welsh Cob) were used for non-elite data collection. Data were collected from three horses (age: 10.3 ± 2.3, two mares, one gelding, breed: TB, Welsh Cob) at Craven College, each ridden by a different rider. All three riders had similar experience (14-20 years) and riding ability (competed at BS Discovery-Foxhunter). Data were collected from five horses (age: 9.2 ± 1.1, one mare, four geldings, breed: ISH) at Hargate Hill, and were ridden by one experienced rider (14 years, competed at unaffiliated 1.0m SJ). At the time of data collection, this group of horses were mainly used for riding school lessons (novice, intermediate, advanced lesson horse). However, all three horses from Craven College had previous experience competing in low-level SJ (85-90cm unaffiliated and BS Discovery). All horses were physically fit and were capable of executing a 1.0m fence. Figure 7.5 illustrates an example of a non-elite horse, which was used as a school horse and had no competition experience.

Figure 7.5 An example of a non-elite subject used for data collection.

7.2.2 Animal preparation

Horses were warmed up in accordance with Section 4.5.2(i). Kinematic marker and sEMG sensor application were conducted in accordance with Sections 4.5.2(ii) and 5.2.2, respectively. For non-elite horses, sEMG sensors were applied both sensor locations described in Section 5.2.2(ii).

7.2.3 Jump arrangement and equipment set up

Equipment was set up in accordance with Sections 4.5.3 and 4.5.4 for both non-elite data collection sessions. Both sessions were conducted in indoor riding arenas. An extended calibration was performed in accordance with Sections 4.3.2(i) and 4.5.3. Figure 7.6 illustrates equipment set up from one non-elite data collection session at Craven College.

Figure 7.6 Equipment set up for non-elite data collection at Craven College.

7.2.4 Procedure

The data collection procedure was conducted in accordance with Section 4.5.5. Non-elite horses did not execute fences larger than the 1.0 m vertical fence. Figure 7.7 illustrates one non-elite horse during a jump trial.

Figure 7.7 A non-elite horse during a 1.0m vertical jump trial.

7.3 Data Analysis

This section describes the data processing and analysis techniques used for sEMG and kinematic data from elite and non-elite groups. As described in Section 7.2.1, three horses from the non-elite group had similar experience in low level jumping competition to horses used for pilot work (Section 4.5.1) (BE 80, unaffiliated SJ 85-90cm, BS Discovery). The horses tested during pilot work exhibited high fidelity sEMG signals and high quality kinematic data. A decision was therefore made to incorporate data from pilot work into data analysis for the main study of the thesis and to divide horses into three, more specific, groups based on competition experience. Horses were therefore split into "elite", "novice competition" (NC) and "school" groups. The elite group (n=7) was comprised of horses described in Section 7.1.1, which had competed at a minimum level of BS Foxhunter. The NC group (n=7) was comprised of all horses described in Section 4.5.1 and the three horses from Craven College (Section 7.2.1) with competition experience. The school group (n=5) was comprised of horses from Hargate Hill, which were used as school horses and are described in Section 7.2.1.

Processing and analysis techniques for sEMG and kinematic data are described separately in the following sections. Processing and analysis of kinematic and sEMG data was conducted in V3D (C-Motion Inc., USA). Data were exported from V3D to Microsoft Excel (Microsoft Corporation, USA) and SPSS 22 (IBM Corp, USA) for further: data analysis, tabulation and descriptive and inferential statistical analysis.

7.3.1 EMG Data Analysis

The phasic activity and magnitude of sEMG signals were analysed to determine the fundamental activity patterns of selected superficial muscles from each group. Phasic activity patterns were explored visually with the aid of kinematic gait events described by Holt et al. (2017) and in Section 6.2. Magnitude analysis of signals was conducted by calculating integrated EMG (iEMG), average rectified value (ARV) and peak amplitude (PA) values, which are described in detail in the following sections.

7.3.1(i) Signal filtering

sEMG signals were shifted forward by 5 frames to correct for the constant delay between kinematic and sEMG acquisition systems (Section 4.4). Raw sEMG signals were DC offset removed and high pass filtered using a zero-lag, 4^{th} order Butterworth filter with a cut off frequency of 80Hz, in accordance with Section 5.3.

7.3.1(ii) Accept/ reject criteria for sEMG signals

An evaluation of the fidelity of each sEMG signal was conducted prior to phasic and magnitude analysis. A signal quality check was performed in two stages. The first stage was comprised of a visual observation of signal fidelity. The second stage was based on evaluation of iEMG, ARV and PA values, calculated from signals, which had progressed past stage one. In stage one, each signal was scrutinised based on its phasic pattern and whether it exhibited a realistic magnitude, based on typical sEMG signals within each horse. For each horse, the variability of magnitude was examined and, as a general rule, signals with over 30% variability from initial trials were rejected for further magnitude analysis. Signals that exhibited magnitudes, which varied considerably from the majority of trials within horses, were rejected for further magnitude analysis. However, signals, which were rejected based on magnitude but still exhibited a valid phasic pattern, were grouped together accordingly.

All signals were sorted based on an accept/reject criteria composed of three different classifications of signal quality. Classification groups were generated based on a traffic light system, with green, amber and red groups. The green group included signals, which exhibited high fidelity and were suitable for full signal analysis (magnitude and phasic). Signals of acceptable magnitude, which exhibited areas of noise were classified as green, but were specified with an asterix to signify that data from the entire signal could not progress to full signal analysis. Hoof on and off events were applied to green* signals to identify which areas could be used for full signal analysis. The amber classification represented signals, which exhibited excessively high magnitudes and were only suitable for phasic analysis. Signals classified as red, were of poor signal quality and were not suitable for magnitude or phasic analysis. The accept/reject criteria were reviewed and independently verified by two researchers, the first researcher being the author of the thesis and the second with over 20 years' experience in sEMG signal analysis. Appendix D includes the accept/reject criteria for all EMG signals used in the main study of this thesis.

Examples of signals allocated to each traffic light criteria are illustrated in Figure 7.8. Figure 7.9 illustrates the classification method for green* signals, and uses the green* signal from Figure 7.8 as an example. Note that the stance phase highlighted in red (Figure 7.9a) shows movement artefact and was therefore removed from analysis. The remaining stance phases were included due to their acceptable phasic activity pattern and magnitude (Figure 7.9b). Figure 7.9 illustrates the importance of scrutinising each signal, as movement artefact skewed the y-axis scale of the signal-time graph. Therefore, an in-depth examination of each signal was required to ensure areas of acceptable magnitude were not discarded. Additional examples of signals from each criterion are included in Appendix D.

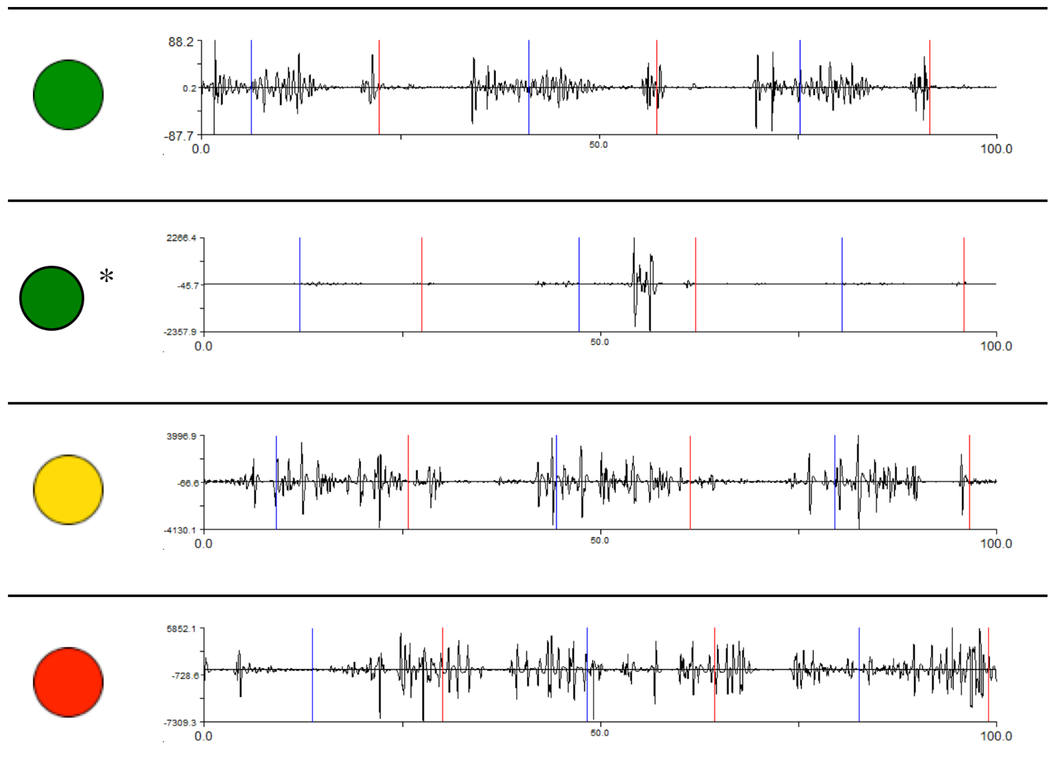


Figure 7.8 Examples of each traffic light criteria employed for accept/ reject criteria for EMG signals. EMG signals are from the Trapezius in one elite horse during canter. Forelimb hoof on and off events are illustrated by blue and red vertical lines, respectively to show phasic activity patterns within the signal.

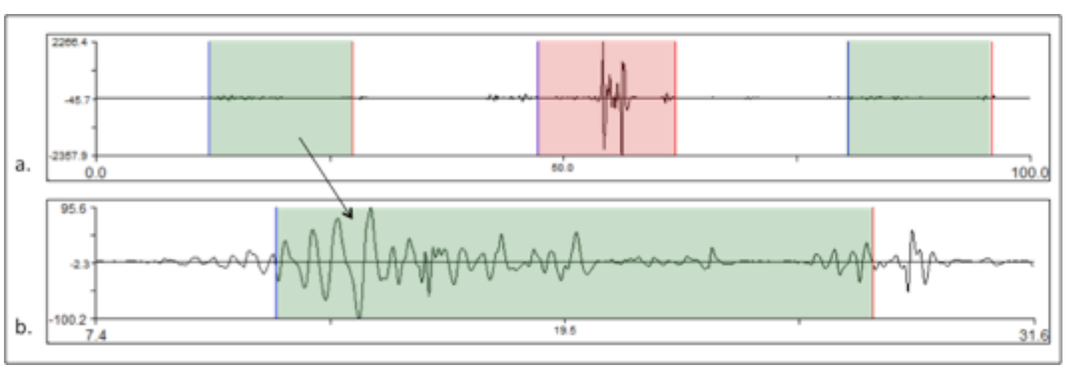


Figure 7.9 Classification system for Green* signals. a.) signal taken from Green* signal in Figure 7.8. The stance phase highlighted in red was removed from further data analysis due to its high magnitude. b.) stance phases highlighted in green revealed a similar phasic activity and magnitude to the Green signal in Figure 7.8.

The second stage of the signal quality check was conducted on signals grouped within the green /* classification. This stage was based on an examination of iEMG, ARV and PA data, which were calculated from green/* signals. The calculation and extraction of these variables is described in detail in sections below. Data points or signals, which exhibited values that varied considerably from the majority of trials within each horse, were explored and reviewed. Within and between-subject EMG data exhibited continuous variation and outliers were detected based on obvious discontinuous data within the data set. Outliers were independently verified by both researchers and were rejected for further analysis.

7.3.1 (iii) Integrated EMG (iEMG)

iEMG were calculated to quantify the work done by superficial muscles during canter and jump trials. iEMG refers to the area under the rectified EMG trace for a specified temporal domain (Winter et al., 1980; Konrad, 2006; Richards et al., 2008b). iEMG is therefore reported in mV•s or μV•s (Winter et al., 1980) and is directly dependent on the time duration selected for analysis, making it useful for comparison analysis (Konrad, 2005). iEMG is frequently used to quantify EMG activity and the work done by a muscle (Richards et al., 2008b), with little controversy surrounding its use (Morey-Klapsing et al., 2004). Studies have explored the reliability of iEMG, with the majority reporting high correlation values for repeated measures (Taylor and Brooks, 1995; Goodwin et al., 1999), which are dependent on the muscle studied (Goodwin et al., 1999). Previous equine sEMG studies have employed iEMG to calculate muscle activity for specific strides to directly compare the work done by muscles under varying conditions (Robert et al., 2000, 2001a, b; 2002). Precise definition and identification of gait event timings are imperative for calculating iEMG during continuous activities (i.e. canter) (Richards et al., 2008b). Therefore, hoof on and off events were carefully considered and defined for the purposes of this research and are described in Section 6.2.

iEMG were calculated in accordance with Winter et al (1980) using DC offset removed, high pass filtered and full-wave rectified signals (Section 7.3.1(i)). Kinematic gait events were created in accordance with Holt et al. (2017) and Section 6.2, and were applied to sEMG signals to define the time duration for iEMG calculation. Visual examination of sEMG signals revealed that all muscles were active during stance phase and were generally inactive during swing phase for canter and jump conditions. Stance phase was therefore chosen as the time domain for iEMG calculation, as this would best represent where differences in muscle activity between groups occurred. iEMG were calculated using the "Metric_Integrate" command in the V3D pipeline between hoof on and hoof off events, demarcating stance phase (Leach et al., 1984a; Clayton, 1989; Leach, 1993). FL and HL stance phase represented the time domain for muscles of the neck and thoracic limb (Splenius, Trapezius, Triceps Brachii) and pelvic limb (Superficial Gluteal, Biceps Femoris), respectively.

7.3.1(iv) Average rectified value (ARV)

ARV was calculated to explore the average amplitude measured during stance duration. ARV is often used interchangeably with iEMG; however, this is incorrect, as the ARV is the absolute average amplitude of the full-wave rectified signal for a specified time period and is reported as mV or μV (Winter et al., 1980; Merletti and Farina, 2016). ARV was calculated to provide further insight into iEMG values. For example, ARV could be used to determine whether potential differences in iEMG values were the result of differences in time domain or signal amplitude. ARV were calculated using stance phase as the time domain in accordance with Section 7.3.1(iii). The "Metric_Mean" command in the V3D pipeline was used to calculate ARV between hoof on and hoof off events.

7.3.1(v) Peak amplitude (PA)

A linear envelope was applied to full-wave rectified signals to calculate PA, using a low-pass filter with a cut-off frequency of 25Hz, in accordance with Section 5.4.3(i). Smoothing the rectified signal is frequently cited as a useful tool for extracting amplitude-related information (Basmajian and De Luca, 1985), as smoothing reduces inherent variation in the signal, providing a clearer representation of the time-varying EMG amplitude (Winter et al., 1980; Soderberg and Cook, 1984; Richards et al., in press). The "Metric_Maximum" pipeline command in V3D was used to calculate peak EMG values between hoof on and hoof off events, in accordance with Section 7.3.1(iii).

7.3.1(vi) Normalisation of sEMG data

iEMG, ARV and PA data were exported from V3D into Microsoft Excel for outlier detection (second stage of signal quality check, see Section 7.3.1(ii)) and normalisation. Normalising the amplitude of EMG signals to a reference value is frequently employed, as it allows for direct comparison between individuals, muscles, or testing sessions (Basmajian and De Luca, 1985; Lehmen and McGill, 1999; Richards et al., 2008b; Burden, 2010). In this study, normalisation was necessary to mitigate inter and intra-horse differences in sEMG signals due to intrinsic and extrinsic factors such as: differences in subcutaneous tissue, the number of active motor units, body temperature and sweat production, to name a few (Cram and Rommen, 1989; Winkel and Jørgensen, 1991; De Luca, 1997; Lehman and McGill, 1999; Halaki and Ginn, 2012; Sousa and Tavares, 2012).

Normalising to the maximal voluntary contraction (MVC) has been extensively used in human research (Richards et al., 2008b; Burden, 2010), however obtaining true isometric MVC measurements from animal subjects is not possible (Valentin and Zsoldos, 2016; Vögele et al., 2016). Normalisation can also be conducted using the maximum EMG signal observed during a related activity, which allows the researcher to explore proportional changes in muscle activity between individuals and conditions (Richards et al., 2008b). The reference value and subsequent activity must therefore be meaningful to the proportional change. Questionnaire results (Chapter 3) revealed that quality canter carried the greatest importance in a training programme for improving jump technique. Canter also represents the gait in which the horse normally approaches the fence (Clayton, 1989). It was therefore decided that the maximum signal observed during canter would be used as the reference value for normalisation of iEMG, ARV and PA values, which would permit examination of the proportional change in muscle activity between canter and jump. For each horse and muscle, maximum iEMG, ARV, and PA values during canter were determined and normalised values were calculated by dividing each EMG value (numerator) by the respective canter reference value (denominator) (Burden, 2010). Normalised values for each horse were presented as a percentage value (%) of each muscles activity relative to the maximum value observed during canter.

When calculating normalised values, the numerator is generally lower than the denominator, leading to a percent value of muscle activity that is less than 100% of the MVC, or associated task. However, in this study, values for the canter reference value (denominator) were generally lower than those obtained during jump strides (numerator), leading to normalised jump values greater than 100% of the reference value. Normalisation techniques, which employ sub-maximal MVC (sub-MVC) as a reference value have been used in human EMG research (i.e. Sinclair et al., 2014) and are not uncommon in clinical research where the MVC may affected by pain (Marras and Davis, 2001). Isometric sub-MVC have been reported as more reliable than MVC (Yang and Winter, 1983) with the reproducibility of an MVC being affected by the level of sincerity or motivation exhibited during the exertion, which is believed to introduce experimental error (Marras and Davis, 2001). This is an important consideration for the main study of the thesis, as elite horses executed submaximal fences, while many non-elite horses were jumping higher fences than normal. This would undoubtedly affect the level of exertion both between and within horses. Therefore, although sEMG collected during the jump stride was more representative of an MVC, this was not considered to be an appropriate reference value for normalisation due to the variability of exertion, and subsequent reproducibility of this value. It is not mandatory that the reference value be a maximum exertion, so long as the reference value relates to the relative contribution of the muscle and is constant across: muscles, exertions and subjects (Marras and Davis, 2001; Dankaerts et al., 2004). This further justifies the use of canter as a reference value for normalisation of EMG data within the main study of the thesis.

7.3.2 Kinematic Data Analysis

7.3.2(i) Data Processing

Kinematic data were digitized in QTM software, in accordance with Section 4.5.6(ii). A rigid-body segmental model for the fore and HL was created for each horse using the static trial and was applied to dynamic files in accordance with Section 4.5.6(ii). LCS, SCS and joint angle computation were also defined in accordance with Section 4.5.6(ii).

7.3.2(ii) Signal filtering

Kinematic data were interpolated with a maximum gap of 10 frames. Data were filtered using a zero-lag, 4th order Butterworth low-pass filter with a cut-off frequency of 12Hz, in accordance with Section 6.1.

7.3.2(iii) Computation of gait events and linear and temporal kinematics

Kinematic gait events for fore and hind hoof on (impact) and hoof off (lift off) were calculated in accordance with Holt et al. (2017) and Section 6.2. Linear and temporal kinematics were calculated in accordance with Section 6.3.2(i).

Standardised terminology for equine jump kinematics, as described by Clayton (1989), were used throughout kinematic data analysis. The terminology described by Clayton (1989), uses TrH impact to define the beginning and end of strides during jumping. However, in this study, data were only collected from the right side of the horse and data from the TrH were not consistently available. Therefore, A1, jump and departure strides were denoted by successive right HL hoof on events, regardless of whether the HL acted as LdH or TrH. In this study, take-off refers to the final FL and HL stance phase prior to jump suspension, and landing refers to the first FL and HL stance phase following jump suspension.

7.3.2 (iv) Kinematic measurement of movement traits denoting "quality" canter and jump technique

A description of the methods used for the kinematic measurement of desired movement traits for canter and jump are provided in Section 6.3.

7.3.4(v) Normalisation of kinematic variables.

To correct for inter-individual variation between horses (i.e. conformation), absolute joint angles were normalised to those recorded during static trials for each horse (Back et al., 1994, 1995a, b). Normalised joint angles were calculated by subtracting the static angle from the absolute joint angle. Normalised joint angles are therefore presented as angular changes from the standing position (Back et al., 1995a, b). It was not necessary to normalise angular velocity, linear, and temporal kinematic data.

7.3.5 Statistical Analysis

7.3.5(i) Descriptive Statistics

Descriptive statistics were conducted on normalised EMG and kinematic variables in Microsoft Excel. Mean and standard deviations were calculated to describe variables from Sections 7.3.1 and 7.3.2, as well as subject metrics (i.e. age). For each variable, ensemble averages (mean ± SD) were calculated across trials to examine differences between subjects and groups.

7.3.5(ii) Inferential Statistics

The aim of this study was to investigate differences in EMG and kinematic data between groups. Inferential statistical analyses were conducted using SPSS 22 (IBM Corp., USA), with significant differences identified at $P \leq 0.05$. Due to the large number of inter-related variables investigated in this study, statistical analyses were conducted for each dependent variable under canter and jump conditions. It is generally accepted that multiple analyses increase the likelihood of type I error and the alpha level is subsequently adjusted to control for this (Bland and Altman, 1995). Sinclair et al (2013) argue that, in studies were multiple comparisons are required; the consequences of controlling for type II error outweigh those of controlling for type I, due to the increased likelihood of overlooking a valid effect. The justification put forth by Sinclair et al (2013) is relevant to this study, as multiple comparisons were necessary to explore the effect of two independent variables (limb and group) on many dependent variables using a small sample size. It was therefore considered more important to control for type II error and the alpha level was not adjusted to control for multiple comparisons. In regards to the statistical assumptions of analysis of variance (ANOVA) for comparative analysis, Keppel and Wickens (2004) indicate that the F statistic is extremely robust to distributional violations (i.e. normality and homogeneity). As such, given the nature of the measurements and the relatively small sample size, which was typical of equine research in this area, it was decided that examining the data for normal distribution and equality of variance was not necessary.

Differences between leading and trailing limb were first tested using a paired t-test for paired samples, as significant differences would indicate that limb must be included as an independent variable in further statistical analysis using ANOVA. However non-significant differences would suggest that data from both limbs could be grouped.

A 2 x 3 mixed factorial ANOVA was employed to determine the effect of group and limb for each kinematic and EMG variable investigated in this study. Pairwise comparisons were investigated where significant main effects were found. Significant interactions between group and limb were explored using one-way ANOVA and independent samples t-tests. Effects sizes were established using partial eta^2 (pn^2).

Chapter 8. Results

Results presented in this chapter will be used as evidence to fulfil Objectives 3 and 4 for the main study of the thesis. Findings from this study were disseminated through oral presentations at: the "Improving Sport Horse Performance: Bridging the Gap Between Science and Practice" workshop held at Myerscough College (December 8, 2015), The University of Liverpool's School of Veterinary Science (Leahurst Campus) (February 26, 2015), and at the 8th International Conference on Canine and Equine Locomotion (ICEL) (August 19, 2016). Further information and abstracts are included in Appendix E.

8.1 Effect of canter and approach stride lead on kinematic and EMG data

Paired samples t-tests revealed significant differences between limbs for normalised EMG canter data from Biceps Femoris and Splenius muscles. Paired t-tests also revealed significant differences between limbs for several kinematic variables. These findings indicated that data from the leading (Ld) and trailing (Tr) limb should be presented separately and a 2 x 3 mixed factorial ANOVA, which included limb as a variable, was therefore employed for further statistical analysis. To avoid presenting results twice, significant differences between limbs for the aforementioned kinematic and sEMG variables are presented in the preceding sections, which describe results from ANOVA tests. The number of strides and stance phases used to calculate group means for each kinematic and sEMG variable are presented in tabular form in Appendix C.

8.2 Linear and Temporal Kinematic Variables for Canter Stride

Linear and temporal kinematic variables for canter are presented in Table 8.1. Low standard deviation values across groups indicated low variability for kinematics during canter. ANOVA results for FL stance duration data showed significant main effects for limb $F_{(1,16)} = 26.57$, $P<0.0001$, $pn^2=0.62$. Pairwise comparisons showed that FL stance duration was significantly longer ($P<0.0001$) for TrF. A significant main effect was also found for group for stride velocity data $F_{(2,16)} = 3.86$, $P<0.05$, $pn^2=0.33$. The school group exhibited significantly greater ($P<0.05$) stride velocity than NC and elite groups. Interestingly, all remaining variables presented in Table 8.1 were similar between group and limb.

Table 8.1 Linear and temporal values for each group at canter, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Within a row, significant differences (P<0.0001) between limbs are represented by grey shaded cells. Note: Duty factor calculated using HL stance duration.

Variable	**Elite** *n*= 7		**NC** *n*= 7		**School** *n*= 5	
	Tr	Ld	Tr	Ld	Tr	Ld
Stride velocity (m/s)	a		b		a, b	
	4.50 (0.46)	4.43 (0.41)	4.38 (0.46)	4.59 (0.49)	4.97 (0.26)	5.06 (0.28)
Stride length (m)	2.69 (0.29)	2.63 (0.28)	2.54 (0.22)	2.62 (0.21)	2.79 (0.16)	2.87 (0.13)
Stride duration (s)	0.60 (0.03)	0.59 (0.03)	0.58 (0.03)	0.57 (0.04)	0.56 (0.02)	0.57 (0.03)
FL stance duration (s)	0.29 (0.01)	0.28 (0.02)	0.29 (0.04)	0.26 (0.03)	0.27 (0.01)	0.25 (0.02)
HL stance duration (s)	0.33 (0.04)	0.32 (0.05)	0.31 (0.03)	0.32 (0.04)	0.30 (0.01)	0.31 (0.02)
Duty factor (% stride duration)	54.44 (4.62)	53.64 (5.67)	53.84 (4.27)	56.08 (6.07)	54.28 (2.12)	55.08 (2.45)

8.3 Linear and Temporal Kinematic Variables for Approach and Jump Stride

Linear and temporal kinematic variables for A1 stride are illustrated in Table 8.2. ANOVA results showed significant main effects for group for: stride velocity $F_{(2,10)}$ =5.15, P<0.05, pn^2=0.51 and HL stance duration $F_{(2,9)}$=4.54, P<0.05, pn^2=0.50 data. Pairwise comparisons revealed that the elite group exhibited a significantly shorter (P<0.05) HL stance duration during A1 stride than NC and school groups, which displayed very similar HL stance durations. The elite group also showed a significantly greater (P<0.05) velocity during A1 stride than NC and school groups. A significant main effect was found for limb for A1 duty factor data $F_{(1,9)}$ =5.16, P<0.05, pn^2=0.36. Pairwise comparisons revealed that duty factor was significantly greater (P<0.05) in the LdH. No significant interactions between limb and group were found for any of the remaining linear and temporal kinematic variables examined for A1 stride. Interestingly, FL stance duration values were remarkably similar between limbs during A1 stride, but showed significant differences (P<0.05) for canter stride, as described in Section 8.2. Although non-significant, the elite group consistently exhibited shorter stride length, stride duration, and FL stance duration values than NC and school groups across both limbs.

Table 8.2 Linear and temporal values for each group during A1 stride, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number subjects used to calculate mean (±SD) for each group. *n* values differed for FL stance duration and are indicated. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Significant differences (P<0.05) between canter leads are represented by grey shaded cells. Note: Duty factor calculated using HL stance duration.

Variable	**Elite** *n= 7* *n=4 (FL stance)*		**NC** *n= 7* *n=6(FL stance)*		**School** *n= 5* *n=2(FL stance)*	
	Tr	Ld	Tr	Ld	Tr	Ld
Stride velocity (m/s)	a, b		a		b	
	6.51 (0.59)	6.65 (0.43)	5.90 (0.48)	5.95 (0.43)	5.29 (0.47)	6.02 (0.42)
Stride length (m)	2.34 (0.33)	2.29 (0.16)	2.52 (0.42)	2.58 (0.41)	2.43 (0.19)	2.30 (0.21)
Stride duration (s)	0.35 (0.05)	0.34 (0.03)	0.42 (0.06)	0.42 (0.05)	0.44 (0.05)	0.37 (0.02)
FL stance duration (s)	0.16 (0.04)	0.16 (0.01)	0.20 (0.03)	0.20 (0.05)		0.19 (0.05)
HL stance duration (s)	a, b		a		b	
	0.20 (0.05)	0.19 (0.03)	0.24 (0.03)	0.25 (0.04)	0.24 (0.03)	0.22 (0.01)
Duty factor (% stride duration)	55.31 (7.96)	56.41 (8.36)	57.42 (5.04)	60.21 (4.05)	56.01 (1.25)	58.21 (2.14)

Linear and temporal kinematic variables for jump stride are illustrated in Table 8.3. A significant main effect for group was found for stride length $F_{(2,12)}$ =4.78, P<0.05, pn^2=0.44 and stride duration $F_{(2,11)}$ =12.74, P<0.05, pn^2=0.70. Pairwise comparisons revealed the school group exhibited significantly shorter (P<0.05) jump stride length and duration than elite and NC groups. For jump stride duration, significant main effects were also found for limb $F_{(1,11)}$ =5.30, P<0.05, pn^2=0.33, with TrH exhibiting significantly longer (P<0.05) stride duration. Interestingly, significant differences between limb for stride duration were not observed in A1 (Table 8.2) or canter (Table 8.1) stride data. Although significant differences between groups were found for stride velocity during A1 and canter strides, jump stride velocity was similar across groups. FL and HL stance duration, which ultimately represent stance phase at take-off, were also very similar between groups and lead.

Table 8.3 Linear and temporal values for each group during jump stride, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number of stride variables used to calculate mean (±SD) for each group and stride. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Significant differences (P<0.05) between limbs are represented by grey shaded cells. Note: Duty factor calculated using HL stance duration.

	Elite *n= 7*		**NC** *n= 7*		**School** *n= 5*	
Variable	Tr	Ld	Tr	Ld	Tr	Ld
Stride velocity (m/s)	6.53 (0.63)	6.60 (0.43)	6.09 (0.63)	6.24 (0.62)	5.90 (0.51)	6.17 (0.45)
Stride length (m)	a		b		a, b	
	4.75 (0.63)	4.75 (0.64)	4.58 (0.56)	4.40 (0.57)	3.84 (0.48)	3.84 (0.21)
Stride duration (s)	a		b		a, b	
	0.78 (0.05)	0.78 (0.04)	0.81 (0.04)	0.78 (0.04)	0.73 (0.03)	0.70 (0.03)
FL stance duration (s)	0.22 (0.05)	0.22 (0.03)	0.23 (0.03)	0.23 (0.05)	0.24 (0.02)	0.23 (0.03)
HL stance duration (s)	0.23 (0.04)	0.23 (0.04)	0.26 (0.06)	0.27 (0.04)	0.26 (0.02)	0.25 (0.04)
Duty factor (% stride duration)	29.90 (4.98)	29.89 (4.97)	31.90 (7.48)	35.28 (6.07)	34.81 (3.12)	35.83 (3.91)

8.4 Results of phasic and magnitude analysis of sEMG data

8.4.1 General phasic activity patterns of sEMG data during canter and jump

Figures 8.1 and 8.2 provide an overview of the general phasic activity of muscles investigated in this study during canter and jump conditions, respectively. A detailed description of phasic activity patterns and magnitude analysis of each muscle are provided in the succeeding sections. However, Figures 8.1 and 8.2 provide an introductory visual representation of the relationship between kinematic and sEMG data during canter and jump. It should be noted that photographic representations of gait events in Figures 8.1 and 8.2 are for visual purposes only and do not directly correspond with kinematic gait events. In addition to high-pass filtered sEMG data used to illustrate phasic activity patterns and magnitude from each muscle in Sections 8.4.2 – 8.4.6, time-normalised, linear enveloped sEMG data are presented in Appendix D. Linear enveloped data are presented as mean (± SD) from one horse per group and provide further supplementary information relating to the phasic activity patterns and magnitude of sEMG data from each muscle.

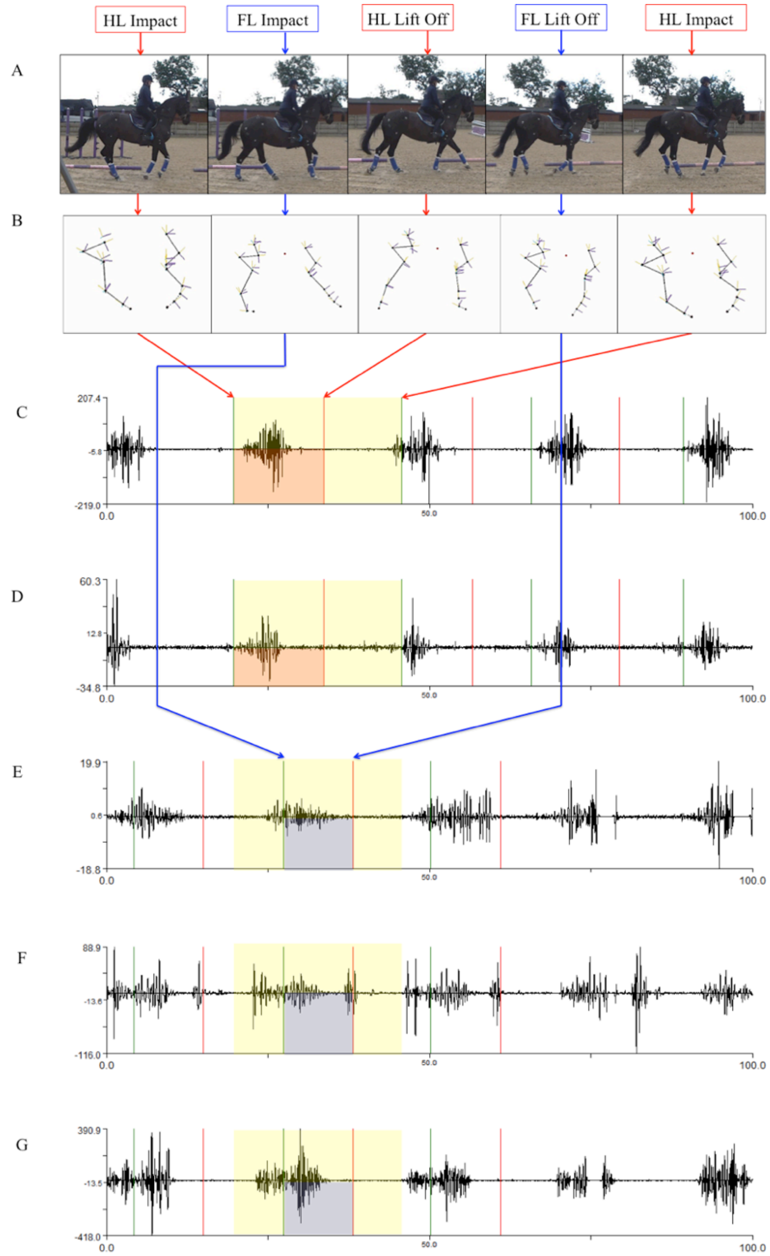


Figure 8.1 Phasic activity patterns of superficial muscles during canter. A) photographic representation of kinematic gait events from one elite horse. B) Screen shots of 3D kinematic model taken at each gait event. EMG activity (µV) from C) Biceps Femoris, D) Superficial Gluteal, E) Triceps Brachii, F) Trapezius, G) Splenius muscles during canter in one elite horse. Green and red vertical lines represent hoof on and hoof off events, respectively. Green and red vertical lines represent HL gait events in C and D, and FL gait events in E, F, G. Yellow shaded areas represent one canter stride, determined from consecutive HL hoof on events. Red and blue shaded areas represent HL and FL stance phase, respectively. sEMG signals are normalised to canter trial duration.

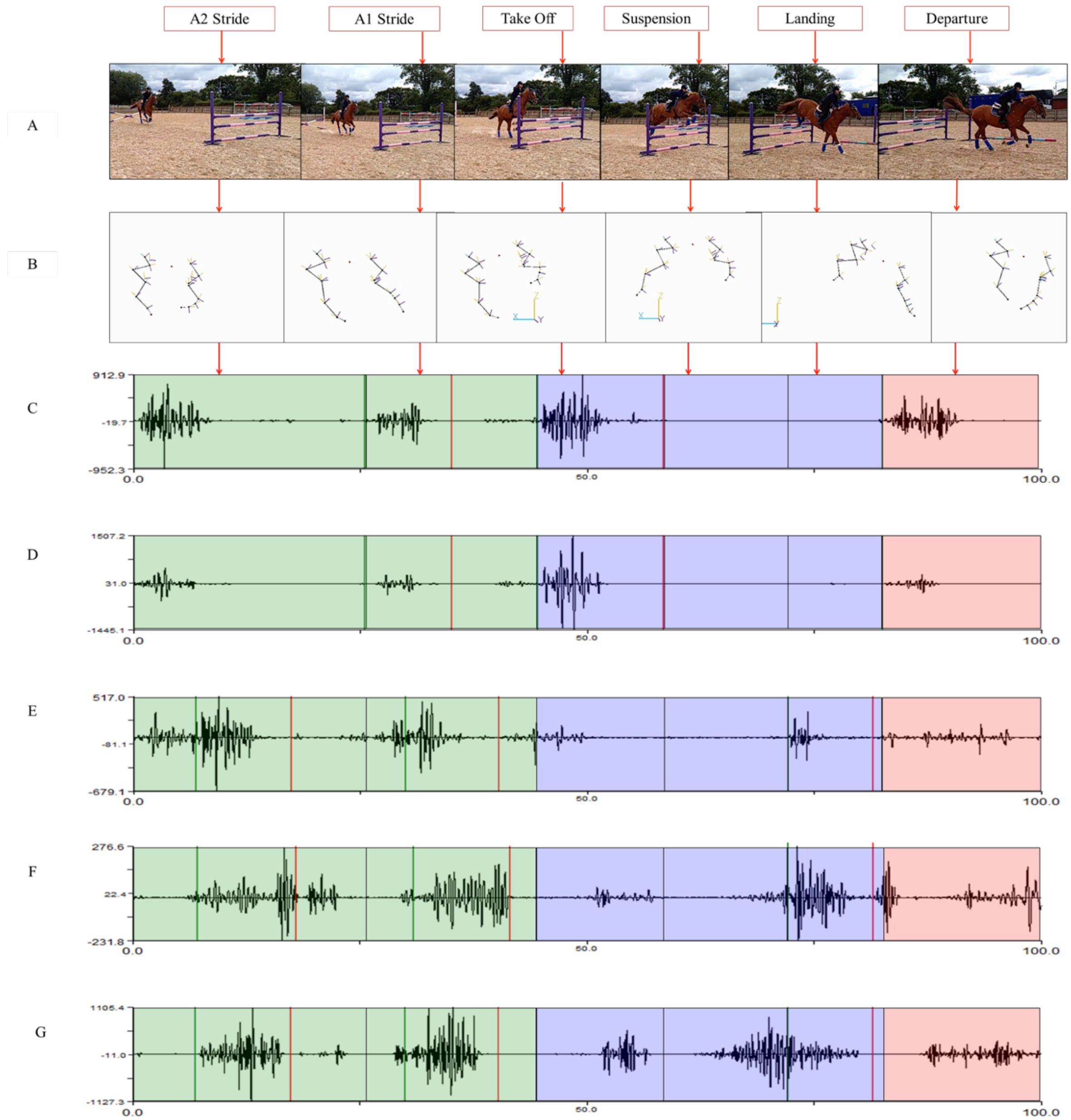


Figure 8.2 Phasic activity patterns of superficial muscles during jump over a 1.0 m vertical fence. A) photographic representation of kinematic gait events from one elite horse. B) Screen shots of 3D kinematic model taken at each gait event. EMG activity (µV) from C) Biceps Femoris, D) Superficial Gluteal, E) Triceps Brachii, F) Trapezius, G) Splenius muscles during jump in one NC horse. Green and red vertical lines represent hoof on and hoof off events, respectively. Green and red vertical lines represent HL gait events in C and D, and FL gait events in E, F, G. Green, blue and red shaded areas represent A1, jump and departure stride, respectively. sEMG signals are normalised to jump trial duration.

8.4.2 Biceps Femoris

8.4.2(i) Canter

Phasic activity patterns from Biceps Femoris for all groups during canter are presented in Figure 8.3. Visual examination of Biceps Femoris muscle activity revealed a consistent pattern between all groups. Activity began approximately at, or just prior to, HL hoof impact event. Biceps Femoris remained active for approximately 50-75% of stance, with inactivity occurring between middle and late stance phase. This pattern was consistent for LdH and TrH limbs (Figure 8.3). Biceps Femoris was generally inactive throughout swing phase, however, some horses displayed activity onset in late swing phase, just prior to HL hoof impact.

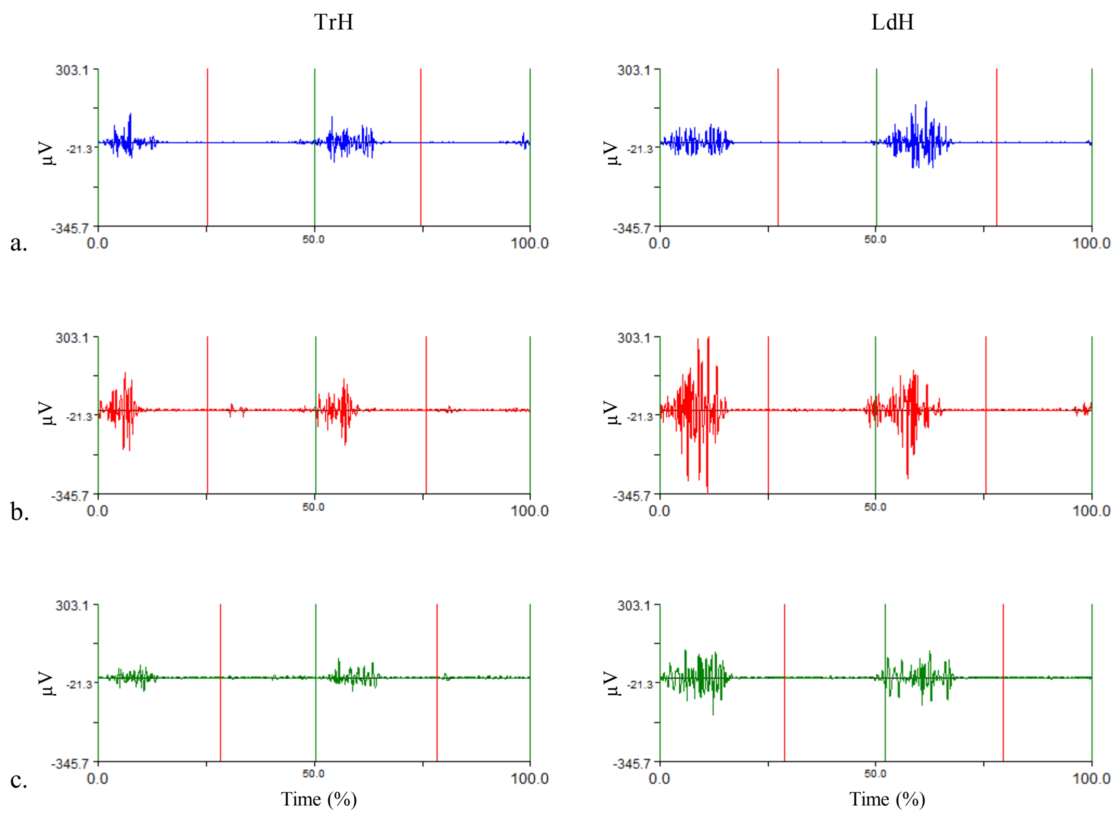


Figure 8.3 Representative sEMG signals from one horse per group for the Biceps Femoris muscle from LdH and TrH across two canter strides. Signals from one horse from each group are presented: a.) elite, b.) NC c.) school. Green and red vertical lines represent HL hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised across two canter strides.

Mean ±SD normalised data (%) for iEMG, ARV and PA during canter are presented in Table 8.4. ANOVA results showed a significant main effect for group $F_{(2,12)}$ =5.03, P<0.05, pn^2=0.46, and limb $F_{(1,12)}$ = 37.40, P<0.0001, pn^2=0.76 for normalised iEMG data. Significant main effects were also found for group $F_{(2,12)}$ =7.10, P<0.05, pn^2=0.54 and limb $F_{(1,12)}$ =35.97, P<0.0001, pn^2 =0.75 for normalised ARV data. Pairwise comparisons revealed that normalised iEMG and ARV values were significantly greater for LdH (P<0.001). iEMG and ARV in elite and school groups exhibited significantly greater (P<0.05) values than the NC group. Significant main effects for PA data were only found for limb $F_{(1,12)}$ =30.75, P<0.0001, pn^2=0.72. In accordance with iEMG and ARV, normalised PA values were also significantly greater (P<0.0001) for LdH. Statistically significant differences for normalized EMG data from Biceps Femoris during canter are illustrated in Table 8.4 and Figure 8.4.

Table 8.4 Mean (±SD) normalised values (%) from sEMG signal analysis for Biceps Femoris from LdH and TrH in each group during canter. *n* represents the number of subjects used to calculate mean (±SD) normalised values. Within a row, shaded cells represent within-subject significant differences (P<0.05) between LdH and TrH. Within a row, corresponding letters represent significant differences (P<0.05) between groups.

Variable	**Elite** *n=7*		**NC** *n=5*		**School** *n=3*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	a		a, b		b	
	60.52 (15.20)	80.13 (17.94)	38.18 (17.39)	71.09 (19.29)	61.96 (19.81)	83.40 (12.81)
ARV	a		a, b		b	
	60.73 (16.06)	81.82 (13.71)	39.10 (18.44)	71.37 (19.52)	63.87 (20.18)	84.70 (12.53)
PA	57.10 (17.54)	76.69 (15.27)	43.86 (22.67)	65.52 (22.49)	60.99 (23.11)	71.82 (17.17)

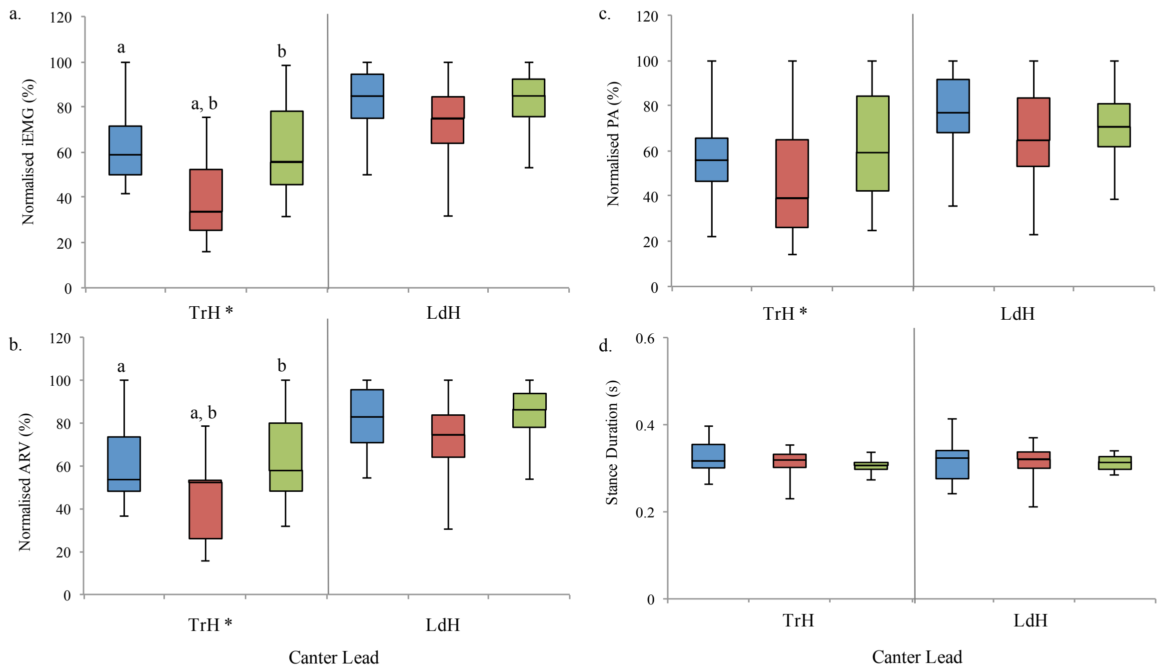


Figure 8.4 Normalised values from sEMG signal analysis for Biceps Femoris from LdH and TrH in each group during canter. Box and whisker plot, showing medians, 25% and 75% quartiles, and minimum and maximum values of a) normalised iEMG (%); b) normalised average rectified value (%); c) normalised peak amplitude (%); d) HL stance phase duration for each group during canter. Significant differences between groups (P<0.05) are represented by corresponding superscripts within the TrH portion of each graph. Significant differences between limb (P<0.0001) are represented by *.

8.4.2(ii) Jump

Phasic activity patterns for Biceps Femoris across all groups during A1 and jump strides are presented in Figure 8.5. Visual examination of EMG signals revealed a similar pattern between group and limb. Biceps Femoris exhibited a similar activity pattern to that observed during canter, with activity beginning at, or just prior to, HL hoof impact events. Muscle activity onset during late swing phase was more common for jump than for canter, and was frequently observed at take-off. Biceps Femoris generally remained active for the first half of stance duration. However, certain horses displayed prolonged activity, with the muscle remaining active for the majority of HL stance phase. This prolonged activity was observed in all groups, but primarily in the elite group during HL stance phase at take-off. Prolonged activity was also observed in some horses across all groups during HL stance at A1 and departure strides, however this was less common. Biceps Femoris was largely inactive during swing phase in A1 and during the jump suspension phase.

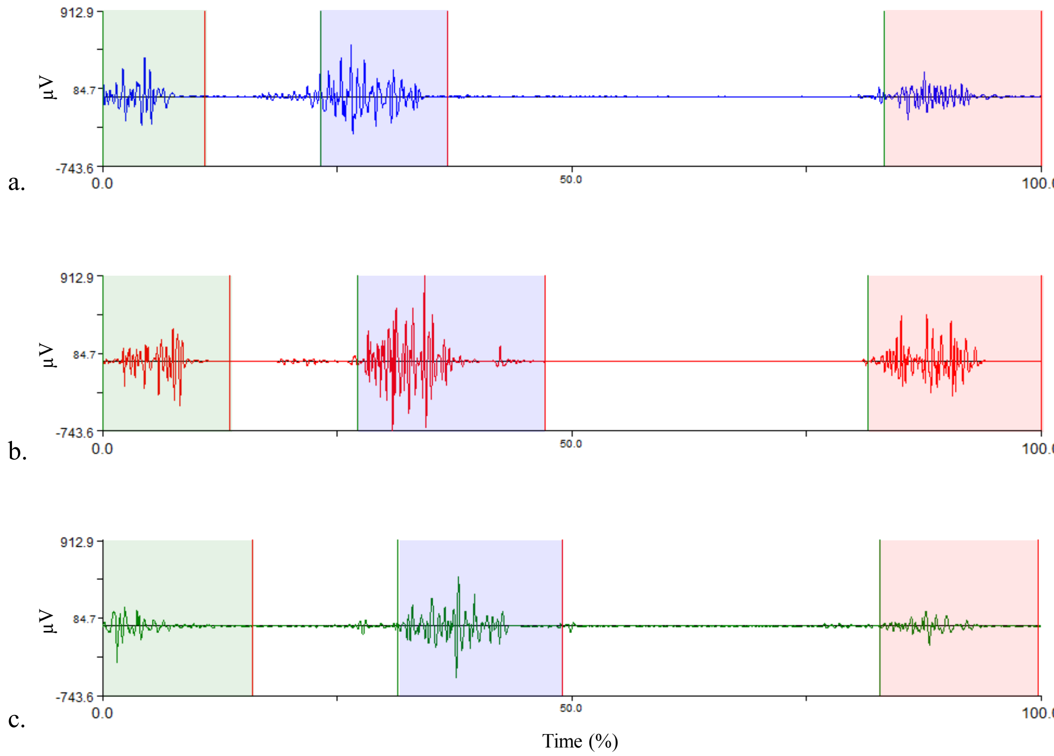


Figure 8.5 Representative sEMG signals from one horse per group for the Biceps Femoris muscle from TrH during approach (A1) and jump strides. Signals from one horse from each group are presented: a.) elite, b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

Mean ±SD normalised EMG data (%) for Biceps Femoris from A1, take-off and landing phases are presented separately in Tables 8.5, 8.6 and 8.7, respectively. No significant differences were found between group and limb for normalised EMG data from A1 stride (Table 8.5), which is interesting considering the significant differences ($P<0.0001$) found between limbs for canter. During A1, iEMG values were similar across groups. Although non-significant, the elite group exhibited the greatest mean normalised ARV and PA values during A1, with the school group consistently exhibiting the lowest.

Table 8.5 Mean (±SD) normalised values (%) from sEMG signal analysis for Biceps Femoris from LdH and TrH in each group during approach stride (A1). *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	Elite *n=5*		NC *n=4*		School *n=3*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	133.56 (24.33)	128.73 (47.67)	127.54 (44.03)	142.56 (34.75)	133.93 (6.05)	90.61 (31.45)
ARV	224.99 (59.23)	221.72 (81.90)	198.16 (50.86)	169.67 (68.15)	155.31 (50.88)	98.69 (21.53)
PA	166.55 (54.53)	153.64 (71.02)	128.80 (43.89)	138.17 (65.24)	110.01 (29.70)	99.94 (4.38)

No significant differences between group and limb were found for normalised EMG data during take-off phase (Table 8.6). Although non-significant, the elite group exhibited the greatest mean normalised iEMG, ARV and PA values, with the school group consistently exhibiting the lowest. Within each group, mean normalised values were very similar between limbs.

Table 8.6 Mean (±SD) normalised values (%) from sEMG signal analysis for Biceps Femoris from TrH and LdH in each group during take-off phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	Elite *n=7*		NC *n=4*		School *n=3*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	314.84 (80.04)	332.06 (93.87)	244.10 (83.02)	299.07 (92.41)	227.01 (86.16)	216.80 (163.30)
ARV	429.75 (113.53)	462.34 (107.75)	330.36 (88.46)	312.67 (172.46)	272.31 (118.66)	245.11 (114.88)
PA	313.88 (108.44)	351.62 (115.21)	236.56 (59.20)	204.87 (99.45)	183.44 (87.69)	179.60 (91.49)

Results for normalised ARV during landing phase revealed a significant main effect for group $F_{(2,5)} = 7.78$, $P<0.05$, $pn^2=0.76$. Pairwise comparisons showed that ARV values for the elite group were significantly greater ($P<0.05$) than the school group. Figure 8.6 and Table 8.7 illustrate statistically significant differences for ARV landing phase data. No significant differences between group and limb were found for normalised iEMG and PA data during landing.

Table 8.7 Mean (±SD) normalised values (%) from sEMG signal analysis for Biceps Femoris from LdH and TrH in each group during landing phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values. Within a row, corresponding letters represent significant differences (P<0.05) between groups.

Variable	Elite *n=5*		NC *n=3*		School *n=3*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	218.42 (185.69)	179.73 (61.94)	144.09 (42.25)	140.18 (30.24)	148.00 (74.26)	145.40 (102.28)
ARV	a				a	
	293.48 (255.41)	248.40 (94.67)	193.73 (36.16)	183.02 (72.57)	210.82 (101.97)	113.48 (21.48)
PA	184.14 (121.69)	176.99 (59.98)	176.11 (87.06)	142.74 (60.81)	200.97 (114.46)	109.25 (19.12)

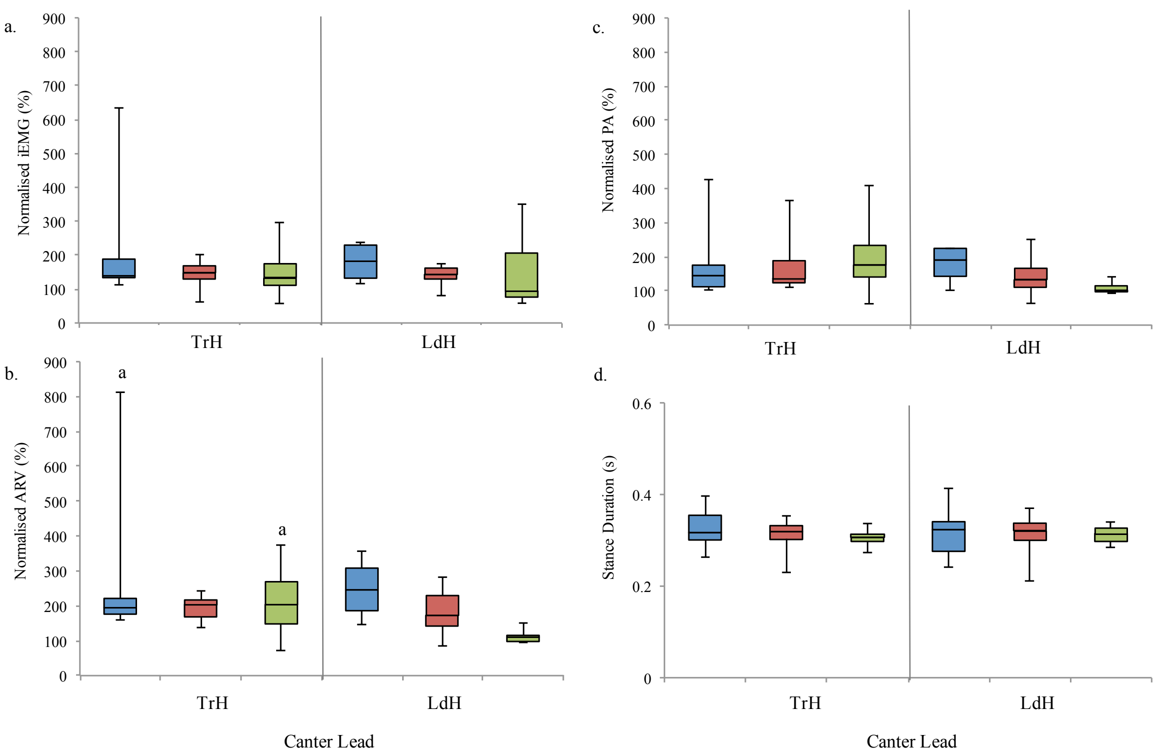


Figure 8.6 Normalised values from sEMG signal analysis for Biceps Femoris from LdH and TrH in each group during landing phase. Box and whisker plot, showing medians, 25% and 75% quartiles, and minimum and maximum values of a) normalised iEMG (%); b) normalised average rectified value (%); c) normalised peak amplitude (%); d) HL stance phase duration for each group during landing. Significant differences between groups (P<0.05) are represented by corresponding superscripts within the TrH portion of each graph.

8.4.3 Superficial Gluteal

8.4.3(i) Canter

Phasic activity patterns for Superficial Gluteal across all groups during canter are presented in Figure 8.7. Visual examination of EMG signals showed that activity onset occurred during late swing phase, generally reaching peak activity during the first half of stance phase. Activity generally ceased at, or just prior to, middle stance phase. The Superficial Gluteal was inactive for the latter 50% of stance phase and for the majority of swing phase. This activity pattern was consistent across group and limb. Within a stride, two bursts of activity were observed in the majority of horses, with the first occurring during late swing and the second at early to middle stance. The second peak generally exhibited the greatest amplitude.

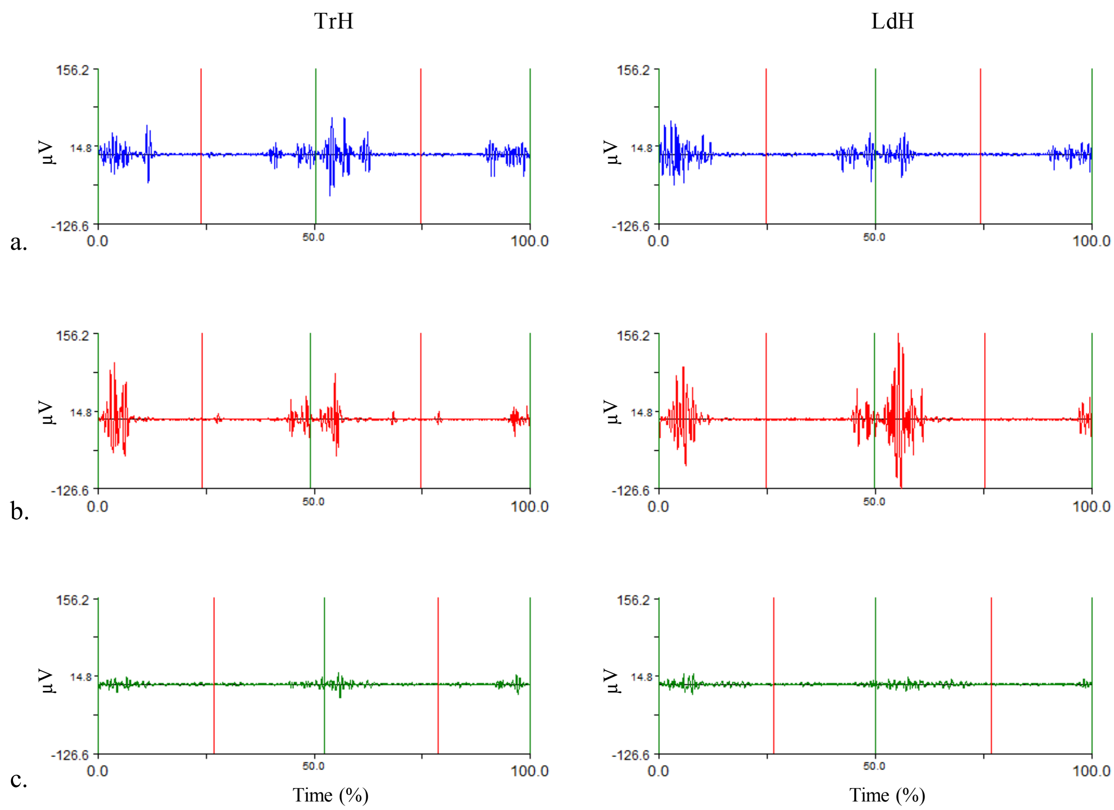


Figure 8.7 Representative sEMG signals from one horse per group for the Superficial Gluteal muscle from LdH and TrH across two canter strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised across two canter strides.

Mean ±SD normalised (%) iEMG, ARV and PA data from Superficial Gluteal during canter are presented in Table 8.8. No significant differences were found between limb and group for normalised EMG values. Although non-significant, EMG values for TrH were consistently greater than LdH in the elite group, but were consistently lower than LdH in the school group. Interestingly, mean normalised values for TrH and LdH were similar in the NC group.

Table 8.8 Mean (±SD) normalised values (%) from sEMG signal analysis for Superficial Gluteal from LdH and Trh in each group during canter. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=7*		**NC** *n=7*		**School** *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	73.34 (20.86)	54.86 (23.91)	70.68 (17.68)	65.28 (16.00)	63.98 (26.01)	75.95 (21.70)
ARV	73.74 (20.16)	58.65 (22.25)	69.32 (18.71)	62.92 (16.09)	66.36 (26.29)	75.85 (21.53)
Peak	66.36 (21.37)	55.74 (24.63)	56.77 (17.88)	57.73 (21.09)	67.77 (29.90)	70.75 (22.45)

8.4.3(ii) Jump

Superficial Gluteal EMG signals from the jump condition are presented in Figure 8.8. Visual examination of EMG signals during jump revealed a similar phasic activity pattern to canter, with activity onset occurring at late swing phase. Prolonged muscle activity was observed in A1, take-off and landing phases, but was most common during take-off. It was not uncommon for Superficial Gluteal activity to last for the majority of HL stance phase at take-off, especially in elite and NC groups. Muscle activity ceased between middle to late HL stance phase and remained inactive for the majority jump suspension. This pattern was similar across group and limb. The distinct double burst of muscle activity observed during canter was rarely observed during jump and muscle activity displayed a more continuous increase in amplitude.

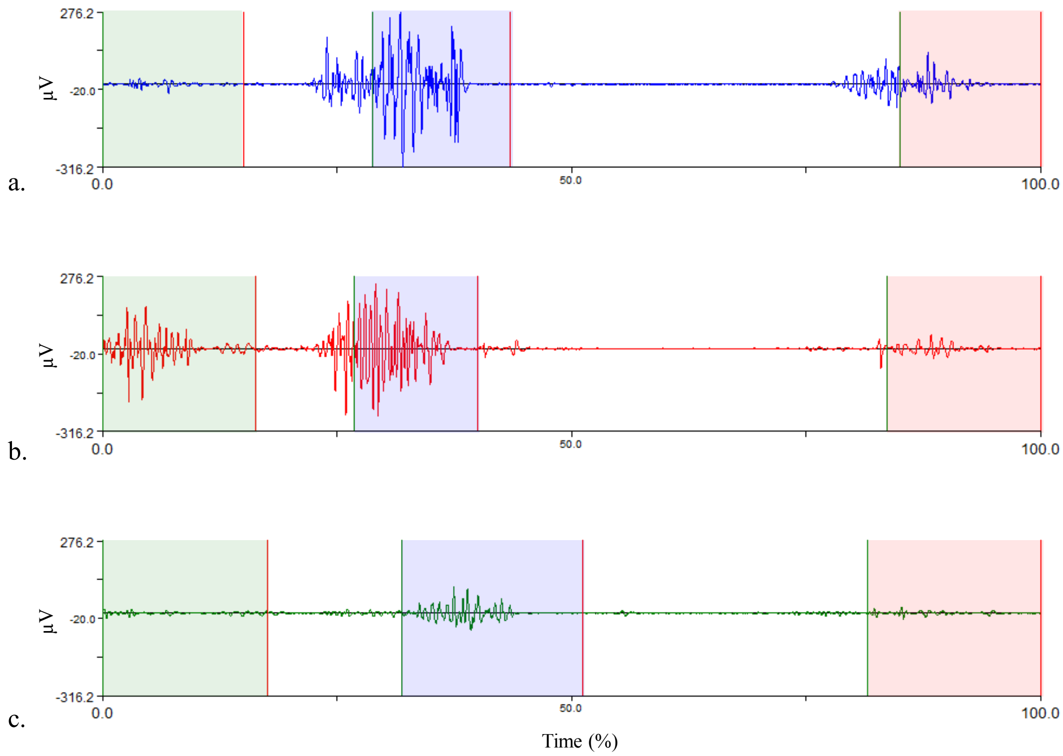


Figure 8.8 Representative sEMG signals from one horse per group for the Superficial Gluteal muscle from TrH during A1 jump and departure strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

Mean ±SD normalised EMG data (%) for Superficial Gluteal from A1, take-off and landing phases are presented separately in Tables 8.9, 8.10 and 8.11, respectively. A significant main effect was found for group $F_{(2,4)}$ =7.36, P<0.05, pn^2=0.79 for normalised iEMG data during A1 stride. Pairwise comparisons showed normalised iEMG values from the NC group were significantly greater (P<0.05) than elite and school groups. Figure 8.9 and Table 8.9 illustrate statistically significant differences for iEMG data during A1 stride. Significant differences between limb and group were not found for normalised ARV and PA values during A1.

Table 8.9 Mean (±SD) normalised values (%) from sEMG signal analysis for Superficial Gluteal from LdH and TrH in each group during A1 stride. *n* represents the number of subjects used to calculate mean (±SD) normalised values. Within a row, corresponding letters represent significant differences (P<0.05) between groups.

Variable	**Elite** *n=5*		**NC** *n=3*		**School** *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	a		a, b		b	
	96.50 (50.31)	117.97 (50.51)	249.61 (65.34)	202.55 (69.62)	97.28 (12.75)	62.98 (19.96)
ARV	149.60 (62.56)	185.73 (56.70)	310.97 (92.91)	281.19 (110.66)	123.77 (14.65)	86.79 (29.57)
PA	77.85 (26.03)	110.38 (25.53)	175.42 (71.16)	151.68 (52.76)	115.65 (47.24)	64.16 (25.45)

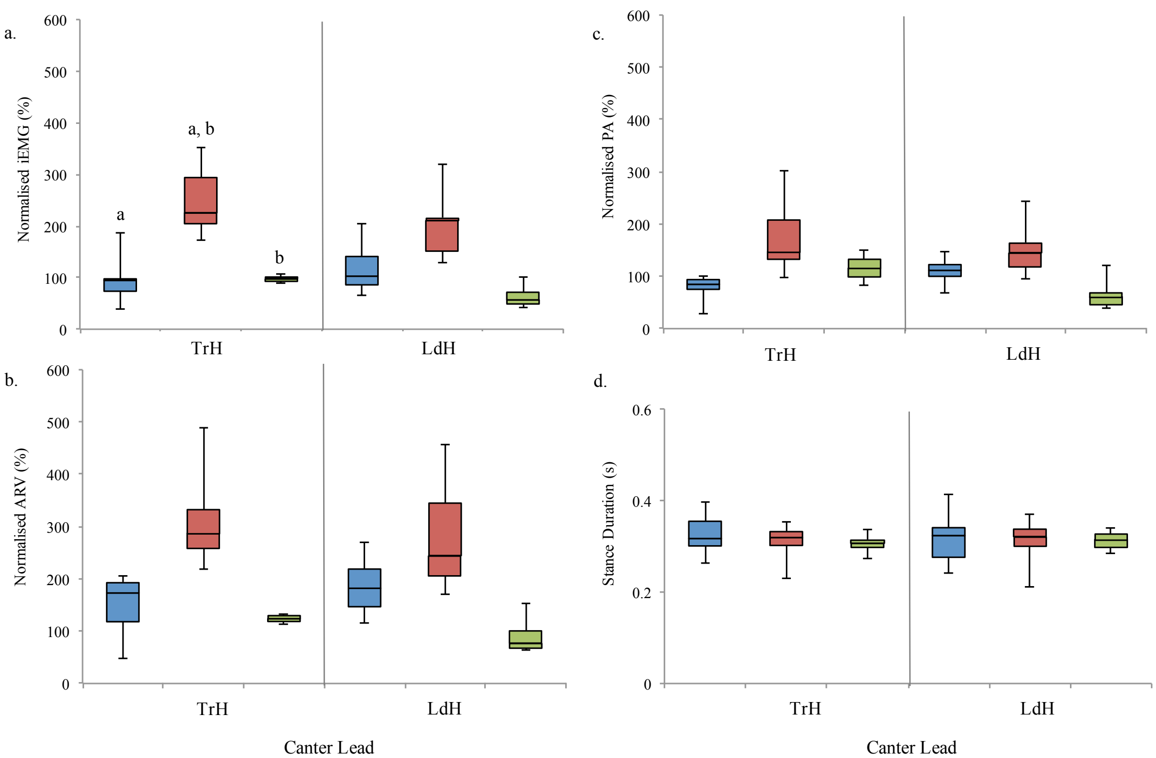


Figure 8.9 Normalised values from sEMG signal analysis for Superficial Gluteal from LdH and TrH in each group during A1 stride. Box and whisker plot, showing medians, 25% and 75% quartiles, and minimum and maximum values of a) normalised iEMG (%); b) normalised average rectified value (%); c) normalised peak amplitude (%); d) HL stance phase duration for each group during A1 stride. Significant differences between groups (P<0.05) are represented by corresponding superscripts on the left lead portion of each graph.

Mean ±SD normalised EMG data (%) for Superficial Gluteal from take-off phase are presented in Table 8.10. A significant main effect for group was found for normalised: iEMG $F_{(2,9)}$ =9.97, P<0.05, pn^2= 0.69, ARV $F_{(2,9)}$ =12.50, P<0.05, pn^2=0.74, and PA $F_{(2,9)}$ =4.83, P<0.02, pn^2=0.52 data during take-off. Pairwise comparisons showed that normalised iEMG and ARV values for the NC group were significantly greater (P<0.05) than elite and school groups. Normalised ARV values for the elite group were also significantly greater (P<0.05) than the school group. The NC group exhibited significantly greater (P<0.05) normalised PA values than the school group. Figure 8.9 and Table 8.10 illustrate statistically significant differences between normalised EMG data for the Superficial Gluteal during take-off. No significant differences were found between limb and group for normalised EMG data from the Superficial Gluteal during landing phase (Table 8.11). Although non-significant, EMG values for the TrH at landing were consistently higher than LdH, but values for both limbs were remarkably similar for NC and school groups.

Table 8.10 Mean (±SD) normalised values (%) from sEMG signal analysis for Superficial Gluteal from LdH and TrH in each group during take-off phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values. Within a row, corresponding letters represent significant differences (P<0.05) between groups.

Variable	**Elite** *n=6*		**NC** *n=3*		**School** *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	a		a, b		b	
	513.31 (242.91)	450.71 (178.33)	867.36 (342.13)	701.31 (255.57)	173.61 (111.38)	154.05 (178.69)
ARV	a, b		a, c		b, c	
	665.53 (235.78)	629.12 (152.00)	1034.53 (431.95)	910.39 (420.59)	208.36 (127.83)	173.92 (153.13)
PA			a		a	
	423.37 (264.14)	368.18 (79.93)	605.92 (190.05)	440.06 (86.38)	215.44 (157.54)	211.93 (199.54)

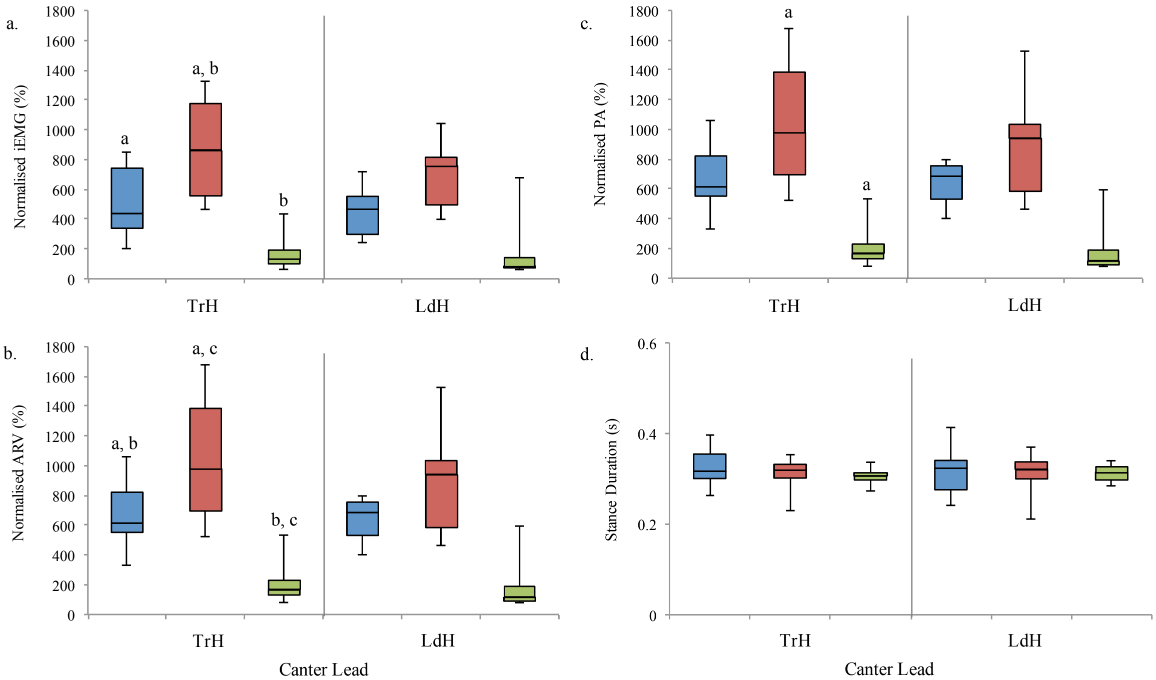


Figure 8.10 Normalised values from sEMG signal analysis for Superficial Gluteal from TrH and LdH in each group during take-off phase. Box and whisker plot, showing medians, 25% and 75% quartiles, and minimum and maximum values of a) normalised iEMG (%); b) normalised average rectified value (%); c) normalised peak amplitude (%); d) HL stance phase duration for each group during take-off. Significant differences between groups (P<0.05) are represented by corresponding superscripts on the left lead portion of each graph.

Table 8.11 Mean (±SD) normalised values (%) from sEMG signal analysis for Superficial Gluteal from LdH and TrH in each group during landing phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=5*		**NC** *n=2*		**School** *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
iEMG	168.00 (147.14)	87.86 (19.89)	88.85 (22.65)	92.68 (71.07)	113.99 (36.88)	111.23 (42.62)
ARV	221.83 (162.38)	126.66 (29.96)	101.21 (26.51)	99.71 (60.22)	142.23 (46.99)	138.99 (48.53)
PA	209.91 (261.59)	89.63 (16.47)	67.57 (20.19)	88.67 (83.59)	141.75 (73.57)	147.88 (72.62)

8.4.4 Triceps Brachii

8.4.4(i) Canter

Typical EMG signals from Triceps Brachii are presented for all groups during canter in Figure 8.11. Visual examination of EMG signals revealed that the muscle became active between middle and late swing phase, continuing into FL stance phase. The timing of muscle onset within swing phase varied between horses, with the majority showing activity around mid-swing and some during late-swing, closer to the hoof impact event. When the muscle was active, two distinct bursts of activity were observed in the majority of horses. The first burst occurred during late swing and the second occurred during early stance phase, with the second burst generally exhibiting the greatest amplitude. However, in some horses the first peak exhibited the greatest amplitude. Interestingly, elite horses were less likely to display obvious peaks and instead exhibited a more gradual rise in amplitude before reaching peak in early stance phase. Inactivity of the Triceps Brachii was observed during late stance and early swing phase. Phasic activity patterns were similar for TrF and LdF.

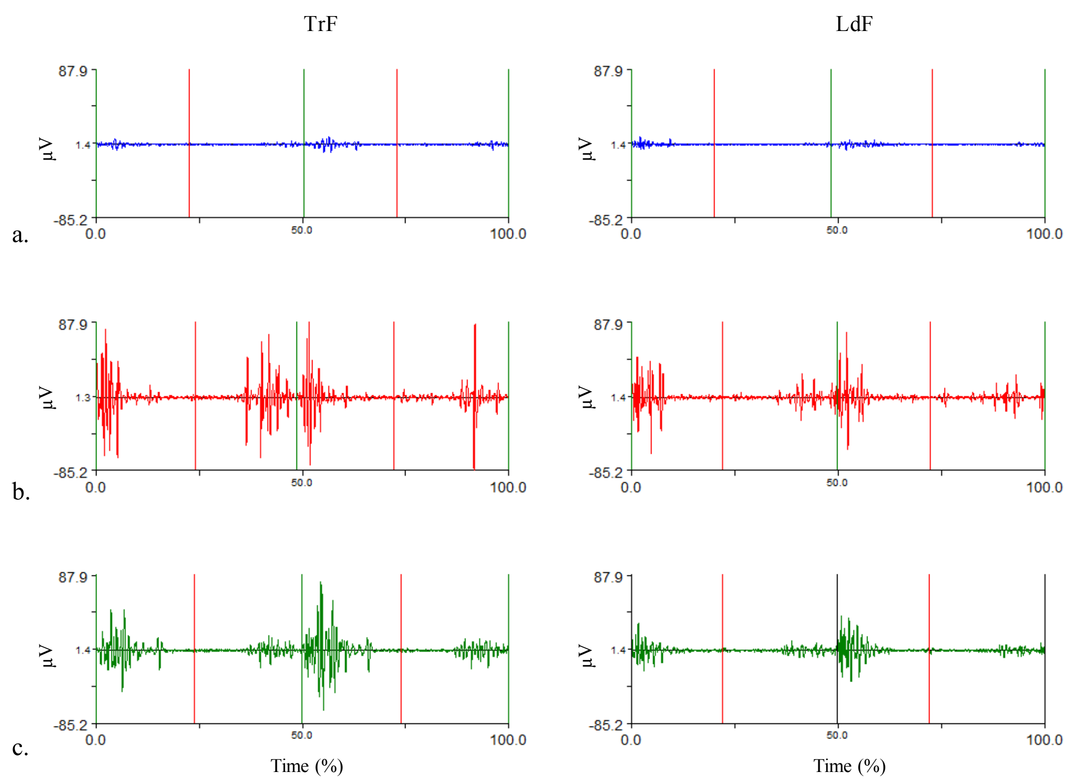


Figure 8.11 Representative sEMG signals from one horse per group for the Triceps Brachii from LdF and TrF across two canter strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80 Hz. EMG activity are presented in µV and graphs are normalised across two canter strides.

Mean ±SD normalised EMG data (%) from Triceps Brachii during canter are presented in Table 8.12. No significant differences were found between group and limb for normalised EMG variables during canter. Average iEMG, ARV and PA values were fairly similar both between and within groups.

Table 8.12 Mean (±SD) normalised values (%) from sEMG signal analysis for Triceps Brachii from LdF and TrF in each group during canter. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	Elite *n=7*		NC *n=7*		School *n=5*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	76.57 (20.60)	63.91 (19.99)	61.56 (18.51)	66.35 (18.06)	74.75 (15.99)	67.28 (21.53)
ARV	70.90 (20.33)	63.57 (18.13)	56.99 (18.88)	64.94 (18.08)	71.49 (16.51)	68.81 (20.32)
Peak	53.73 (27.37)	49.89 (22.43)	51.02 (18.84)	55.35 (24.55)	63.66 (22.22)	57.66 (23.28)

8.4.4(ii) Jump

EMG signals from the Triceps Brachii across all groups during jump are presented in Figure 8.12. During jump, the Triceps Brachii displayed a similar phasic activity pattern to canter, with activity beginning between middle and late swing. The majority of horses exhibited prolonged muscle activity during FL stance phase at A1 and take-off, with inactivity occurring at middle or late stance phase, depending on the horse. The majority of subjects displayed a burst of activity following FL hoof off event at take-off, however in some horses this burst occurred during middle to late jump suspension. The amplitude and duration of this burst varied, however elite horses frequently displayed high amplitudes. The phasic activity pattern of was similar for TrF and LdF.

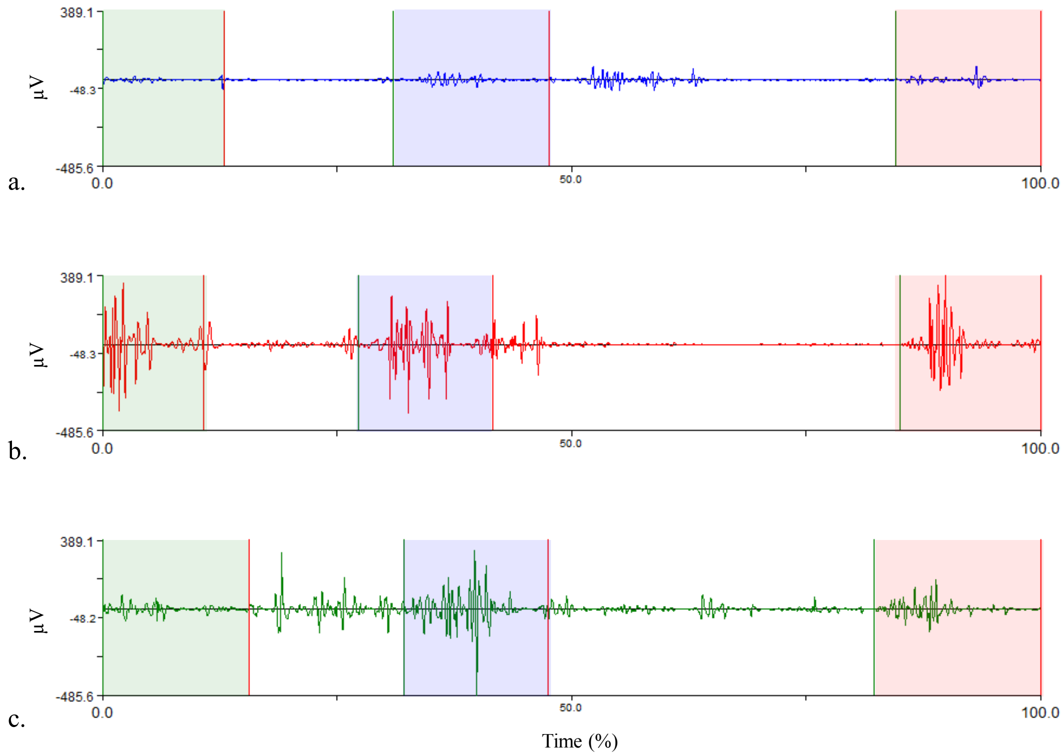


Figure 8.12 Representative sEMG signals from one horse per group for the Triceps Brachii muscle from LdF during A1, jump and departure strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent fore stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

Mean ±SD normalised EMG data (%) for Triceps Brachii during A1, take-off and landing phases are presented separately in Tables 8.13, 8.14 and 8.15, respectively. No significant differences were found between group and limb for normalised EMG variables from all jump phases. Insufficient data from the school group were available for A1 and statistical analysis using ANOVA could not be conducted, as the group variable only had one level. Therefore an examination of differences between group and the interaction could not be explored for A1. Data from the school group during A1 are presented in Table 8.13, however conclusions cannot be drawn from this data. Although non-significant, the elite group exhibited lower iEMG values that the NC group during A1, with the NC group exhibiting greater SD values indicating greater variability. Mean and SD values for normalised ARV and PA during A1 were very similar between elite and NC groups and between limbs, except for PA values from LdH in the elite group.

Table 8.13 Mean (±SD) normalised values (%) from sEMG signal analysis for Triceps Brachii from LdF and TrF in each group during A1. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=4*		**NC** *n=4*		**School** *n=1*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	239.65 (58.53)	256.43 (112.63)	443.88 (300.28)	300.60 (231.50)		98.36
ARV	453.90 (144.57)	447.46 (212.69)	496.27 (281.89)	449.42 (393.46)		128.75
PA	276.90 (138.06)	531.09 (602.97)	312.43 (163.33)	269.04 (214.37)		75.11

Although non-significant, the school group consistently exhibited lower mean and SD normalised EMG values than elite and NC groups during take-off (Table 8.14) and landing (Table 8.15). The LdF consistently showed greater mean normalised EMG values at take off in all groups, with the exception of mean iEMG for the school group. During take-off, elite and NC groups showed similar mean normalised EMG values, with the elite group generally exhibiting slightly higher values than NC. During landing, mean normalised EMG values for elite and NC groups were greater than elite and school groups, but this was not significant.

Table 8.14 Mean (±SD) normalised values (%) from sEMG signal analysis for Triceps Brachii from LdF and TrF in each group during take-off phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=6*		**NC** *n=5*		**School** *n=3*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	412.30 (271.70)	485.89 (277.82)	325.23 (303.24)	387.68 (229.15)	140.28 (45.78)	136.86 (110.31)
ARV	542.24 (342.26)	554.27 (313.98)	264.82 (278.25)	601.63 (293.49)	129.89 (58.97)	233.61 (155.59)
PA	396.50 (311.01)	474.52 (451.80)	263.17 (249.39)	477.82 (258.73)	88.29 (39.48)	179.05 (117.13)

Table 8.15 Mean (±SD) normalised values (%) from sEMG signal analysis for Triceps Brachii from LdF and TrF in each group during landing phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=4*		**NC** *n=5*		**School** *n=3*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	263.51 (141.96)	304.76 (139.71)	383.37 (281.37)	523.14 (281.85)	116.43 (49.70)	162.99 (82.12)
ARV	275.86 (130.89)	269.28 (109.84)	497.38 (292.28)	509.53 (417.91)	199.42 (81.39)	123.15 (87.01)
PA	226.55 (150.00)	184.30 (104.33)	416.84 (277.36)	544.02 (304.29)	172.96 (99.79)	135.38 (21.54)

8.4.5 Trapezius

8.4.5(i) Canter

Visual examination of EMG signals from the Trapezius revealed two different phasic activity patterns for TrF and LdF, which are illustrated in Figure 8.13. In the TrF, the muscle became active after hoof impact at early to middle stance phase. Two bursts of muscle activity were present during stance and early swing, with the second burst occurring around late stance and continuing into early swing where activity ceased. In the LdF, Trapezius activity began during late swing phase. Two bursts of muscle activity were also present in the LdF, with the second burst occurring middle to late stance, but generally ceasing activity prior to hoof lift off. For both limbs, the second burst of activity generally exhibited the greatest amplitude. The two bursts of activity were less distinct in certain horses, as seen in Figure 8.13a for TrF in the elite subject. Although different phasic activity patterns were observed between limbs, statistical tests on normalised EMG data revealed no significant main effect for group or limb. Mean ± SD values for normalised EMG variables from the Trapezius during canter were very similar across groups and limbs and are presented in Table 8.16. Although non-significant, the TrF consistently exhibited greater mean normalised values for elite and NC groups, but values were very similar between limbs in the school group.

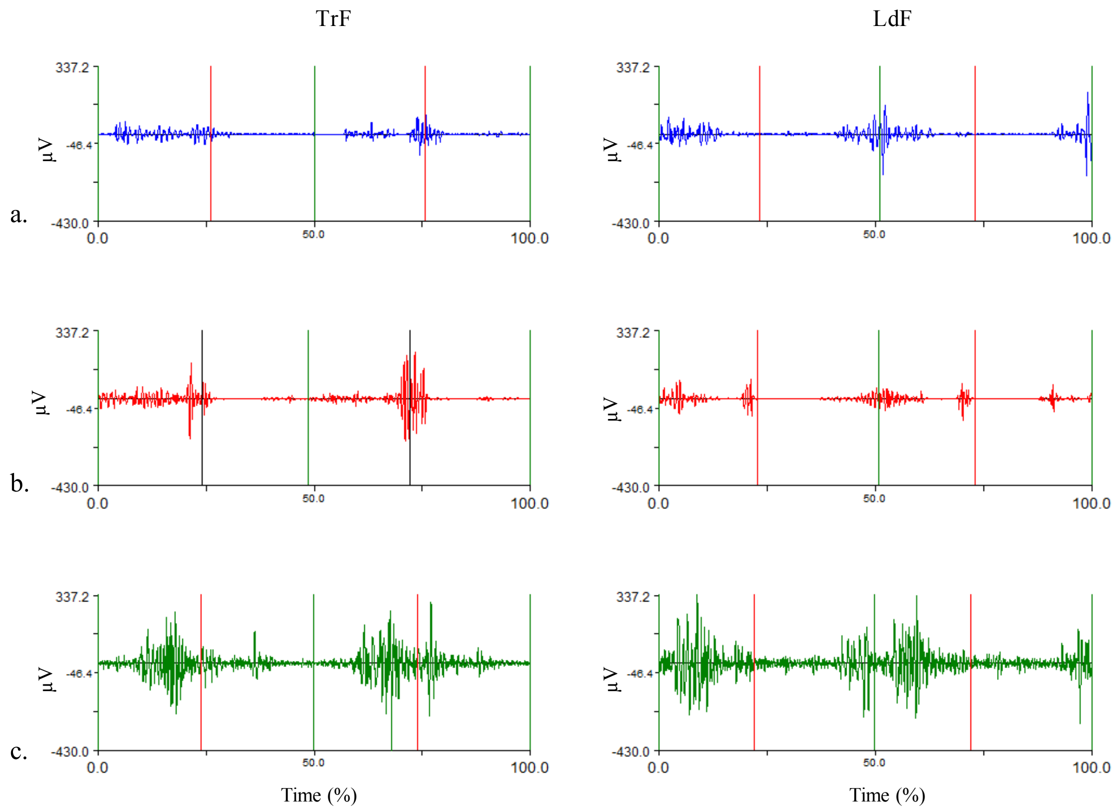


Figure 8.13 Representative sEMG signals from one horse per group for the Trapezius muscle from LdF and TrF across two canter strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised across two canter strides. Note: RHOFF events for b) left lead are presented as black vertical lines for visibility.

Table 8.16 Mean (±SD) normalised values (%) from sEMG signal analysis for Trapezius from TrF and LdF in each group during canter. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=4*		**NC** *n=6*		**School** *n=5*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	92.47 (15.35)	61.93 (28.06)	69.73 (20.66)	53.25 (20.46)	66.35 (17.05)	69.66 (22.61)
ARV	85.56 (14.07)	60.52 (31.81)	69.59 (20.80)	58.00 (21.15)	62.73 (16.57)	70.34 (22.35)
Peak	70.90 (22.04)	59.64 (23.72)	67.43 (23.04)	44.07 (22.79)	62.75 (23.28)	63.57 (23.67)

8.4.5(ii) Jump

The Trapezius muscle proved to be the most difficult muscle to collect EMG data from during jump, especially in the school group. As a result, limited data were deemed suitable during the traffic light accept/reject criteria for magnitude analysis (Section 7.3.1(ii)). In order to provide the best representation of typical Trapezius signals during jump, the A1 stride is not included in Figure 8.14, as data from this stride were particularly limited.

During jump, the Trapezius muscle displayed a similar phasic pattern to canter, however differences between limbs were less consistent. At take-off and landing phases, muscle activity began during early to middle stance phase. Some horses exhibited muscle activity onset just prior to FL hoof on at take-off and landing, which generally occurred in the LdF, but was occasionally observed in TrF. The two bursts of activity observed for canter also occurred during jump. Double activity bursts were most frequently observed during landing (Figure 8.14b) and were less common during take-off. At take-off, muscle activity generally ceased during middle to late stance, and occasionally during early jump suspension (Figure 8.14c). The muscle was fairly inactive during jump suspension. However, similar to the Triceps Brachii, the majority of subjects displayed a burst of activity following FL hoof off at take-off. The amplitude and duration of this burst varied and occurred between early and mid-jump suspension.

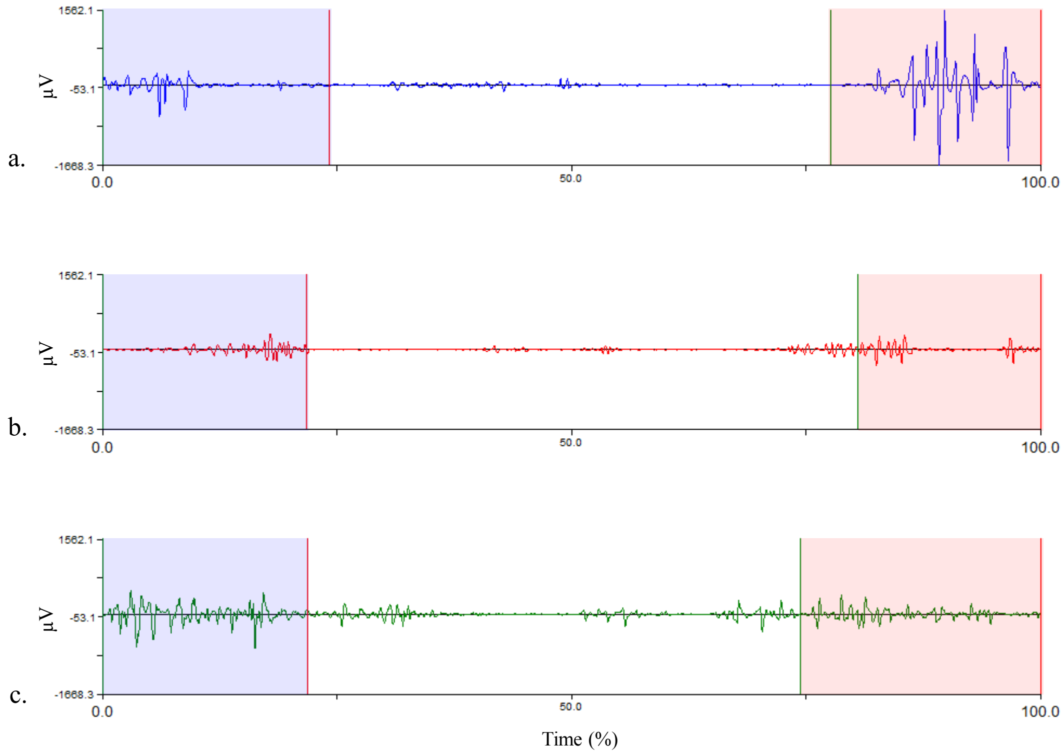


Figure 8.14 Representative sEMG signals from one horse per group for the Trapezius muscle from LdF during the stride. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent fore stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised between hoof impact event at take-off and hoof off event at landing.

Mean ± SD normalised EMG values for Trapezius during A1, take-off and landing are presented in Tables 8.17, 8.18 and 8.19, respectively. Insufficient data were available for A1 in elite and school groups and statistical analysis using ANOVA could not be conducted, as the group variable only had one level. Therefore an examination of differences between group and the interaction could not be explored for A1. However, no significant differences between limbs were found for normalised EMG data during A1. Significant main effects were not found for normalised EMG data from take-off (Table 8.18) or landing (Table 8.19) phases. During take-off, the elite group consistently exhibited the lowest mean and SD values for all normalised EMG variables, which the school group consistently exhibiting the highest. Limited data were available from the elite group during landing, however mean and SD values were fairly similar between group and limb.

Table 8.17 Mean (±SD) normalised values (%) from sEMG signal analysis for Trapezius from LdF and TrF in each group during A1 stride. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=2*		**NC** *n=4*		**School** *n=1*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG		92.42 (28.74)	150.56 (43.58)	134.99 (53.63)		115.70
ARV		148.23 (42.80)	189.37 (87.73)	210.74 (105.38)		189.21
PA		115.52 (18.61)	186.91 (103.62)	190.11 (76.09)		157.40

Table 8.18 Mean (±SD) normalised values (%) from sEMG signal analysis for Trapezius from LdF and TrF in each group during take-off phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=3*		**NC** *n=6*		**School** *n=2*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	138.05 (53.82)	181.11 (58.92)	193.95 (80.73)	171.19 (89.85)	260.61 (216.85)	227.85 (94.41)
ARV	163.17 (74.45)	211.70 (82.27)	244.65 (79.30)	232.13 (140.43)	277.94 (236.82)	261.30 (115.10)
PA	76.32 (2.26)	168.21 (57.62)	229.68 (222.92)	180.97 (114.55)	276.48 (278.25)	241.83 (172.35)

Table 8.19 Mean (±SD) normalised values (%) from sEMG signal analysis for Trapezius from LdF and TrF in each group during landing phase. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=1*		**NC** *n=5*		**School** *n=2*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	200.00	210 (127.28)	94.72 (49.05)	194.15 (91.75)	176.20 (142.65)	161.23 (110.68)
ARV	305.26	197.37 (107.93)	114.83 (52.86)	242.73 (114.02)	191.65 (157.06)	187.38 (135.51)
PA	167.03	150.55 (43.51)	130.14 (94.34)	178.73 (54.25)	197.39 (170.02)	171.98 (138.53)

8.4.6 Splenius

8.4.6(i) Canter

Typical EMG signals from Splenius are presented for all groups during canter in Figure 8.15. Visual examination of EMG signals revealed a similar phasic pattern to the Trapezius. In the TrF Splenius activity began in early to middle stance phase and ceased during early swing phase, where it was inactive until the next stance phase. In the LdF, activity onset occurred in middle to late swing and ceased during middle to late stance phase. Similar to the Trapezius and Triceps Brachii muscles, two activity bursts were often observed in one stride. The double activity burst pattern was most frequently observed in the LdF, where the first burst occurred during late swing and the second during early stance. In the TrF, the first burst occurred during middle stance and the second between late stance and early swing (Figure 8.15a, b).

Statistical tests for normalised iEMG values from the Splenius revealed a significant main effect for limb $F_{(1,11)}$ =7.62, $P<0.05$), pn^2=0.41. Pairwise comparisons showed that normalised iEMG values for the TrF were significantly greater ($P<0.05$) than the LdF and are illustrated in Figure 8.16. Normalised EMG values for Splenius during canter are presented in Table 8.20. Significant differences between limbs were not found for normalised ARV and PA values; however the TrF was consistently higher for elite and NC groups, with the school group exhibiting remarkably similar normalised ARV and PA values for both limbs. Mean and SD values for normalised EMG data were remarkably similar across groups.

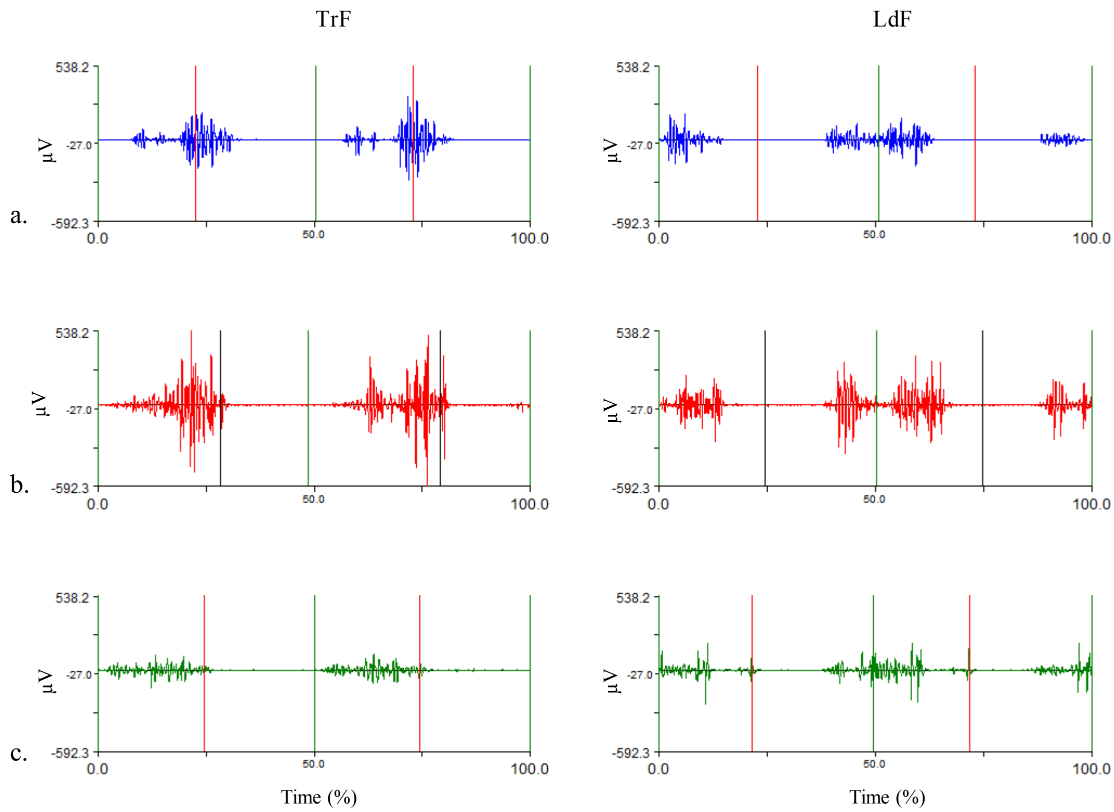


Figure 8.15 Representative sEMG signals from one horse per group for the Splenius muscle from LdF and TrF across two canter strides. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised across two canter strides. Note: RHOFF events for b) are presented as black vertical lines for visibility.

Table 8.20 Mean (±SD) normalised values (%) from sEMG signal analysis for Splenius from LdF and TrF in each group during canter. Within a row, shaded cells represent within-subject significant ($P<0.05$) differences between LdF and TrF. *n* represents the number of subjects used to calculate mean (±SD) normalised values.

Variable	**Elite** *n=7*		**NC** *n=7*		**School** *n=5*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	77.47 (17.98)	57.88 (19.75)	69.65 (16.41)	43.56 (19.03)	76.93 (16.12)	74.35 (20.76)
ARV	75.38 (17.70)	58.91 (20.39)	68.49 (16.73)	46.41 (19.61)	72.71 (16.33)	74.10 (21.36)
Peak	73.05 (18.86)	60.13 (21.77)	72.51 (19.44)	56.30 (21.16)	60.36 (21.84)	63.85 (27.35)

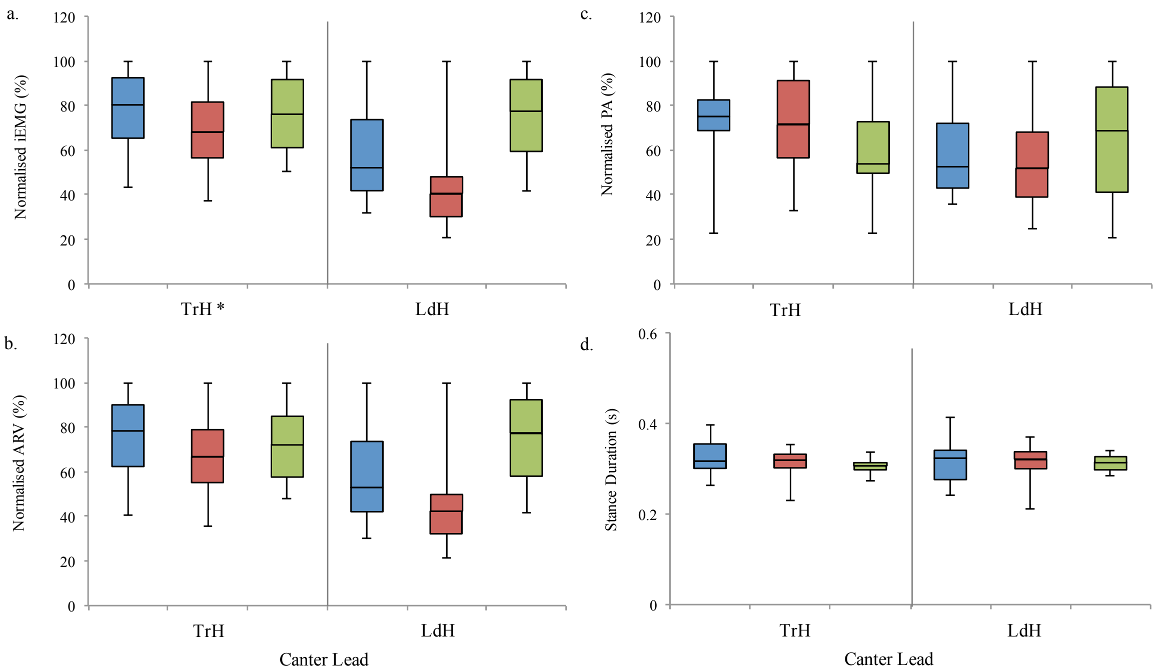


Figure 8.16 Normalised values from sEMG signal analysis for Splenius from LdF and TrF in each group during canter. Box and whisker plot, showing medians, 25% and 75% quartiles, and minimum and maximum values of a) normalised iEMG (%); b) normalised average rectified value (%); c) normalised peak amplitude (%); d) FL stance phase duration during canter. Significant differences between limbs ($P<0.05$) are represented by *.

8.4.6(ii) Jump

Limited EMG data from the Splenius during A1 stride were deemed suitable for further analysis following the traffic light accept/reject criteria, particularly in elite and school groups (Table 8.21). As a result, Splenius sEMG signals from the jump condition are only presented between take-off and landing in Figure 8.17 to provide the best representation of typical signals. During jump, the Splenius muscle displayed a similar phasic pattern to the Trapezius, with muscle onset occurring between late swing and early stance phase and ceasing at middle to late stance at take-off. At landing, muscle onset generally occurred during early stance phase, but occurred during late jump suspension, prior to FL hoof on in some horses (Figure 8.17c). The distinct differences in phasic activity between LdF and TrF at canter were not discernible in jump. The double burst activity pattern was rarely observed during jump and mainly occurred at landing phase. Similar to the Triceps Brachii and Trapezius, the majority of subjects displayed a burst of Splenius activity during early-middle jump suspension, which varied in duration and amplitude.

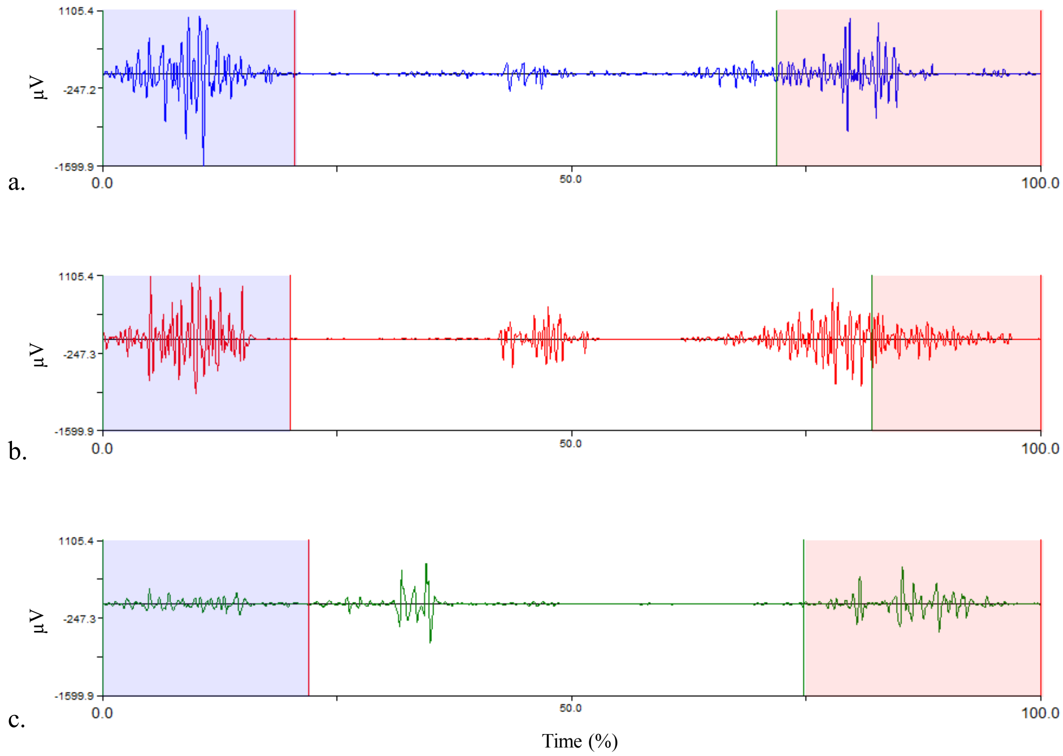


Figure 8.17 Representative sEMG signals from one horse per group for the Splenius muscle from TrF during jump stride. Signals from one horse from each group are presented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent fore stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset and high pass filtered at 80Hz. EMG activity are presented in µV and graphs are normalised between hoof impact event at take-off and hoof off event at landing.

Mean ± SD normalised EMG values for Splenius during A1, take-off and landing are presented in Tables 8.21, 8.22 and 8.23, respectively. Limited data were available for A1 in elite and school groups and statistical analysis using ANOVA could not be conducted due to insufficient degrees of freedom. No significant differences between group and limb were found for normalised data from take-off and landing phases. Although not significant, the elite group consistently exhibited the lowest mean and standard deviation for normalised EMG values at take-off (Table 8.22). NC and school groups showed similar average normalised iEMG and ARV values at take-off, however PA values from the school group were lower than NC. Standard deviation values for landing phase showed that the elite group had the lowest variability across all normalised EMG values, with the school group exhibiting very high variability.

Table 8.21 Mean (±SD) normalised values (%) from sEMG signal analysis for Splenius from LdF and TrF in each group during approach stride (A1). ***n*** **represents the number of subjects used to calculate mean (±SD) normalised values.**

Variable	**Elite** *n=1*		**NC** *n=4*		**School** *n=1*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG		25.32 (4.66)	106.83 (18.35)	135.08 (58.05)		196.52
ARV		46.45 (8.49)	123.90 (18.42)	162.21 (85.78)		321.04
PA		35.29 (15.13)	118.09 (56.02)	152.86 (79.89)		271.31

Table 8.22 Mean (±SD) normalised values (%) from sEMG signal analysis for Splenius from LdF and TrF in each group during take-off phase. ***n*** **represents the number of subjects used to calculate mean (±SD) normalised values.**

Variable	**Elite** *n=5*		**NC** *n=6*		**School** *n=3*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	117.91 (40.22)	84.16 (57.85)	157.05 (83.44)	194.47 (102.95)	153.77 (100.17)	213.53 (91.03)
ARV	136.52 (64.50)	114.21 (88.85)	204.68 (100.09)	248.22 (136.45)	180.73 (129.68)	255.93 (114.84)
PA	126.53 (92.15)	98.95 (55.36)	208.72 (117.93)	260.17 (167.25)	137.06 (97.81)	212.42 (111.97)

Table 8.23 Mean (±SD) normalised values (%) from sEMG signal analysis for Splenius from LdF and TrF in each group during landing phase. ***n*** **represents the number of subjects used to calculate mean (±SD) normalised values.**

Variable	**Elite** *n=4*		**NC** *n=6*		**School** *n=3*	
	TrF	LdF	TrF	LdF	TrF	LdF
iEMG	84.29 (20.04)	56.35 (11.17)	114.01 (33.92)	149.72 (61.82)	86.98 (100.04)	151.94 (161.73)
ARV	89.54 (19.15)	70.71 (13.99)	135.48 (71.65)	203.23 (100.43)	93.07 (99.98)	177.47 (196.71)
PA	108.79 (34.88)	65.25 (16.00)	199.74 (137.09)	222.56 (111.79)	74.27 (98.38)	167.03 (205.01)

8.5 Kinematic investigation of quality movement traits during canter and jump

8.5.1 Canter

Kinematic data and statistical test results for desirable movement traits in canter, as outlined in Section 6.3, are presented in Sections 7.5.1(i) – (iv).

8.5.1(i) Impulsion

Stride velocity, HL stance duration and duty factor represent kinematic variables used to investigate impulsion and are presented in Section 7.2. Mean ± SD values for remaining kinematic variables for impulsion are presented in Table 8.24. Maximum hock angular velocity during HL stance phase is graphically represented in Figure 8.18. Significant main effects for group $F_{(2,15)}$ =6.99, $P<0.05$, pn^2=0.48 and limb $F_{(1,15)}$ =87.47, $P<0.0001$, pn^2=0.85 were found for maximum hock angular velocity data. Pairwise comparisons revealed that hock angular velocity was significantly greater (P<0.0001) in the LdH. The school group displayed significantly greater (P<0.05) hock angular velocity values during stance phase than elite and NC groups. For tracking up, smaller values indicate greater protraction of the HL prior to hoof impact. No significant differences between groups or limb were found for this variable. However, elite and NC groups showed similarly lower average values for "tracking up" than the school group.

Table 8.24 Kinematic variables used to explore impulsion for each group at canter, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Significant differences (P<0.0001) between limbs are represented by grey shaded cells.

	Elite *n=7*		NC *n=7*		School *n=5*	
Variable	Tr	Ld	Tr	Ld	Tr	Ld
Tracking up (m)	0.85 (0.23)	0.77 (0.22)	0.77 (0.20)	0.81 (0.19)	0.96 (0.16)	0.96 (0.13)
Max hock angular velocity (°/s)	a 398.30 (106.78)	a 495.38 (88.41)	b 461.13 (98.58)	b 608.82 (103.86)	a, b 509.67 (41.27)	a, b 711.03 (71.70)

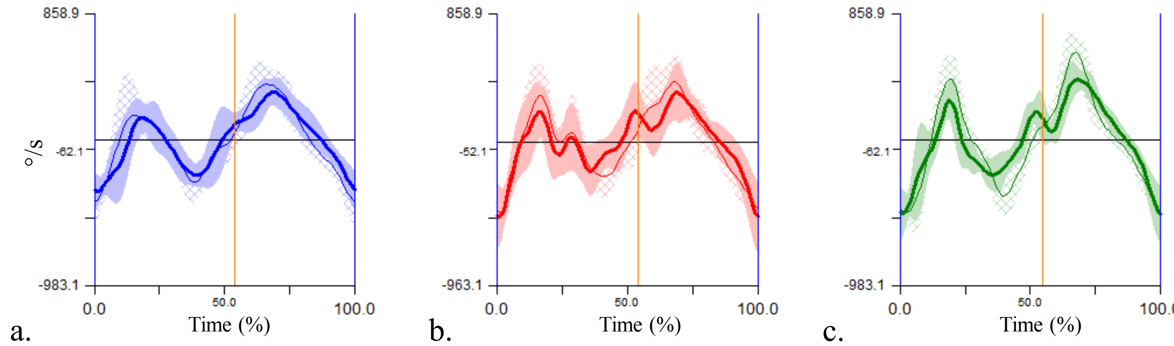


Figure 8.18 Mean and SD hock angular velocity (°/s) data for each group a) elite (blue), b) NC (red), c) school (green). Data are normalised over one canter stride. Mean data are presented for Ld (not bold line) and Tr (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate hoof on and hoof off events, respectively.

8.5.1(ii) Collection

Mean ± SD values for kinematic variables used to investigate collection during canter are presented in Table 8.24 and illustrated in Figure 8.19. A significant main effect for limb was found for all kinematic variables comprising the collection theme, except for CM elevation, where a significant interaction was found. For HL pro/retraction ROM, significant main effects were found for group $F_{(2,16)}$ =4.21, P<0.05, pn^2=0.35 and limb $F_{(1,16)}$ =48.94, P<0.0001, pn^2=0.75. Pairwise comparisons showed that the school group exhibited significantly greater HL pro/retraction ROM than the elite group. HL pro/retraction ROM was significantly greater (P<0.0001) in the LdH.

A significant main effect for limb was found for HL protraction $F_{(1,16)}$ =359.70, P<0.0001, pn^2=0.96, and retraction $F_{(1,16)}$ =294.53, P<0.0001, pn^2=0.95. Interestingly, protraction was significantly greater (P<0.0001) for LdH, while retraction was significantly greater (P<0.0001) for TrH. A significant main effect was also found for group $F_{(2,16)}$ =13.91, P<0.0001, pn^2=0.64, with HL retraction values in the elite group being significantly less than school (P<0.0001) and NC (P<0.05) groups. The school group exhibited the greatest HL retraction values, which were also significantly greater (P<0.05) than the NC group. FL elevation was explored using vertical displacement of proximal scapula and CM markers. Results for vertical displacement of the proximal scapula marker, showed a significant main effect for limb $F_{(1,15)}$ =10.83, P<0.05, pn^2=0.42, with significantly greater (P<0.05) elevation of the forehand occurring in the LdF. Interestingly, a significant interaction between group and limb $F_{(2,13)}$ =7.43, P<0.05, pn^2=0.53 was found for CM elevation. Post hoc analysis of the interaction using paired t-tests showed that CM elevation was significantly higher t (6) =2.45, $P<0.05$ for the Ld limb (right lead canter). Significant differences were not found for CM elevation between groups.

Table 8.25 Kinematic variables used to explore collection for each group at canter, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number subjects used to calculate mean (±SD) for each group. *n* values differed for variables in NC and school groups and are indicated. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Within a row, significant differences (P<0.05) between limbs are represented by grey shaded cells.

	Elite *n=7*		**NC** *n=7* *n=6 (prox scap &CM elevation)*		**School** *n=5* *n=3 (CM elevation)*	
Variable	Tr	Ld	Tr	Ld	Tr	Ld
HL protraction (°)	9.68 (7.64)	20.12 (2.11)	6.89 (2.17)	22.54 (2.15)	6.54 (1.90)	19.81 (1.70)
HL retraction (°)	a, b		a, c		b, c	
	-34.94 (4.99)	-26.36 (2.18)	-37.87 (1.42)	-28.46 (1.56)	-41.17 (0.95)	-31.53 (1.16)
HL pro/retraction ROM (°)	a				a	
	44.62 (4.58)	46.48 (3.46)	44.76 (2.54)	51.00 (2.45)	47.71 (1.52)	51.35 (2.07)
Proximal scapula displacement (m)	0.15 (0.04)	0.17 (0.03)	0.15 (0.02)	0.18 (0.02)	0.15 (0.02)	0.16 (0.02)
CM displacement (m)	0.14 (0.03)	0.16 (0.03)	0.15 (0.01)	0.16 (0.02)	0.16 (0.02)	0.14 (0.02)

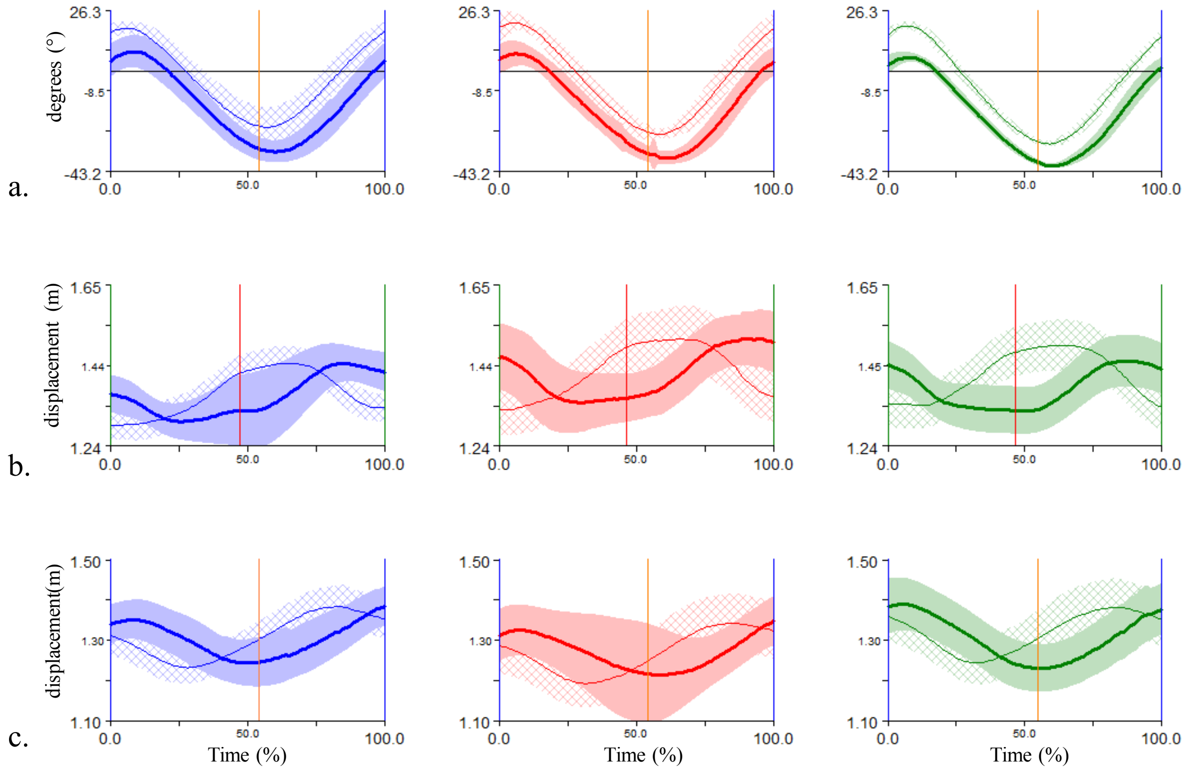


Figure 8.19 Mean and SD data for a) HL pro/retraction (°), b) vertical displacement of proximal scapula marker (m), c) vertical displacement of CM marker (m). Data are presented for elite (blue), NC (red) and school (green) groups and are normalised over one canter stride. Mean data are presented for Ld (not bold line) and Tr (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate HL hoof on and hoof off events, respectively. Green and red vertical lines represent FL hoof on and hoof off events, respectively.

8.5.1(iii) Joint Articulation

Mean ± SD values for kinematic variables used to investigate joint articulation during canter are presented in Table 8.25 and illustrated in Figure 8.20. A significant main effect for limb was found for FL protraction $F_{(1,16)}$ =278.15, P<0.0001, pn^2=0.95, retraction $F_{(1,16)}$ =242.90, P<0.0001, pn^2=0.94, and pro/retraction ROM $F_{(1,16)}$ =14.27, P<0.05, pn^2=0.47. FL protraction was significantly greater (P<0.0001) for TrF, while retraction was significantly greater (P<0.0001) for LdF. FL pro/retraction ROM was also significantly greater (P<0.05) for LdF. These findings are in accordance with those reported for HL pro/retraction in Section 7.5.2. FL retraction also showed a significant main effect for group $F_{(2,16)}$ =5.50, P<0.05, pn^2=0.41, with the school group exhibiting significantly greater (P<0.05) FL retraction than NC and elite groups.

A significant main effect for limb was found for hock flexion $F_{(1,16)}=77.63$, $P<0.0001$, $pn^2=0.83$ and for elbow flexion $F_{(1,16)}=30.62$, $P<0.0001$, $pn^2=0.66$. Both elbow and hock joints showed significantly greater ROM (P<0.0001) in the LdF. No significant differences between groups were found for shoulder, hock and elbow flexion during canter.

Table 8.26 Kinematic variables used to explore joint articulation in canter for each group, showing mean (±SD). Data are presented for Ld and Tr limbs. *n* represents the number subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts. Within a row, significant differences (P<0.05) between limbs are represented by grey shaded cells.

Variable	**Elite** *n=7*		**NC** *n=7*		**School** *n=5*	
	Tr	Ld	Tr	Ld	Tr	Ld
FL protraction (°)	31.37 (7.79)	43.06 (3.70)	30.53 (2.94)	47.77 (5.20)	29.52 (1.86)	43.68 (2.42)
FL retraction (°)	a -29.01 (5.96)	-18.08 (2.63)	b -30.48 (2.10)	-18.10 (3.49)	a, b -34.72 (1.74)	-22.55 (1.26)
FL pro/retraction ROM (°)	60.38 (4.81)	61.14 (5.01)	61.02 (3.27)	65.86 (4.52)	64.24 (1.58)	66.23 (2.80)
Elbow ROM (°)	60.08 (5.89)	68.18 (5.81)	56.36 (8.50)	65.50 (5.33)	64.19 (2.80)	71.63 (4.82)
Shoulder ROM (°)	10.60 (2.70)	11.82 (2.25)	9.77 (1.41)	9.46 (1.52)	11.49 (1.74)	10.93 (1.55)
Hock angle (°)	13.01 (5.27)	17.43 (3.71)	13.42 (4.48)	19.66 (3.47)	14.35 (5.12)	22.00 (2.71)

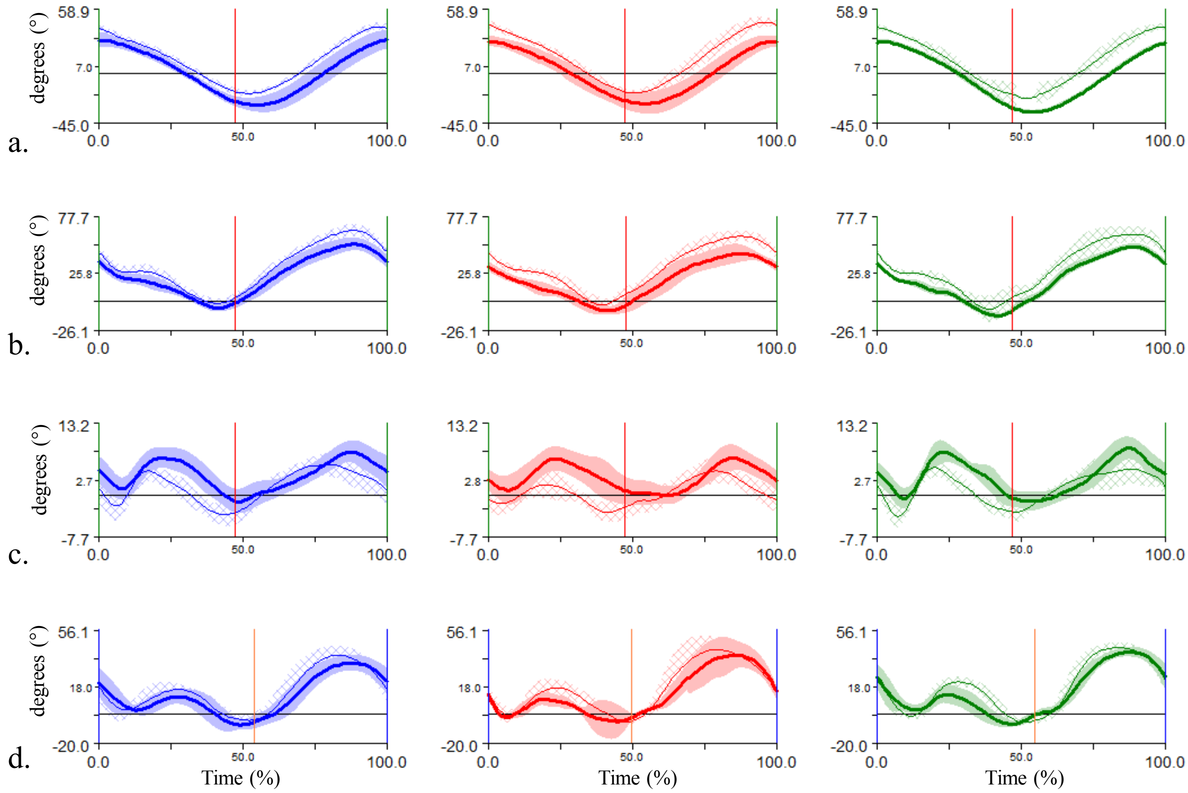


Figure 8.20 Mean and SD time-angle (°) curves for a) FL pro/retraction, b) elbow, c) shoulder, d) hock. Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over one canter stride. Mean data are presented for Ld (no bold line) and Tr (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate HL hoof on and hoof off events, respectively. Green and red vertical lines represent FL hoof on and hoof off events, respectively.

8.5.1(iv) Rhythm

Stride length and stride duration represented the kinematic variables used to explore rhythm in canter. Data for this variable are presented in Section 7.2.

8.5.2 Jump Technique

Kinematic data and statistical test results for desirable movement traits for jump, as outlined in Section 6.3, are presented in the following Sections 7.5.2(i) – (iv).

8.5.2(i) Joint Articulation

Mean ± SD data from the FL and HL are presented separately in Tables 8.26 and 8.27, respectively. No significant differences between Ld and Tr limbs were found for FL and HL kinematic variables used to investigate joint articulation. In the FL, data were remarkably similar across lead and group for joint articulation variables and a significant main effect was only found for group for maximum radius inclination at take-off $F_{(2,4)}=8.63$, $P<0.05$, $pn^2=0.81$. Elite and school groups displayed significantly greater ($P<0.05$) radius inclination at take-off than the NC group. No significant differences were found between group or limb for any other kinematic variable investigated in the FL. Although non-significant, it is interesting to note that the NC group consistently exhibited lower flexion and FL shortening values than elite and school groups. Elite and school groups showed fairly similar values, with the exception of scapula inclination where all groups exhibited similar values. Mean ± SD data for FL joint articulation variables are presented in Figure 8.21.

Table 8.27 Kinematic variables used to explore joint articulation in the FL during jump, showing mean (±SD) for each group and limb. *n* represents the number subjects used to calculate mean (±SD) for each group. *n* values differed within elite and NC groups, and are indicated. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts.

Variable	**Elite** *n=7* *n=6(FL shortening, carpus flexion)*		**NC** *n=7* *n=4(FL shortening)*		**School** *n=5*	
	TrF	LdF	TrF	LdF	TrF	LdF
Maximum FL shortening (m)	0.50 (0.05)	0.50 (0.06)	0.42 (0.07)	0.43 (0.08)	0.48 (0.04)	0.50 (0.04)
Maximum FL shortening (% change)	53.76 (5.66)	54.21 (5.83)	48.49 (7.04)	50.33 (9.39)	55.63 (4.06)	57.77 (6.08)
Maximum Elbow flexion (°)	83.61 (5.43)	84.66 (5.20)	79.80 (10.23)	80.34 (9.32)	85.63 (7.21)	80.71 (10.32)
Maximum carpus flexion (°)	124.02 (12.12)	125.52 (12.41)	116.27 (8.84)	119.56 (11.32)	129.52 (14.80)	133.98 (13.46)
Maximum radius inclination (°)	a 78.66 (9.67)	83.41 (4.08)	a, b 68.70 (8.71)	62.84 (11.30)	b 80.31 (9.24)	81.10 (5.48)
Maximum shoulder flexion (°)	13.15 (4.30)	13.20 (3.56)	9.57 (5.59)	8.93 (3.73)	11.15 (3.17)	10.32 (2.09)
Maximum scapula inclination (°)	46.29 (14.55)	51.70 (5.35)	49.32 (11.45)	51.19 (9.84)	44.85 (7.60)	41.99 (8.30)

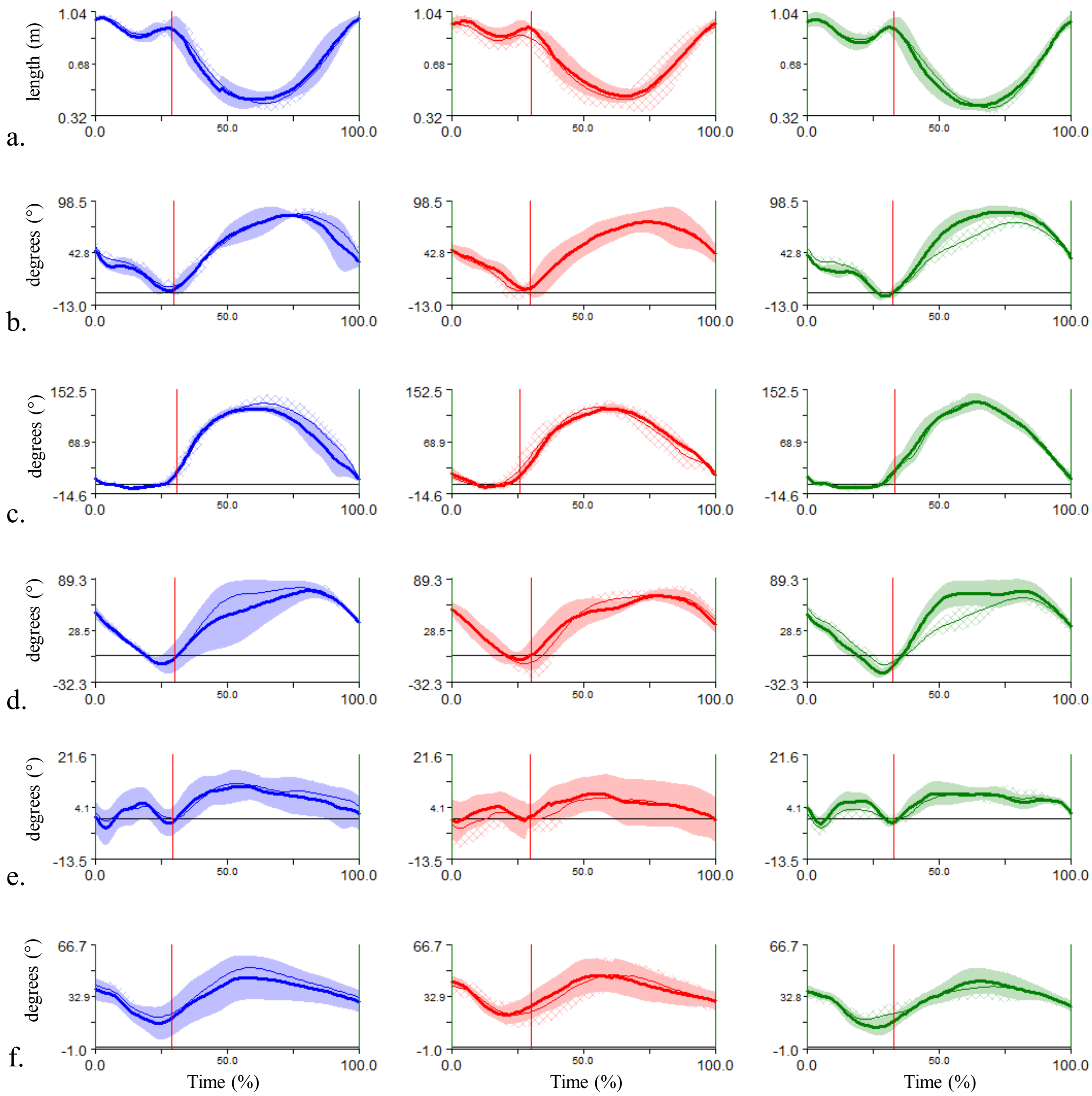


Figure 8.21 Mean and SD data for: a) FL shortening (m) and time-angle (°) curves for: b) elbow, c) carpus, d) radius inclination, e) shoulder, f) scapula inclination. Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over jump stride. Mean data are presented for LdF (not bold line) and TrF (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Green and red vertical lines represent FL hoof on and hoof off events, respectively.

In the HL (Table 8.27), a significant main effect was found for group for shortening of the HL segment during jump suspension $F_{(2,14)}$ =4.58, P<0.05, pn^2=0.40. The elite group shortened the HL segment significantly more (P<0.05) than NC and school groups. Although non-significant, the school group exhibited greater HL retroflexion than elite and NC groups. Mean ± SD data for HL joint articulation variables are presented in Figure 8.22.

Table 8.28 Kinematic variables used to explore joint articulation in the HL during jump, showing mean (±SD) for each group and limb. *n* represents the number subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts.

Variable	Elite *n=7*		NC *n=7*		School *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
Max HL shortening (m)	a, b		a		b	
	0.43 (0.08)	0.47 (0.05)	0.38 (0.04)	0.38 (0.04)	0.37 (0.08)	0.35 (0.09)
% change HL shortening	a, b		a		b	
	30.77 (5.58)	33.45 (3.10)	28.32 (3.44)	28.09 (2.49)	27.32 (5.01)	26.05 (5.53)
Max HL retroflexion (°)	48.41 (3.60)	44.79 (6.05)	48.73 (3.83)	49.15 (4.54)	51.70 (5.01)	52.76 (5.33)

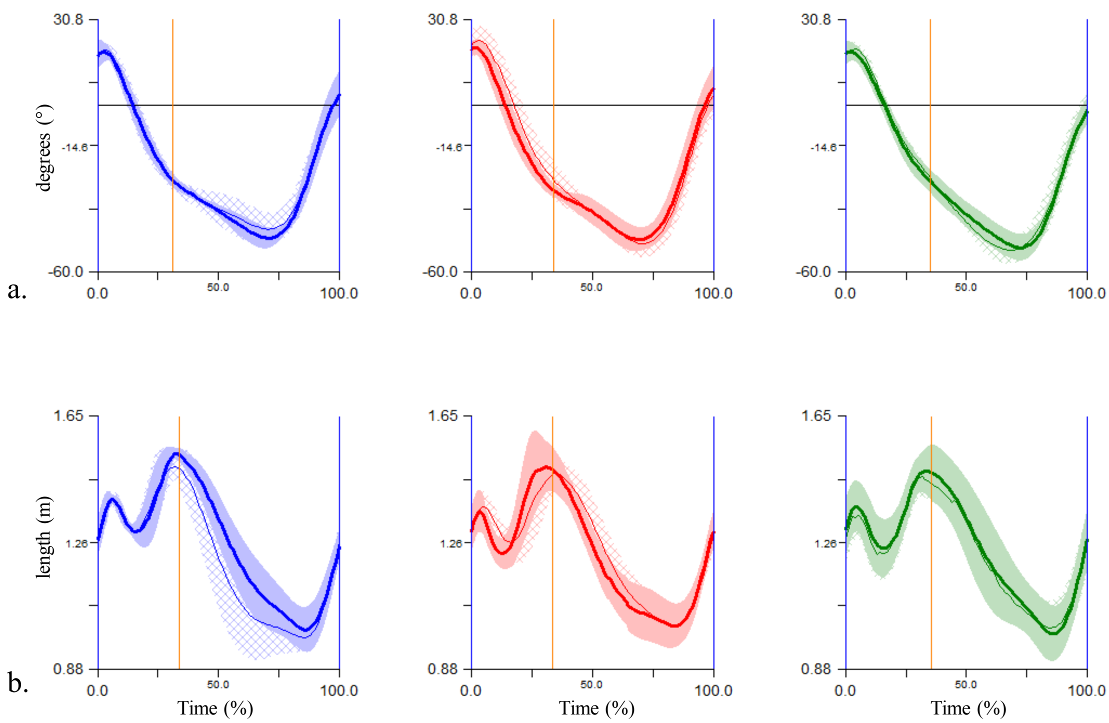


Figure 8.22 Mean and SD data for a) HL pro/retraction (°), b) HL shortening (m). Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over jump stride. Mean data are presented for LdH (not bold line) and TrH (bold line). SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate HL hoof on and hoof off events, respectively.

8.5.2(ii) Impulsion

HL stance duration, stride velocity and duty factor were used to investigate impulsion during A1 and jump strides and are presented in Section 7.3. Mean ± SD values for remaining kinematic variables for impulsion are presented in Table 8.28 and Figure 8.23. Significant main effects were found for group for CM vertical displacement $F_{(2,13)} = 5.27$, $P<0.05$, $p\eta^2=0.45$, with the school group exhibiting significantly less ($P<0.05$) elevation of the CM than elite and NC groups during jump suspension. Percent change data for revealed that the CM in elite and NC groups was elevated approximately 4% higher during jump suspension that school groups.

Table 8.29 Mean (±SD) vertical displacement of CM, used to investigate impulsion for each group and limb during jump. *n* represents the number subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts.

Variable	**Elite** *n=7*		**NC** *n=7*		**School** *n=5*	
	Tr	Ld	Tr	Ld	Tr	Ld
Vertical displacement of CM (m)	a		b		a, b	
	0.44 (0.06)	0.46 (0.06)	0.42 (0.08)	0.39 (0.08)	0.34 (0.05)	0.31 (0.05)
Vertical displacement of CM (% change)	a		b		a, b	
	24.96 (3.01)	26.05 (2.66)	24.69 (3.79)	23.52 (4.08)	20.03 (2.95)	18.44 (3.04)

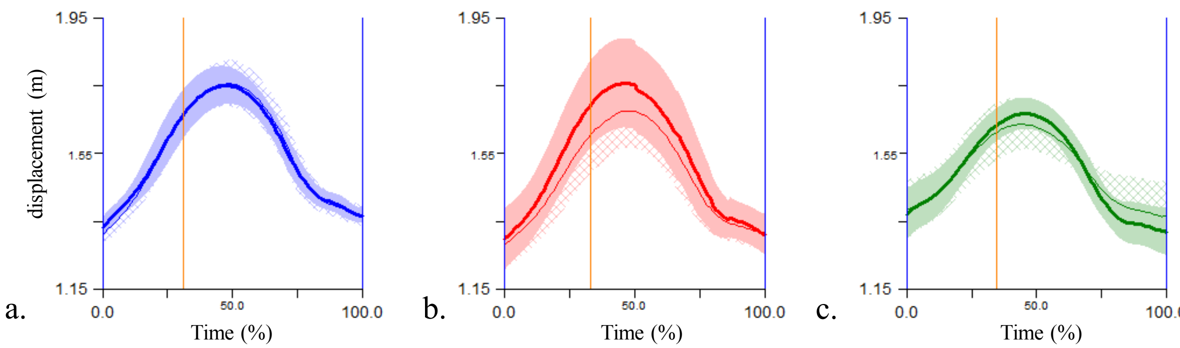


Figure 8.23 Mean and SD time-displacement (m) curves for vertical displacement of CM. Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over jump stride. Mean data are presented for Ld (not bold line) and Tr (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate HL hoof on and hoof off events, respectively.

8.5.2(iii) Reflex

Data for FL stance duration during jump stride were used to investigate reflex and are presented in Section 7.3. Mean ± SD data for remaining kinematic variables used to examine reflex are presented in Table 8.29 and Figure 8.24. No significant main effects were found for group and limb for angular velocity data from shoulder, elbow and carpus joints. Mean ± SD angular velocity data for all FL joints investigated were similar across groups.

Table 8.30 Mean (±SD) angular velocity (°/s) data for each group and limb during jump. *n* represents the number subjects used to calculate mean (±SD) for each group.

Variable	Elite *n=7*		NC *n=7*		School *n=5*	
	TrF	LdF	TrF	LdF	TrF	LdF
Maximum shoulder angular velocity (°/s)	222.61 (72.38)	195.08 (63.19)	156.71 (68.38)	168.10 (43.22)	203.52 (56.95)	156.58 (30.65)
Maximum elbow angular velocity (°/s)	624.24 (86.10)	557.50 (88.59)	578.24 (221.38)	599.36 (159.88)	686.96 (170.70)	534.37 (117.28)
Maximum carpus angular velocity (°/s)	1093.87 (104.82)	1079.35 (87.20)	1013.48 (193.97)	1019.01 (100.85)	1218.70 (296.41)	1088.46 (142.63)

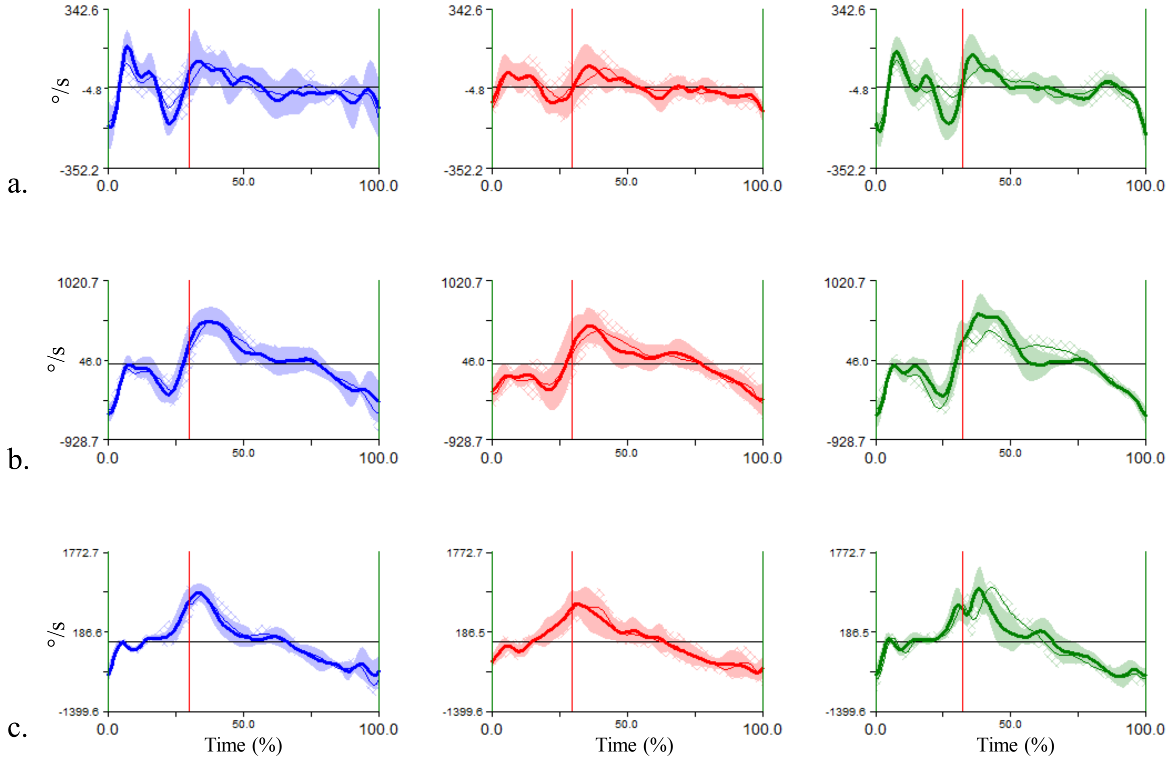


Figure 8.24 Mean and SD time-angle (°/s) curves for angular velocity data from a) shoulder b) elbow, c) carpal joints. Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over jump stride. Mean data are presented for LdF (not bold line) and TrF (bold line). SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Green and red vertical lines represent FL hoof on and hoof off events, respectively.

8.5.2(iv) Engagement

Kinematic variables used to investigate engagement are presented in Table 8.30 and Figure 8.25 as mean ± SD. No significant main effects were found for group and limb for any of the kinematic variables investigated. Mean values were similar across group and limb, and exhibited low variability. Although non-significant the elite group displayed the least amount of hock flexion and lifted of the forehand more (proximal scapula elevation) at take-off.

Table 8.31 Kinematic variables used to explore engagement during take-off, showing mean (±SD) for each group and limb. *n* represents the number subjects used to calculate mean (±SD) for each group. *n* values differed within the elite group, and are indicated.

Variable	**Elite** *n=7* *n=6 (tracking up)*		**NC** *n=7*		**School** *n=5*	
	Tr	Ld	Tr	Ld	Tr	Ld
Vertical displacement of proximal scapula (m)	0.49 (0.05)	0.51 (0.05)	0.46 (0.08)	0.43 (0.09)	0.41 (0.06)	0.39 (0.08)
Maximum hock flexion (°)	27.98 (4.82)	27.33 (6.75)	35.44 (6.63)	37.05 (9.51)	31.53 (5.46)	31.18 (6.55)
Tracking up (m)	0.48 (0.20)	0.55 (0.24)	0.52 (0.48)	0.52 (0.38)	0.67 (0.23)	0.41 (0.24)

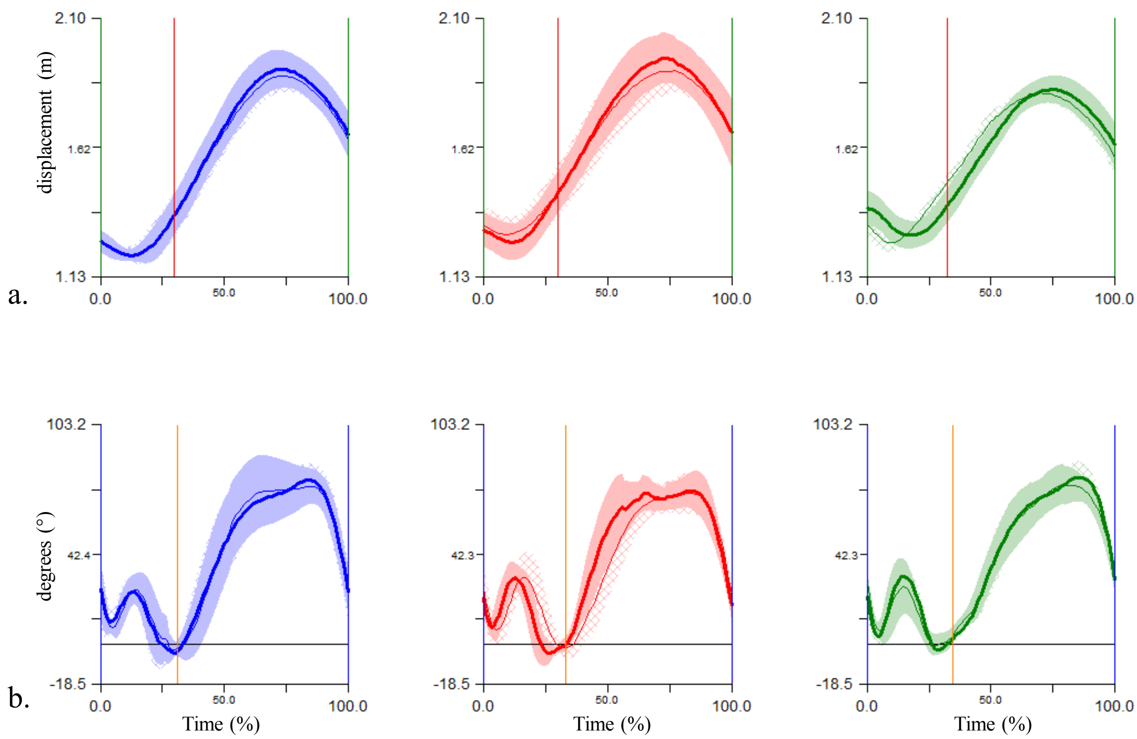


Figure 8.25 Mean and SD data for a) vertical displacement of proximal scapula marker (m) and b.) hock angle (°). Data are presented for: elite (blue), NC (red) and school (green) groups and are normalised over jump stride. Mean data are presented for LdF (not bold line) and TrF (bold line) limbs. SD data are presented for Ld (crosshatch area) and Tr (shaded area) limbs. Blue and orange vertical lines indicate HL hoof on and hoof off events, respectively. Green and red vertical lines represent FL hoof on and hoof off events, respectively.

Chapter 9. Discussion

The discussion of findings from the main study of the thesis aims to first provide an overview of movement and muscle activity patterns observed in kinematic (Sections 9.1) and sEMG data (Section 9.2), respectively. Section 9.3 combines fundamental muscle activity and movement patterns, to examine how "quality" movement traits are facilitated by muscular action. Section 9.4 provides a discussion of how findings from the preceding sections may be extrapolated to make suggestions for scientifically evidenced training and selection methods for the equine jumping athlete. Finally, Section 9.5 summarises the practical applications for sEMG in equine athletes. This section also describes the challenges encountered in this study and provides a discussion for further work and development in this field.

9.1 Fundamental movement patterns in elite and non-elite horses during canter and jump.

The importance of quality movement and jump technique for selection of the equine jumping athlete have been discussed throughout the thesis. To the author's knowledge, this is the first study to base kinematic investigation solely on traits defined by equine industry professionals. As described in Chapter 2, extensive research has examined the temporal, linear and angular kinematics of the equine jump. Research has also been conducted to study differences in movement strategies between horses with varying levels of talent and experience (i.e. Barrey et al., 1993; Barrey and Galloux, 1997; Schamhardt et al., 1993; Powers and Harrison, 2000; Powers, 2005; Bobbert et al., 2005; Santamaria et al., 2006). In the majority of these studies, horses ranged from 3-5 years of age and did not have established performance records at competition. However, biomechanical examination of horses established at elite level provides the most reliable information relating to near-optimal movement patterns (Bogert et al., 1994). This is the first known study to compare kinematic data for elite horses, with an established performance record at Foxhunter level or higher, against non-elite horses, working as riding school and novice competition horses. Therefore, this study offers the most comprehensive exploration of movement strategies employed by horses of varying calibre, training level and experience during canter and jump to date.

9.1.1(i) Fundamental movement patterns during canter

Findings from the questionnaire study (Chapter 3), illustrated the relationship between quality canter and jump technique, as perceived by equestrians. The development of quality canter was also defined as playing the most important role for improving jumping performance. However, few studies have kinematically investigated the canter, which is surprising considering its prevalence in sport horse training and competition.

Equestrians described the HL as the most important contributor to quality canter, which is in accordance with impulsion representing the most prevalent theme for the definition of quality canter. Interestingly, no significant differences were found between groups for duty factor, HL stance duration or stride length, which have previously been associated with increased strength and impulsion during trot (Back et al., 1994). The equestrian definition of impulsion states that it is not achieved through increased speed, but through increased muscular power in the HL, which permits increased engagement of the HL (Fédération Equestre Internationale, 2016). Impulsion is therefore linked to collection, which is kinematically associated with decreased stride velocity, stride length and HL stance duration (Holmström et al., 1995). Elite horses complied with the equestrian definitions of collection and impulsion by displaying greater average HL protraction and "tracking up" values, than NC and school horses. Decreased HL retraction has been observed during collected gaits (Holmström et al., 1995) and was also exhibited by elite horses, which showed significantly less HL retraction than NC and school horses (Section 8.5.1(ii)).

Recently, the degree of FL and HL limb protraction has been related to balancing strategies employed by horses during trot (Hobbs et al., 2016). Horses that exhibited hind-first diagonal limb dissociation were found to have more protracted limb angles and a more caudal position of the centre of pressure (COP), resulting in a more "uphill" posture (Hobbs et al., 2016). Conversely, horses that exhibited fore-first dissociation showed greater limb retraction angles and positive rotation around the CM, indicating a more "nose-down", or "falling forwards" trunk inclination (Hobbs et al., 2016). This is in accordance with earlier work by Holmström et al. (1993, 1994, 1995), who found that positive diagonal advanced placement and increased limb protraction were characteristic traits of horses with "good" quality trot, leading these authors to suggest that this trait was indicative of natural balance and ability to weight-bear on the HL (Holmström et al, 1994a, b). However, as previously described in Section 6.3.3(vi), research has not found conclusive evidence for a caudal shift of the CM based on the ratio of vertical impulse in the FL and HL during collected gaits. In fact, recent studies suggest that substantial alteration to the location of CM within the horse's body is unlikely, and that balancing strategies for collected gaits are more dependent on changes in: location of COP, limb, rotation around the CM, and postural alterations to the limbs and trunk (Hobbs and Clayton, 2013; Hobbs et al., 2016). Further work is required to determine whether these strategies are present during canter, which would require GRF data and an examination of fore-aft motion of the CM. However, this was beyond the scope of this study. These findings suggest that elite and NC horse are likely to exhibit balancing strategies that are more indicative of collected gait than school horses, which appear to adopt a less collected gait through significantly greater HL retraction and stride velocity.

Increased fore and hind stance duration, which is associated with more collected gaits has been reported to result in decreased suspension phase duration (Clayton et al., 1994b). This may offer an explanation for the non-significant differences found in this study for vertical displacement of CM during canter strides (Section 8.5.1(ii)). Suspension is desirable in the dressage horse (Fédération Equestre Internationale, 2016), however an exaggerated suspension phase may be disadvantageous to SJ horses, as up-and-down motion in faster gaits is energetically demanding and is recognized as an inefficient strategy (Witte et al., 2006). This is because the increased potential energy associated with producing a higher CM trajectory during suspension is not completely recovered (Pratt, 1984). It is therefore likely that elite jumping horses adopt a more economical cantering technique, which results in less suspension during collected gait to conserve energy. However, further work is required to study the effects of collection on CM movement during canter before this can be confirmed. In this study, rhythm was apparent in all horses, as low standard deviation was found for stride length and stride duration, indicating a consistent cadence (Clayton et al., 1994b).

Flexion of the stifle, hock and MTP joints are associated with good movement at trot, due to their action as dampers during stance phase (Back et al., 1994; Hjertén et al., 1994; Holmström et al, 1994a). However, when evaluating quality canter, equestrians described a preference for hock flexion during stance, with no reference made to hip, stifle or MTP joint flexion. As a result, only hock flexion was investigated in this study, with no significant differences observed between groups (Section 8.5.1(iii)). The amount of positive work generated by the HL has been directly related to an increase in the total length change of the HL during stance (Bobbert and Santamaria, 2005). However, hock flexion alone is not an adequate indicator of HL shortening. This in an important consideration for interpreting HL muscle function due to the relationship between limb compliance and the storage and release of elastic strain energy (McGuigan and Wilson, 2003; Harrison et al., 2010). HL shortening during stance phase at canter was therefore explored for discussion purposes, using the method described for “HL tuck” in Section 6.3.3(xii) and are presented in Table 9.1.

Average group values for HL shortening revealed that the HL in elite horses shortened more than NC and school horses, with the TrH in elite horses experiencing twice as much limb compression as the school group. Interestingly, Holmström et al. (1995, 1997) suggest that collection may actually be achieved by carrying the same amount of weight on the HL over a longer stance duration, which results in increased HL shortening. These findings further indicate that elite horses in this study were capable of increased collection and suggest that the HL in the school group was less compliant. Based on these findings, it is difficult to determine why the school horse group exhibited increased hock angular velocity, as horses with superior gait quality have been found to exhibit this trait (Holmström et al., 1997). Holmström et al. (1997) attributed increased joint angular velocity to an increased ability to compress the HL (flex HL joints) during limb loading at stance, which is a determinant for the amount of elastic strain energy stored and returned in the muscle-tendon unit (Roberts et al., 1997; Bienwener, 1998; Wilson et al., 2001; McGuigan and Wilson, 2003; Bobbert and Santamaria, 2005; Butcher et al., 2009; Harrison et al., 2010). However, the opposite trend was found in this study. The majority of equine research has focused on limb compliance in the FL (Bienwener, 1998; McGuigan and Wilson, 2003; Butcher et al., 2009; Harrison et al., 2010) and further research on the HL is required to investigate this finding. Nevertheless, these results further illustrate that elite horses in this study display a better capability for HL engagement and subsequent collected gait, which is in accordance with both equestrian and kinematic definitions of the term (see Section 6.3).

Table 9.1 Mean (±SD) maximum hindlimb shortening for each group and limb during HL stance duration in canter. *n* represents the number of subjects used to calculate mean (±SD) for each group. Within a row, shaded cells represent within-subject significant differences (P<0.05) between LdH and TrH

Variable	Elite *n=7*		NC *n=7*		School *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
Maximum HL shortening (m)	0.08 (0.05)	0.17 (0.01)	0.06 (0.03)	0.16 (0.02)	0.04 (0.02)	0.15 (0.02)
Percent change HL shortening (%)	5.53 (3.72)	11.81 (0.81)	4.07 (2.28)	12.10 (1.59)	2.82 (1.13)	11.25 (0.75)

In the FL, industry professionals described a strong preference for FL protraction during swing phase when evaluating quality canter. These findings are in accordance with previous studies reporting that judges relate increased FL protraction to quality movement at trot (Holmström et al., 1993, 1994). In this study, no significant differences were found between groups for FL protraction. However, in accordance with the HL, the school group showed significantly greater FL retraction than elite and NC horses. "Use of shoulder" was also frequently reported as being important to equestrians, but all groups exhibited remarkably similar shoulder joint ROM for both limbs. Questionnaire results revealed that industry professionals appear to associate FL protraction with shoulder ROM, which is unsurprising as equestrian texts generally describe a relationship between "freedom of shoulder" and increased stride length and limb protraction (Back et al., 1994; Holmström et al., 1994; Cano et al., 2001). However, it is generally accepted that FL protraction is driven by the elbow joint (Dutto et al., 2006; Clayton et al., 2011). This was supported by Holmström et al. (1994), who found that scapula inclination and shoulder joint angles were similar at maximum FL protraction and hoof impact events, indicating that this trait is unlikely to provide a valid indicator of quality movement. Furthermore, average ROM for the shoulder joint reported in this study ranged between 9.46° and 11.49°, suggesting that "use of shoulder" may be difficult for the human eye to interpret.

The elbow joint has been suggested as a better determinant for good FL movement, due to the relationship between elbow flexion and maximum protraction angle (Holmström et al., 1993). In this study, no significant differences were found between groups for elbow ROM, which is in accordance with non-significant differences for FL protraction. All groups exhibited similar elbow flexion angles, but the slightly larger ROM for elbow joint in school horses was due to increased extension angle relating to FL retraction. It is difficult to conclude which FL traits are indicative of quality movement, as non-significant differences were generally found between groups. However, these findings suggest that equestrians should consider adopting evaluation methods that favor elbow ROM over the shoulder joint, which is currently prioritized.

In this study, significant differences between limbs were found for kinematic variables in the FL and HL. This is in agreement with previous research that has described the different functional roles of leading and trailing limbs during canter (Merkens et al., 1993; Back et al., 1997). During canter the leading limb is often referred to as the swinging limb, which is brought more forward during swing phase, while the trailing limb is generally referred to as the supporting limb (Back et al., 1997). These definitions have been supported by GRF (Merkens et al., 1993) and kinematic (Back et al., 1997) studies investigating differences between leading and trailing limbs during canter. The trailing limbs exhibit the greatest propulsory forces, with the TrF experiencing the greatest vertical impulse and vertical loading of approximately 1.5 times the horse's body weight (Merkens et al., 1993). In contrast, the LdF exhibits the greatest retardatory forces and minimal propulsory force highlighting its function to raise the CM prior to suspension phase (Merkens et al., 1993). Results from this study are in accordance with Back et al. (1997), who reported significantly greater retraction of trailing limbs. The retracting limb must overcome forces associated with GRF and inertia of the trunk (Payne et al., 2005) Therefore greater retraction in the trailing limbs has been linked to their closer orientation to the CM and the fact that they experience greater MCPJ and MTPJ extension during stance (Back et al., 1997), which are associated with greater vertical limb loading (McGuigan and Wilson, 2003). Back et al. (1997) also reported significantly greater protraction in the leading limbs, which was driven by significantly greater hip and elbow flexion during swing. These findings are also in accordance with this study, as protraction and elbow joint ROM were significantly greater in the leading limbs. Agreement between findings from this thesis and previous literature demonstrates the validity of kinematic data from canter.

In this study, significant differences were found for stance duration between LdF and TrF (Section 8.2), which does not agree with previous studies that have reported non-significant differences between limbs at canter (Merkens et al., 1993; Back et al., 1997). The TrF was found to exhibit significantly greater stance duration, which may indicate a compensatory strategy to decrease increased limb loading rate and peak vertical forces experienced by this limb (Merkens et al., 1993; Weishaupt et al., 2004; 2006b). However, further work using GRF data is required to confirm this theory. In the HL, no significant differences were found between LdH and TrH limbs for stance duration during canter (Section 8.2). This finding is also not in accordance with previous research that has reported small but significant differences in stance durations, with the LdH exhibiting significantly longer stance duration (Back et al., 1997). Differing findings for FL and HL stance duration may be related to methodological differences between studies. Back et al. (1997) investigated canter at a speed of 7m/s, which is much faster than stride velocity values reported in this study for each group and limb. In this study, stride velocity values fit within the range reported by Clayton (1994b) for medium canter, while the values reported by Back et al. (1997) are better representative of extended canter. Studies have shown that stance duration decreases with increasing speed at canter and gallop (Witte et al., 2004, 2006; Clayton 1994b), which may offer a possible explanation for differences. Furthermore, Back et al. (1997) presented data from unridden horses on a treadmill, which is known to influence gait parameters, including artificial lengthening of stance duration (Buchner et al., 1994).

9.1.1(ii) Fundamental movement patterns during jump

Linear and temporal kinematics for A1 and jump stride were different to those found for canter (Section 8.3). During A1, elite horses exhibited significantly greater stride velocity than NC and school groups. Unsurprisingly, the elite group also experienced significantly shorter HL stance duration, which is known to decrease with increasing speed (Crook et al., 2010; Clayton, 1994b; Corley and Goodship, 1994; Witte et al., 2004, 2006). This finding is in accordance with Barrey and

Galloux (1997), who reported that experienced horses could execute the fence from a greater approach velocity due to their ability to efficiently convert horizontal velocity into vertical velocity at take-off. No significant differences were found between groups for stride length during A1, indicating that there were no differences in the amount of "gather" exhibited in each group (Colborne et al., 1995). However, the gather stride, as described in Section 2.6.2(i), is also characterised by lowering of the CM due to lowering of the head and neck (Clayton and Barlow, 1991; Clayton, 1994a). This was not explored in this study, as the head and neck segment were not included in the kinematic model. Further work is therefore required to investigate the gather technique in elite and non-elite horses.

Contrary to linear and temporal kinematics during A1 stride, no significant differences were found for jump stride velocity. However, the elite group showed greater average stride velocity than NC and school horses. School horses were also found to exhibit a significantly shorter jump stride length and duration than elite and NC horses, which was associated with a significantly lower CM trajectory during jump suspension. No significant differences were found for stance duration between leading and trailing limbs during the jump stride. This is not surprising, as studies have shown that FL limb function becomes more symmetrical with increases in speed (Witte et al., 2004) and that both HL exhibit similar stance duration during the take-off phase, acting more symmetrically as fence height increases (Leach and Ormond, 1984b; Clayton, 1989; Schamhardt et al., 1993; Bobbert and Santamaria, 2005).

Apart from bascule, joint articulation was ranked as the most important consideration for evaluation of jump technique by equestrians. Within this theme, specific traits were largely associated with the FL "tucking" action during jump suspension. Interestingly, no significant differences were found for shoulder, elbow and carpus flexion between groups. Subsequently, maximum shortening of the FL segment was not significantly different between groups, with the greatest percent decrease in FL segment length observed in the school group. The only significant difference observed between groups was for radius inclination, with the NC group "lifting" the radius less than elite and school horses. However, non-significant differences in radius inclination between elite and school horses suggests that, although aesthetically pleasing, this trait may not be indicative of performance. These findings are somewhat surprising, as questionnaire results revealed the apparent importance of FL joint articulation for distinguishing good quality jump technique. Furthermore, previous studies have reported greater carpal flexion (Powers and Harrison, 2000), FL shortening (Bobbert et al., 2005; Santamaria et al., 2005) and elbow flexion (Bobbert et al., 2005; Santamaria et al., 2005, 2006) in horses with good jump technique. Contrasting results may be due to methodological differences, as Powers and Harrison (2000) and Santamaria et al (2006) investigated kinematic data from unridden horses of varying ages over a 1.0 m oxer and 1.15 m vertical, respectively. The effect of the rider and the generally greater age and experience level of the horses used for this study makes direct comparisons with previous studies difficult. However, in this study, non-significant findings between groups for FL joint articulation suggest that, in the experienced horse, FL action may not differentiate between elite and non-elite jump technique when ridden over submaximal fences.

In the HL, which was ranked as the most important contributor to quality jump technique, kinematic differences between groups were more apparent than the FL. The importance of HL vertical impulse at take-off for determining the trajectory of the CM during jump suspension has been described throughout the thesis (Barrey and Galloux, 1997). Vertical displacement of the CM during jump suspension provided a kinematic measurement for "scope", which was highlighted by industry professionals as being important for jump technique. In this study, school horses exhibited significantly lower vertical displacement of the CM (Z_{CM}) during jump suspension, with the largest average values observed in elite horses, indicating better ability to lift the CM. An estimated CM target was used in this study and was based on the method described by Bogert et al. (1994). However, mean ± SD values reported in this study for CM height in the standing horse and during jump suspension were similar to those reported in previous research. For 4-year-old horses with an average height of 1.70 ± 0.05 m, Santamaria et al. (2004a, b) reported CM height in the standing horse to be 1.43 ± 0.05 m. This is in accordance with this study, as average height of CM in static trials across all horses was 1.32 ± 0.06 m. The slightly lower standing CM height reported in this study is likely due to horse heights ranging from 1.52 m to 1.73 m, resulting in a lower average height than reported by Santamaria et al. (2004a, b). Furthermore, Santamaria et al. (2004a, b) reported average normalised Z_{CM} values of 0.51m for all horses studied and 0.55 m for a group of the best jumpers. These values are slightly higher than those reported in this study, but again this is likely due to methodological differences, as horses from the study by Santamaria et al (2004a, b) were unridden and executed a slightly larger fence of 1.05 m. Similar absolute Z_{CM}values have also been reported by Powers and Harrison (1999) and Bobbert et al. (2005), however these studies did not present height of CM in the standing horse and normalised values cannot be directly compared to results from this study. Nevertheless, these findings illustrate the method for calculating the estimated CM employed for this study was sufficiently accurate.

Section 6.3.3(xii), provided a discussion of findings from previous studies reporting a positive correlation between vertical velocity of the CM ($\dot{Z}_{CM}$) at take-off and Z_{CM} during jump suspension

(Clayton et al., 1995; Bobbert et al., 2005; Powers, 2005; Santamaria et al., 2004a, b; 2005). Horses with the greatest Z_{CM} during jump suspension were also found to take off and land farther from the fence, and were subsequently airborne for a longer duration than horses with a lower Z_{CM} (Santamaria et al., 2004a, b, 2005). This is in agreement with the significantly shorter jump stride length and duration observed in this study for the school group, which displayed the lowest average Z_{CM}. Increased generation of $\dot{Z}_{CM}$ at take-off has been linked to shorter HL stance duration and higher peak vertical acceleration of CM ($\ddot{Z}_{CM}$) at take-off, indicating that horses are able to generate greater vertical force at HL push off (Santamaria et al., 2004a). Unsurprisingly, equestrians did not describe $\dot{Z}_{CM}$ as an important consideration for evaluating quality jump technique. However, previous research has highlighted its functional significance for jumping. This variable was therefore investigated for discussion purposes to determine whether differences occur between elite and non-elite athletes and whether this is an important consideration for interpreting muscular activity between groups.

Z_{CM} was calculated for take-off according to methods described in Section 6.3. First and second derivative functions were used to calculate $\dot{Z}_{CM}$ and $\ddot{Z}_{CM}$, respectively for the CM target path. Data for Z_{CM}, $\dot{Z}_{CM}$, and $\ddot{Z}_{CM}$ are presented in Table 9.2 and reveal similar patterns to those reported in previous studies. Significant differences were not found between groups for Z_{CM} at take-off, but the greatest average values were observed in the elite group. In agreement with Santamaria et al. (2004a, b, 2005) and Bobbert et al (2005), the school group, which displayed the lowest Z_{CM} at take-off and jump suspension also displayed significantly lower $\dot{Z}_{CM}$ at take-off $F_{(2,13)}=5.49$, $P<0.05$, $p\eta^2= 0.46$ than elite and NC groups ($P<0.05$). Significant differences were not found between groups for $\ddot{Z}_{CM}$ and all groups displayed relatively similar average values. However, although not significant, the elite group experienced shorter HL stance at take-off than other groups, suggesting that elite horses have a better ability to generate greater vertical force at take-off (Santamaria et al., 2004a). Maximum Z_{CM} during jump suspension was investigated under the impulsion theme and these findings fit with the equestrian definition of the term, suggesting that elite horses have a greater capacity to produce impulsion during jumping.

Table 9.2 Mean (±SD) for maximum: vertical displacement (Z_{CM}), vertical velocity ($\dot{Z}_{CM}$), and vertical acceleration ($\ddot{Z}_{CM}$) of the CM during jump take-off for each group and limb. *n* represents the number of subjects used to calculate mean (±SD) for each group. Within each row, significant differences (P<0.05) between groups are represented by corresponding superscripts

Variable	Elite *n=7*		NC *n=7*		School *n=5*	
	TrH	LdH	TrH	LdH	TrH	LdH
Z_{CM} at take-off (m)	0.34 (0.04)	0.35 (0.03)	0.33 (0.09)	0.32 (0.06)	0.30 (0.04)	0.30 (0.04)
$\dot{Z}_{CM}$ at take-off (m/s)	a 1.85 (0.22)	1.99 (0.19)	b 1.96 (0.39)	1.79 (0.36)	a, b 1.37 (0.30)	1.43 (0.35)
$\ddot{Z}_{CM}$ at take-off (m/s^2)	15.68 (3.62)	15.34 (4.75)	16.90 (6.51)	15.42 (4.88)	17.48 (6.69)	14.04 (2.42)

Increased shortening of the FL and HL segments, as well as HL retroflexion, have been observed in horses that exhibit lower Z_{CM} during jump suspension (Powers and Harrison, 2000; Bobbert et al., 2005; Santamaria et al., 2004a, 2005, 2006). There is a degree of contention between authors as to whether lower Z_{CM} and increased limb clearance represents a better, more energetically economical jump technique. Other studies (Powers and Harrison, 1999; Cassiat et al., 2004; Powers, 2005) suggest that the ability to produce greater vertical impulse at take-off and higher Z_{CM} during jump suspension is a better determinant of successes in a jumping horse. Interestingly, the more efficient strategy proposed by Bobbert et al. (2005) and Santamaria et al (2004a, 2005, 2006) was observed in the school group through significantly lower Z_{CM} during jump suspension and $\dot{Z}_{CM}$ at take-off and slightly greater FL shortening and knee flexion than elite and NC horses. However, based on the theory that lower Z_{CM} at jump suspension results in less limb clearance, school horses would also be expected to exhibit increased HL retroflexion and shortening, but this was not the case. Instead, all groups showed remarkably similar average retroflexion values, with the elite group exhibiting significantly greater HL shortening.

Fence height has been shown to affect kinematics (Clayton and Barlow, 1989). Carpal angles and Z_{CM} during jump suspension have been found to increase with fence height in successful jumping horses (Powers, 2005) and it is unlikely that horses generate maximum $\dot{Z}_{CM}$ and limb clearance over submaximal fences, especially elite horses (Santamaria et al., 2004a). Previous studies have identified that a 1.0 m fence was sufficient for illustrating differences in jump technique (Cassiat et al., 2004; Schamhardt et al., 1993). However, results from this study suggest that submaximal fences do not adequately display differences in FL and HL joint articulation. Inspection of data from elite horses jumping larger oxers of 1.10m confirmed this suggestion. In one elite horse, retroflexion angles of 32° and 65° were found for execution of a 1.0 m vertical and 1.10 m oxer, respectively. This is illustrated in Figure 9.1 and suggests that submaximal fence heights do not necessitate HL retroflexion, or "opening out behind", as described by industry professionals. Instead, horses generally opted to shorten the HL segment rather than retroflex the HL. This was especially evident in elite horses that shortened the HL significantly more than other groups. Investigation of HL technique also revealed that elite horses tended to adduct the HL during jump suspension, possibly increasing their ability to shorten the HL.

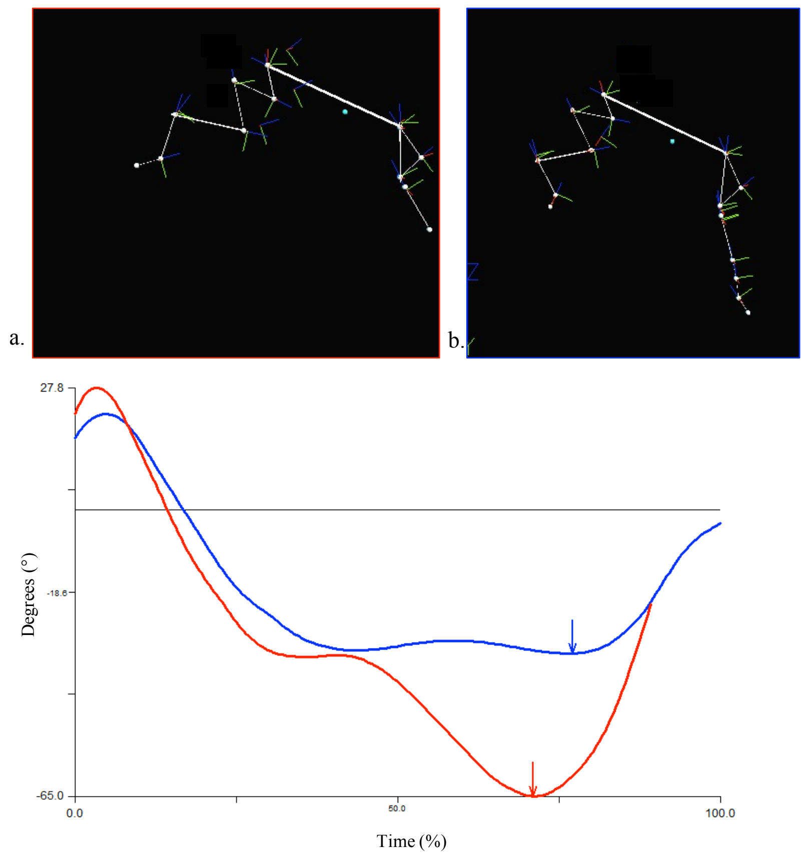


Figure 9.1 Time angle curve for HL retroflexion in one elite horse executing a 1.0m vertical (blue solid line) and a 1.10m oxer (red solid line). Downward arrows represent maximum HL retroflexion events. Visual representation of maximum HL retroflexion events are illustrated by a corresponding snapshot of the model for a). 1.10m oxer and b.) 1.0 m vertical fence.

Kinematic variables used to investigate engagement and reflex showed no significant differences between groups. It is interesting that, for both canter and jump, differences between groups were not found for HL engagement parameters. Previous studies have shown that horses with good jump technique exhibit decreased horizontal distance between the LdH and CM at take-off, which was negatively correlated with increasing fence height and was related to increased Z_{CM} at take-off (Powers, 2005). This "gathering" technique has also been reported in horses successfully clearing a water jump (Colborne et al., 1995). However, Powers and Harrision (2000) reported no significant differences in distance between LdH and CM between good and poor jumpers during free jumping over a 1.0 m fence. This is in accordance with results from this study, as evidenced by non-significant differences between groups for "tracking up". Lowest average hock flexion at take-off was observed in elite horses, further indicating that engagement, as defined by industry professionals, may not be a major determinant for successful jump execution, particularly over submaximal fences. Further studies are required to examine kinematic jump techniques in horses of varying calibres over larger fences, which may provide a better depiction of movement strategies between elite and non-elite athletes. However, this may be difficult, as riders suggested that many of the school, and some NC horses, were reaching the limits of their jumping capability for executing the 1.0m fence employed in this study.

Kinematic results from this study are largely in accordance with previous literature. Many of the movement traits of elite horses appear to comply with equestrian and biomechanical terminology used to describe sport horse movement, namely collection, impulsion and HL engagement at canter. HL engagement was less apparent during the jump stride. However, elite horses exhibited greater impulsion through generation of greater vertical impulse, resulting in greater Z_{CM} and $\dot{Z}_{CM}$. Joint articulation, which was most frequently described as an indicator of jump quality, showed no obvious differences between groups, suggesting that equestrians may consider placing more emphasis on impulsion when evaluating jump technique. Findings also suggest that the HL is a better indicator of quality canter and jump, which is in accordance with questionnaire results. However, overall lack of significant differences between groups reveal that desirable traits, as defined by equestrians, may not be ideal for differentiating between movement of elite and non-elite horses. Although further work is required to analyse additional variables that may provide better indicators of "quality" movement, it is apparent that movement alone may not provide an ideal means of separating good performers from poor ones.

9.2 Fundamental muscle activity patterns in elite and non-elite horses during jumping

9.2.1 Hindlimb muscles

The principal role of equine HL muscles is contribution to propulsion and powerful spring movements (Merkens et al., 1993; Payne et al., 2005; Denoix, 2014), with the gluteal muscles generally accepted as the largest contributors to propulsion and impulsion during stance phase (Payne et al., 2005; Denoix, 2014). In this study, the Superficial Gluteal and the vertebral head of the Biceps Femoris were chosen to investigate HL muscle activity during canter and jump.

As previously described in Chapter 5 and by Valentin and Zsoldos (2016), comparison of findings between equine EMG studies is difficult due to differences in sensor placement and data processing techniques. These differences were therefore carefully considered for discussion of findings from this study. It was found that, studies investigating EMG activity of Biceps Femoris, included vague descriptions of sensor placement (i.e. Tokuriki and Aoki, 1995; Robert et al., 1999), with some studies simply stating that sensor placement was over the midpoint of the muscle belly (Zaneb et al., 2007; Crook et al., 2010). These studies did not always explicitly state which of the three heads of the Biceps Femoris was targeted for sEMG data acquisition, which is particularly problematic due to the differing functional roles of each head (English and Weeks, 1987; Tokuriki and Aoki, 1995; Payne et al., 2005). Therefore, for the purposes of this discussion, only studies that have explicitly investigated the vertebral head will be used to comparatively examine findings from this study.

9.2.1(i) Canter

sEMG signals for the Superficial Gluteal during canter are reflective of its function as a hip flexor and HL limb protractor and abductor (Payne et al., 2005). Muscle activity onset observed in late swing phase, at approximately 85-90% of stride duration is in accordance with maximal hip flexion (Back et al., 1995b; Hodson et al., 2001). Superficial gluteal activity during the first half of stance phase is related to limb loading and subsequent hip flexion, which is thought to be regulated by eccentric contraction of the Gluteus Medius and hamstring muscles (Denoix, 2014). It is generally accepted that propulsion is generated during late stance and is produced by the combined release of stored elastic strain energy and concentric muscular contractions of hip extensors, which facilitate hip flexion and HL protraction during swing phase (Back et al., 1995b; Hodson et al., 2001). However, quiescent muscle activity from approximately mid-stance to late swing suggests that the Superficial Gluteal may have a passive role in HL protraction and propulsion.

This finding is in accordance with Wilson et al. (2003), who described protraction as a largely passive process in horses, which is achieved through elastic recoil rather than active muscle work. This is a feature of energetically economical gait strategies observed in horses (Biewener, 1998) and in other species (Roberts et al., 1997; Biewener et al., 1998). Equine musculoskeletal adaptations for economical gait are briefly discussed in Section 2.3.3(ii), which describes the proximal location of large muscles on the axial skeleton and the mainly passive elastic mechanisms of the distal limb. On their own, tendons exhibit low energy dissipation, and elastic recoil can return up to 95% of work generated by stretching, dissipating only about 7% as heat (Alexander, 2002). During stance, kinetic and gravitational potential energy are lost, but are stored briefly as elastic strain energy and returned during recoil of elastic mechanisms, mainly the long tendons and ligaments of the distal limb, but also within elastic elements of muscles (Alexander and Bennet-Clark, 1977; Biewener, 1998; Alexander, 2002). The elastic recoil of tendons has been estimated to contribute up to 36% of positive work required for galloping in horses (Biewener, 1998). As a result, the storage and recovery of elastic strain energy reduces the amount of work required from active muscular contraction (Roberts et al., 1997; Biewener, 1998; Alexander, 2002). It is however, important to note that active muscles are required during stance to provide the force necessary to support the body and maintain tension in elastic structures (Roberts et al., 1997). The substantial muscle mass of the proximal limb is also required for acceleration, deceleration and for jumping (Roberts et al., 1997; Alexander, 2002). Nevertheless, horses have been shown to display a highly economical locomotor strategy during bouncing gaits and at fast speeds (Biewener, 1998).

With this in mind, it seems reasonable that the Superficial Gluteal is active during the first half of stance phase to limit hip flexion during limb loading. However, elastic recoil and subsequent energy recovery from elastic structures reduces the requirement for active muscle shortening to facilitate hip flexion during swing phase. Previous equine sEMG studies are in agreement with this finding, reporting quiescent muscle activity of the Gluteus Medius during swing phase and late stance (Wentink, 1978; Robert et al., 1999, 2000, 2002). However, equine EMG studies have observed muscle activity of Tensor Fascia Lata during late stance and early swing phase (Wentink, 1978; Tokuriki and Aoki, 1995; Robert et al. 1999, 2000; Deban et al., 2012; Deniox, 2014). This muscle also functions as a hip flexor and has a much larger volume than the Superficial Gluteal (Payne et al., 2005). These findings may therefore suggest that larger hip flexors are actively contracted during late stance and early swing and may produce positive work during swing phase, while the smaller flexors such as the Superficial Gluteal function more passively relying on energy return through elastic recoil. This has not previously been demonstrated in horses during canter and highlights an important area for future research. However, muscle activity patterns of the Superficial Gluteal offer original insight into its function during canter.

To the author's knowledge, Williams et al., (2013) is the only study to investigate sEMG activity of the Superficial Gluteal in the LdH and TrH during canter. Unfortunately, comparisons with this study cannot be made, as phasic activity patterns were not described and sEMG signals were not presented in a manner, which illustrated the stride cycle. Interestingly, the majority of equine sEMG research has investigated activity of the Gluteus Medius (Roberts et al., 1998; 1999, 2000, 2002; Zaneb et al., 2009; Crook et al., 2010) during trot. However, these studies have reported similar phasic activity patterns to those observed in this study for Superficial Gluteal, with activity beginning during late swing and ceasing around middle-late stance (Robert et al., 1999, 2000, 2002). Interest in the Gluteus Medius is understandable, due to its known contribution to power production (Payne et al., 2005). However, this muscle is covered by the Superficial Gluteal and the thick gluteal fascia (König et al., 2007), arguably making it unsuitable for sEMG. The depth of muscle from which MUAP can be detected using surface electrodes has been estimated at approximately 5 – 15 mm for small and large motor units, respectively (Fuglevand et al., 1992; Winter, 2009) and energy in the sEMG signal will be dominated by MUs that have muscle fibres within 10-12mm of the electrode (Fuglevand et al., 1992). To the author's knowledge, no studies have explicitly reported the depth of the Superficial Gluteal. However, depths of 20 – 80mm have been reported for equine muscle biopsy taken from the Gluteus Medius (Rivero et al., 1992; Serrano et al., 1996), implying that a minimum depth of 20 mm is required to reach the Gluteus Medius. It is therefore possible that studies, which have reported sEMG data from the Gluteus Medius may have detected activity from the Superficial Gluteal. However, further work combining sEMG and intramuscular EMG is required to confirm this claim.

This is the only known study to investigate differences in the amount of muscular work done by LdH and TrH limbs at canter and jump using sEMG. It is important to note that, in this study only the right fore and hindlimb were measured. However, data collected from both canter and approach leads permitted investigation of muscle activity when they functioned as leading and trailing limbs. No significant differences were found between group and limb for EMG variables calculated from the Superficial Gluteal. Average normalised iEMG and ARV values were similar and ranged between 54.86 and 75.95% of maximum value observed at canter with consistently low SD observed across groups and limbs. Williams et al. (2013) also reported no significant differences between limbs for mean MUAP from the Superficial Gluteal, but reported highly significant differences between limbs for individual horses, which amounted to 58% of the study population.

However, these findings are likely due to the high levels of variability, as Williams et al. (2013) reported a mean maximum amplitude value of 157.24 ± 57.1 mV. Amplitude values of this range would imply that noise sources were not adequately attenuated from signals, as the average EMG amplitude ranges between a few μV to 2 – 3 mV (Konrad, 2006; Richards et al., 2008b). Other studies have reported significant differences between pelvic limbs from maximum EMG amplitude of the Gluteus Medius during trot (Zaneb et al. 2009). However, findings from this study suggest that muscle activity of the Superficial Gluteal is not altered by the differing functional roles of the LdH and TrH during canter, which have been demonstrated by kinematic findings in this study.

The biarticular Biceps Femoris muscle exhibits complex functionality (Tokuriki and Aoki, 1995) The vertebral head of the Biceps Femoris possesses the largest PCSA of any muscle in the pelvic limb and has long fascicles, demonstrating a high capacity for force production (Payne et al., 2005). sEMG signals presented in this study from the Biceps Femoris during canter are in accordance with functional descriptions for the vertebral head, which works to adduct the HL, extend the hip joint during stance, and flex the stifle during swing (Payne et al., 2005). Previous studies have described activity onset at the beginning of stance phase through to approximately middle stance, as representative of eccentric activity to limit flexion of the hip and stifle during HL impact and limb loading (Robert et al., 1999; Clayton et al., 2002). These findings are in agreement with this study, however it is important to note that there are inherent issues with defining muscle contraction type using sEMG signals alone and this is especially true for dynamic movements (Komi et al., 2000; Richards 2008b). Eccentric contractions produce greater peak force than isometric or concentric contractions, with maximum eccentric force estimated at 1.8 times that of isometric contractions (Lieber, 1992; Alexander, 2002). For a particular load, eccentric contractions generally require less MU activity, whereas concentric contractions will require greater MU activity (Richards et al., 2008b). Therefore, during controlled concentric contraction, sEMG amplitude is generally greater than controlled eccentric contractions (Tesch et al., 1990; Westing et al., 1991; Kellis and Baltzopoulos, 1998; Komi et al., 2000). However, dynamic activities with varying joint angular velocities, muscle forces and increased risk of electrode movement distort this relationship, making identification of contraction type more difficult (Richards et al., 2008b). Definition of contraction type from sEMG studies, must therefore be considered with caution. However, the synchronised collection of sEMG and kinematic data in this study is advantageous in that it allows direct comparison of muscle activity and movement data, which provide evidence for the type of contraction occurring.

Similar to the phasic activity pattern of the Superficial Gluteal, the Biceps Femoris was generally quiet throughout the second half of stance and the majority of swing phase. This observation again indicates that the hip extensor function of the Biceps Femoris during late stance, which has been described as occurring due to concentric contraction (Denoix, 2014), may actually be a largely passive event. No previous studies have investigated muscle activity of the Biceps Femoris during canter. However, during trot, Robert et al. (1999) observed consistent activity onset of the Biceps Femoris (vertebral head) at the end of swing phase, which lasted for the majority of stance phase. These findings are in accordance with Wentik (1978), but do not fully resemble the phasic activity patterns observed in this study during canter, which exhibited shorter activity duration that ceased around 50-75% of stance phase. These phasic activity differences are likely to be gait-dependent, as previous studies have reported the effects of increased speed on the phasic activity patterns of HL muscles (see Section 2.1.7; Robert et al., 2000, 2002; Crook et al., 2010). This finding, along with the fact that HL stance and stride duration are known to decrease significantly with increasing velocity (Leach and Drevemo, 1991; Holmström et al., 1995; McLaughlin et al., 1996; Crook et al., 2010; Harrison et al., 2012) may explain why muscle activity of the Biceps Femoris ceased earlier during canter. Irrespective of slight differences between studies, the phasic patterns observed in this study reflect the function of the Biceps Femoris, which becomes active at hoof impact to limit hip and stifle flexion during limb loading (Robert et al., 1999).

Differences between groups were observed for Biceps Femoris activity during canter, with the elite and school groups exhibiting significantly greater iEMG and ARV values than the NC group. Although non-significant PA data exhibited a similar trend, with elite and school groups displaying greater mean normalised values than the NC group. It is important to note that no significant differences were found between groups for HL stance duration, which represented the temporal domain for iEMG and ARV calculations. Therefore, differences in muscle activity observed between groups can be directly related to differences in EMG amplitude. Normalised iEMG data revealed that the Biceps Femoris of the TrH in NC horses were consistently working at approximately 40% of the maximum value observed at canter. This is approximately 20% less than iEMG values in elite and school horses, which worked at approximately 60% of their maximum observed value. Based on the phasic activity pattern observed in this muscle, it would appear that the Biceps Femoris muscles of NC horses are less active during stance phase. This finding suggests that NC horses were less able to oppose inertial forces at the end of swing phase and to stabilise the hip and stifle during limb loading at the beginning of stance phase. This offers original insight into different neuromuscular strategies in novice horses at canter and highlights an area, which trainers should aim to improve through training.

Interestingly, significant differences between LdH and TrH were found for all normalised sEMG variables from the Biceps Femoris during canter. Differences in average normalised iEMG and ARV values between limbs ranged from 20-30% across all groups, with the LdH performing greater muscular work. Differences in PA values between limbs were less pronounced, however PA values for the LdH were consistently greater than TrH. These findings suggest that, in contrast to the Superficial Gluteal, this muscle is likely to play a role in counteracting the functional differences in LdH and TrH during canter. As previously stated, the LdH experiences greater peak vertical load than the TrH (Merkens et al., 1993). It is therefore probable that the Biceps Femoris must generate eccentric contractions with greater force during stance phase to stabilise the leg and prevent involuntary flexion of the hip and stifle joints during increased limb loading (Breitfuss et al., 2015; Denoix, 2014). However, further work is required to explore this finding, as EMG data alone cannot provide a direct measure of muscular force (see Section 2.7). Furthermore, Back et al. (1997) observed significantly greater extension of the hip joint in the LdH at ground contact, which may indicate that the Biceps Femoris must exert greater effort during late swing to initiate retraction by reducing flexion of the HL joints to overcome inertia in preparation for impact. These findings have not previously been reported and provide objective justification for working the horse equally on both canter leads to promote balanced muscular development.

9.2.1(ii) Jump

In comparison to canter, the phasic activity patterns of the Biceps Femoris and Superficial Gluteal during jumping were relatively similar. Again, quiescent muscle activity for both HL muscles was observed during swing phase and jump suspension. However, prolonged duration and high amplitude activity bursts were observed during stance phases. A notable study by Roberts et al. (1997) examined muscle fibre length, force and activity using strain gauges, sonomicrometery and EMG, respectively, in the lateral gastrocnemius of turkeys during level and inclined running. During level running, the gastrocnemius exhibited "near-isometric" force production with the stretch and recoil of elastic mechanisms supplying the majority of mechanical work. However, increased muscular work and shortening occurred during inclined running, which resulted in greater iEMG values. Findings from Roberts et al. (1997) revealed the different mechanical functions for muscle during level running and for activities requiring net work for: accelerating the body, reducing drag, and lifting the CM at take-off. Therefore, during jumping, HL muscle activity during late stance appears to be reflective of muscle shortening or concentric contractions to facilitate extension of the hip and stifle joints for propulsion. Further work is required to investigate this, however results from this study indicate that the energetically economical strategies observed during canter, were disturbed during jumping.

Normalisation of data permitted investigation of the proportional change of muscle workload between canter and jump. iEMG values from Superficial Gluteal during take-off exhibited an average increase of approximately 7.5 times, 12 times, and 2 times those observed during canter in elite, NC and school groups, respectively. In comparison to the Superficial Gluteal, increases in iEMG values between canter and take-off were much smaller for the Biceps Femoris with increases of approximately 4.5 times, 5 times and 3 times those observed for elite, NC and school groups, respectively. These values were calculated using average normalised iEMG values for each group. iEMG is commonly used to quantify the amount of work done by a muscle and a highly linear relationship has been found between iEMG and exercise intensity (Taylor and Bronks, 1995). Although iEMG cannot discern changes in MU recruitment or rate coding, it does provide an indirect measure of increases in both parameters that occur as a result of increases in exercise intensity (Soderberg and Cook, 1984; Basmajian and De Luca, 1985; Taylor and Bronks, 1995). These large increases in muscular effort are therefore unsurprising, due to the increased net muscle work required to increase kinetic or potential energy of the CM during jumping (Roberts et al., 1997; Biewener and Roberts 2000). Furthermore, increases in iEMG activity are in accordance with previous equine studies that have reported significant increases in HL muscles during work on an incline (Robert et al., 2000, 2002; Crook et al., 2010). The most interesting aspects of this research were the differences in muscle activity observed between groups and these findings will therefore form the focus of this section.

During A1 stride, the Superficial Gluteal of NC horses exhibited significantly greater iEMG values than elite and school groups, with no significant differences found for ARV and PA data. These findings suggest that differences in iEMG values were related to muscle activity duration, with NC horses exhibiting higher amplitude bursts of activity over a relatively longer duration than elite and school groups (Figure 9.2). Interestingly, the amount of work performed by the Superficial Gluteal in A1 stride was similar to a normal canter stride for elite and school horses. Whereas NC horses begin to exhibit greater muscular effort in preparation for the take-off phase, which was exhibited by average iEMG values from A1 stride that were approximately three times greater than those observed during canter. This shows some agreement with Barrey et al. (1993), who postulated that inexperienced horses approach the fence at faster speeds to compensate for the lack of strength required to convert horizontal velocity to vertical velocity at take-off. Findings from this study do not fully agree with this claim, as the elite group exhibited significantly greater stride velocity than NC and school horses during A1 stride. However, NC horses do appear to employ different neuromuscular strategies to compensate for lack of muscular strength through anticipatory increases in muscular activity and longer stance durations for development of muscular force.

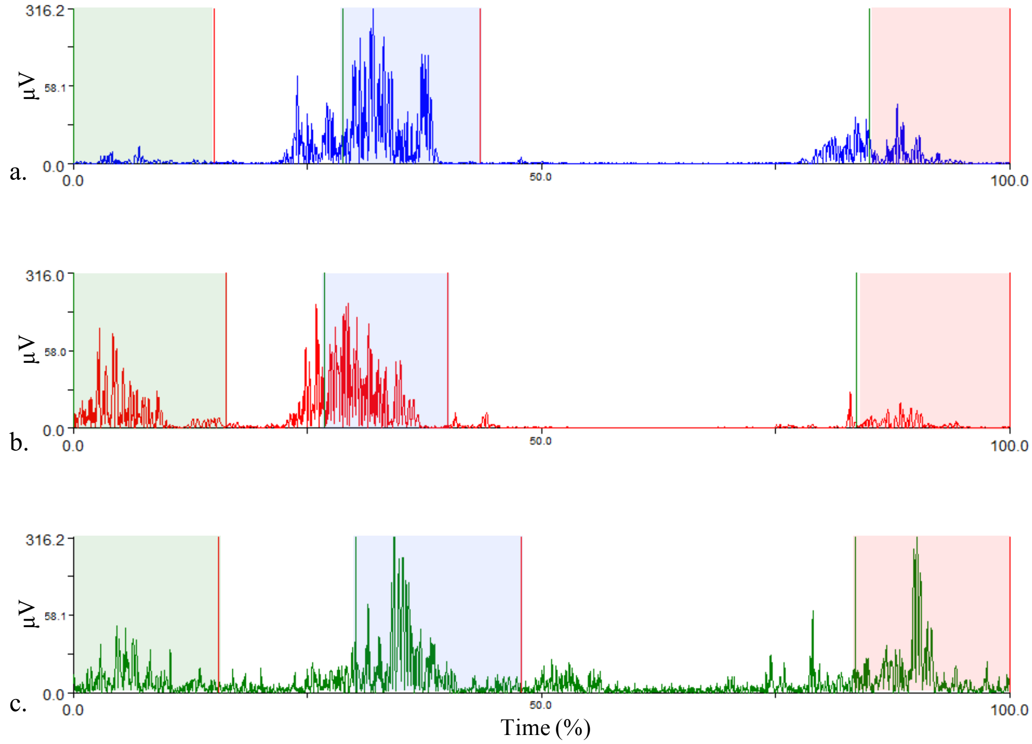


Figure 9.2 Representative sEMG signals from one horse per group for the Superficial Gluteal muscle from TrH during approach (A1) and jump strides. Signals from each group are represented: a.) elite, b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Signals presented are DC offset, high pass filtered at 80 Hz and full-wave rectified. EMG activity are presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

Contrary to the Superficial Gluteal, the Biceps Femoris, which exhibited differences between group and limb at canter, showed no significant differences during A1 and take-off phases of the jump. NC horses displayed similar normalised iEMG, ARV and PA values to elite and school groups during A1. However, the NC group exhibited lower normalised values for canter (Section 9.2.1(i)), which must be considered when examining these findings. For the NC group, average iEMG values from A1 stride that were found to be approximately 2.5 times greater than those observed during canter. Therefore, although no significant differences were found between groups, the Biceps Femoris of NC horses must produce greater muscular work during A1 than elite and NC horses. This is in accordance with the anticipatory activation strategies found for the Superficial Gluteal muscle during A1.

At take-off, significantly greater iEMG, ARV and PA values for the Superficial Gluteal were observed in the NC group compared to elite and school groups, which again indicate that increased work was required to execute the fence. Although the elite group exhibited greater average iEMG values than the school group, no significant differences were found, which is likely the result of higher variability within the elite group. Interestingly, ARV values from the elite group were significantly greater than the school group, but no significant differences were found for PA. Non-significant differences for HL stance duration and PA, suggest that significant differences in ARV are related to increased relative amplitude and generally shorter activity duration in elite horses. For example: although non-significant, average HL stance duration was shorter for elite horses than the school horses necessitating a shorter burst of activity with an abrupt increase in amplitude. Whereas school horses generally exhibited a longer activity burst with a more gradual increase in amplitude (Figure 9.2). Furthermore, muscle activity onset of the Superficial Gluteal generally started earlier in the elite group during late A1 swing phase, which was not accounted for in iEMG and ARV calculations.

Interestingly, normalised iEMG for one elite horse clearing a 1.40 m fence were found to be 852.4% for the TrH, which is very similar to average normalised iEMG values from the TrH of NC horses executing a 1.0 m fence (867.4 ± 342.1%). Although not mutually exclusive, these findings are remarkably similar to Schamhardt et al. (1993) who found that vertical impulse and GRF amplitudes in inexperienced horses jumping a small fence (0.8m) were similar to those experienced by a more talented horse over a 1.30 m fence. These findings suggest that elite horses were capable of increased force production at take-off, through increased MU recruitment or rate coding. However, further studies investigating muscle activity onset, muscle fibre length and GRF data are required to explore this further.

Similar to A1, no significant differences were observed between limb or group for Biceps Femoris during take-off, with the elite group consistently exhibiting the greatest average normalised iEMG, ARV and PA values. Again, these findings were consistent with muscle activity bursts characterised by abrupt increases in amplitude at onset in elite horses, while school horses exhibited bursts of similar duration, but with more gradual increases in amplitude and generally lower peak amplitude. As presented earlier in this section, percent increases revealed that the Biceps Femoris showed less proportional change between canter and take-off compared to the Superficial Gluteal. These findings indicate that the Superficial Gluteal plays a greater role in muscular power production than the Biceps Femoris during jump execution. This is in accordance with human studies that have described the Biceps Femoris as having little positive effect on hip extension during vertical jumping, and instead functions more as a stabiliser (Goodwin et al., 1999).

St. George and Williams (2013) is the only known study to investigate Superficial Gluteal muscle activity during jumping in equine subjects. The phasic activity patterns reported by St. George and Williams (2013) are in agreement with this study. However, mean peak amplitude values for A1 stride were found to be significantly greater than the jump stride, which is not in agreement with this study. Methodological differences between studies make direct comparison of data from sEMG magnitude analysis difficult. It is important to note that data from St. George and Williams (2013) were not normalised or high-pass filtered, and were low-pass filtered with a more aggressive cut-off frequency (10 Hz) than was applied in this study. Furthermore, GE were visually identified using videographic data that were manually synched with EMG data, which is inherently less accurate and is likely to have affected the accuracy of findings. Chapter 5 revealed the importance of appropriate high and low-pass filtering techniques for sEMG data collected from equine subjects during jumping. Therefore, methodological constraints suggest that results from St. George and Williams (2013) should be considered with caution and that findings from this study offer a better representation of Superficial Gluteal activity in the jumping horse.

Comparison of results from the Biceps Femoris with other studies is not possible, as no studies have examined this muscle during jumping. Previous studies have reported high variability in the phasic activity pattern and magnitude of the Biceps Femoris in equine (Tokuriki and Aoki, 1995; Robert et al., 1999), canine (Breitfuss et al., 2015) and human (Goodwin et al., 1999) subjects. Goodwin et al. (1999) attributed high variation to the biarticular function of this muscle, which is affected by the velocity of movement at two joints. However, in this study iEMG, ARV and PA data for all jump phases exhibited low SD values across group and limb, with the highest SD observed during take-off and at landing in the elite group. The low SD reported in this study provides evidence for the importance and reliability of methods developed in Chapter 5 for sEMG data acquisition in equine subjects.

No significant differences between group were found for Superficial Gluteal muscle activity during landing phase. This is surprising considering the hindlimb's role in re-establishing horizontal velocity following landing of the FL (Clayton, 1989; Clayton and Barlow, 1991). However, significant differences were observed in the Biceps Femoris at landing, with elite horses exhibiting significantly greater ARV than school horses. Although, non-significant the elite group also displayed greater normalised iEMG values, suggesting that significant differences were the result of activity bursts with a more abrupt increase in amplitude, which remained higher for a larger proportion of the burst. These findings offer original insight into the differing functional roles of HL muscles at landing. Results suggest that the Biceps Femoris, may contribute more to the regeneration of forward propulsion at landing phase, while the Superficial Gluteal appears to play a greater role for the production of vertical velocity at take-off. However, further work is required to explore the functional role of additional HL muscles in order to confirm this statement.

9.2.2 Forehand Muscles

The mechanisms of the muscle-tendon units (MTU) of the equine thoracic limb have been the focus of much research, which has revealed its function as a passive spring (Wilson et al., 2001; McGuigan and Wilson, 2003; Wilson et al., 2003; Lichtwark et al., 2009). Although the locomotor muscle mass is concentrated on the pelvic limb, the forelimbs experience approximately 60% of vertical impulse (Witte et al., 2004; Hobbs et al., 2014), which is indicative of their role as supporting limbs, with the HL serving a mainly propulsive function (Merkens et al., 1993). The equine forehand is unique in that it does not have clavicles and the thoracic limb is not attached via bony articulation (Payne et al., 2004). Instead, the thoracic limb is attached to the trunk via muscle attachment, or a synsarcosis (Payne et al., 2004). The extrinsic muscle group is responsible for the attachment of the thoracic limb to the trunk (Payne et al., 2004). In this study, the Triceps Brachii (long head) and Cervical Trapezius were investigated to explore muscle activity of the thoracic limb and extrinsic muscle group, respectively, during canter and jump. The Splenius was investigated due to its functional importance for the head and neck complex (Zsoldos et al., 2010b).

9.2.2(i) Canter

The Triceps Brachii functions to extend the elbow and flex the shoulder, working as an antagonist to the Biceps Brachii (Watson and Wilson, 2007). The long and lateral heads of the muscle are ideally located for extending the elbow and decelerating the limb at the end of swing phase (Watson and Wilson, 2007). The Triceps Brachii has received considerable attention in equine EMG studies, which have described the muscle as being active from mid-late swing to mid-late stance phase at canter (Hodson-Tole et al., 2006; Harrison et al., 2012).

Harrison et al. (2012) noted that during walk and trot, the majority of FL muscles display peak EMG activity at the hoof impact event, but two different peaks were observed during mid-stance and in early swing during canter. This finding is in agreement with phasic activity patterns observed in this study for the Triceps Brachii, but also for Trapezius, Splenius and Superficial Gluteal. Hodson-Tole (2006) found that the time of peak EMG amplitude for the Triceps Brachii was strongly associated with the maximum limb protraction event, which is indicative of its function for reversing the limbs rotation in preparation for landing. Although this association was not quantified, Hodson-Tole's (2006) finding is in accordance with phasic activity patterns observed in this study

(Figure 9.3). These findings are also in agreement with kinematic studies that describe the occurrence of elbow extension in late swing, which results in simultaneous extension of the carpus and fetlock joints to lengthen the limb (Back et al., 1995; Hodson et al., 2001). As a result, the lengthened limb works to overcome inertia, initiate retraction and slow the limb in preparation for ground contact (Back et al., 1995; Hodson et al., 2001). EMG studies suggest that, in contrast to the largely passive nature of protraction (Wilson et al, 2003; Lichtwark et al., 2009), FL retraction is not a passive event, as the majority of FL muscles become active during late swing (Jansen et al., 1992; Hodson-Tole et al., 2006; Harrison et al., 2012). As a result, Hodson-Tole (2006) suggest that the Triceps Brachii works eccentrically at the end of swing phase to initiate retraction. This is also in accordance with findings from this study, as phasic activity patterns showed smaller bursts of activity during late swing, which are generally associated with eccentric contractions (Tesch et al., 1990; Westing et al., 1991; Kellis and Baltzopoulos, 1998; Komi et al., 2000). These findings also suggest that the significant differences observed between groups for FL retraction are facilitated by muscle activity during swing phase, which was not investigated in this study.

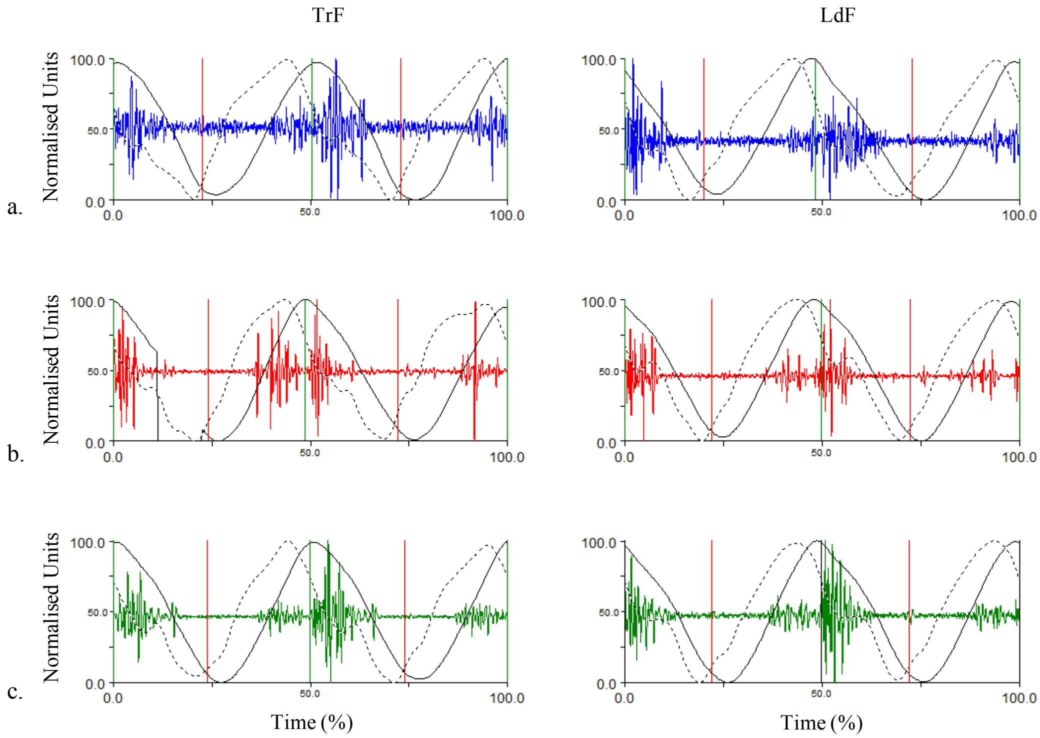


Figure 9.3 Time-angle curves for forelimb pro/retraction (black solid line) and elbow joint (dashed line) overlaid over representative sEMG signals from Triceps Brachii muscle during canter. Signals from one horse from each group are represented: a.) elite, b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80 Hz. Signals are normalised between two canter strides. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

During stance, the Triceps Brachii has been described as playing an anti-gravity role, which contributes to stabilisation of the elbow during limb loading (Roberts et al., 2002; Hodson-Tole et al., 2006; Harrison et al., 2012). Time-angle curves for the elbow joint are illustrated in Figure 9.2 and are similar to those presented by Back et al., (1995), where a period of elbow flexion occurs at approximately 30% of stance phase. Figure 9.3 reveals that the Triceps Brachii is active in the first half of stance phase to stabilise elbow extension and generally ceases its activity at, or just after, the flexion peak in the first half of stance. Although this association between elbow kinematics and muscle activity was not quantified, these findings support the antigravity function of the Triceps Brachii, which has been previously described (Robert et al., 2002; Hodson-Tole et al., 2006; Harrison et al., 2012). Based on analysis of kinematic and sEMG data at trot, Robert et al. (2002) suggest that eccentric activity occurs during stance phase to support the elbow joint. However, a study by Hoyt et al. (2005), which measured muscle fascicle length using sonomicrometry, reported that the lateral head of the Triceps Brachii actually shortens during stance phase at trot. Data from this study cannot discern contraction type during stance, and further work is required to examine muscle fibre length in the long head of the Triceps Brachii during canter. However, to the author's knowledge this is the first equine study to present non-enveloped sEMG traces and angular kinematic data simultaneously, which offers original insight into how superficial muscles facilitate movement.

Average normalised EMG data were remarkably similar across limb and group for the Triceps Brachii and exhibited similarly low SD values. These findings suggest that the Triceps Brachii produces a similar amount of work during stance, irrespective of the calibre or training level of horses. Although not examined in this study, the Biceps Brachii should be considered when investigating muscle activity of the Triceps Brachii, as co-contraction of these muscles has previously been described as important for: joint stability, positional control of the limb and mitigation of shear loading during stance phase at canter (Harrison et al., 2012). The Biceps Brachii has been described as to exhibiting greater PCSA and isometric force generating capacity than the Triceps Brachii (Watson and Wilson, 2007). It has also been likened to a catapult mechanism, where release of elastic strain energy stored in its tendon during stance phase contributes largely to the passive process of limb protraction (Wilson et al., 2003). Therefore, further studies examining the combined activity of Biceps Brachii and Triceps Brachii, may divulge further information related to whether neuromuscular strategies are in fact similar between elite and non-elite athletes during canter.

The Splenius represents one of the largest and most superficial muscles of the dorsal cervical region (Gellman et al., 2002). When contracted bilaterally, its function is to elevate the head and neck and to extend the poll, while unilateral contraction results in lateral flexion and rotation of the neck (Denoix, 2014; Zsoldos and Licka, 2015). This muscle is characterised by a simple, strap-like structure and long muscle fibres, which are indicative of a power-producing muscle (Gellman et al., 2002). However, Gellman et al. (2002) reported that this muscle is predominantly composed of slow-twitch fibres, suggesting that the Splenius may be a large contributor to postural control. sEMG evaluation of the Splenius has mainly been conducted during trot (Robert et al., 1998, 2001a, 2002; Zsoldos 2010a; Kienapfel, 2015), where activity onset has been reported just prior to FL impact, continuing to middle-stance phase (Robert et al., 2001a, 2002). EMG amplitude has been found to increase with increased velocity and slope (Robert et al., 2001a, 2002; Zsoldos et al., 2010a), which has been associated with increased muscular activity required for stabilisation against passive forces exerted on the head and neck during faster gaits (Robert et al., 2002; Zsoldos et al., 2010a). A more elevated head and neck position (HNP) via Splenius contraction has also been described as a mechanism for mitigation of vertical loading during FL stance (Robert et al., 2002; Zsoldos et al., 2010a). This has been observed in studies that have investigated the effect of HNP on GRF data, where more elevated HNP have been reported to reduce vertical GRF in the FL (Weishaupt et al., 2006a). However, Kienapfel (2015) observed that EMG activity of the Splenius was actually greatest during a "free" HNP due to its antigravity function, with the ventral neck muscles showing greater EMG activity during elevated and hyperflexed HNP. In this study, all riders were experienced and rode with contact, but in a manner that did not restrict the head and neck. This may partially explain why similar iEMG, ARV and PA values were observed across groups. It is also possible that muscles which have an antigravity role are less likely to differ between horses.

Equine head and neck segments have been found to demonstrate gait specific oscillations that are closely linked to movement patterns in the limbs (Gellman et al., 2002). Unfortunately, neck movement was not investigated in this study and direct relations cannot be made between Splenius activity and neck movement patterns. However, the different phasic activity patterns observed between limbs and the significantly greater iEMG values found for the TrF, may offer some insight into the relationship between limb movement and Splenius activity. Interestingly, Tokuriki and Aoki (1991) described similar asymmetrical phasic activity patterns for the LdF and TrF at canter, with Splenius activity onset occurring from middle-swing to middle-stance phase in the LdF and from early-stance to early-swing in the TrF. To the author's knowledge, these represent the only studies to describe bilateral neck muscle activity during canter. The differing phasic activity patterns observed in this study appear to be consistent with FL function during canter. Activity onset in the TrF at the end of stance phase may be related to elevation of the head and neck to mitigate the greater vertical forces experienced by this limb (Merkens et al., 1993) and to facilitate the transmission of propulsory forces (Denoix, 2014). This would explain why greater iEMG values were observed for this limb. In contrast, activity onset at middle-swing phase in the LdF may be related to extension and lowering of the head and neck to aid in decelerating the limb, which produces the greatest retardatory forces (Merkens et al., 1993). Further studies are required to investigate these patterns using kinematic data from the head and neck.

There are no collateral ligaments at the equine shoulder, necessitating muscle action for stabilisation of this joint during locomotion. The Cervical Trapezius inserts onto the spine of scapula and functions to move the scapula cranially and dorsally and to facilitate limb protraction (Payne et al., 2004; Zsoldos and Licka, 2015). This muscle is also thought to play an important role for scapula stabilisation during limb loading (Payne et al., 2004). The extrinsic muscle group are described as having little scope for power production due to their relatively small muscle mass. Instead, Payne et al (2004) suggest that these muscles are more suited to power absorption via eccentric contractions. However, very little quantitative data is available on the function of the Trapezius and Kienapfel (2015) is the only known study to investigate its activity patterns during dynamic movements. Kienapfel (2015) describes the antigravity role of the Trapezius, but provides very little information in relation to its phasic activity pattern during locomotion. To explore the proposed function of the muscle, FL pro/retraction and scapula inclination data were overlaid onto sEMG signals during canter (Figure 9.4).

Similar to the Splenius, phasic activity patterns of the Trapezius were found to differ between LdF and TrF during canter. Figure 9.4 reveals that the role of the Trapezius is directly related to the different functions of the FL during canter. Although relationships between kinematic and sEMG data were not quantified in this study, it is interesting to note that LdF and TrF activity onset occurred around maximum scapula protraction and ceased around maximum scapula retraction. Activity onset in the TrF during middle-stance supports its role for stabilising the scapula during vertical limb loading, which is greatest in this limb (Merkens et al., 1993). This is in accordance with greater iEMG values observed for the TrF. The generally smaller initial burst of activity during middle-stance may suggest that stabilisation of the scapula is facilitated through eccentric or isometric contractions, however further work is required to confirm this. The second activity burst at the end of stance phase illustrates facilitation of limb protraction in early swing through transmission of propulsory forces generated in the TrF. In the LdF, FL pro/retraction and scapula inclination were not as synchronous as in the TrF, with scapula inclination occurring prior to maximum limb protraction. This may represent a mechanism for initiating limb retraction in late swing through early stabilisation of the scapula in the more protracted LdF (Back et al., 1997). Muscle activity during early stance is likely associated with stabilisation of the scapula during high retardatory forces, which are experienced by the LdF. Interestingly, peak EMG activity was found to coincide with maximum protraction in the LdF. Findings from this study offer support for the function described by Payne et al. (2004), who state that extrinsic muscles play an important role for adjusting movement of the largely passive thoracic limb. This appears to be true for the Trapezius due to its active role for facilitating limb protraction. Further work should be conducted to quantify the associations observed in this study between kinematic and sEMG data.

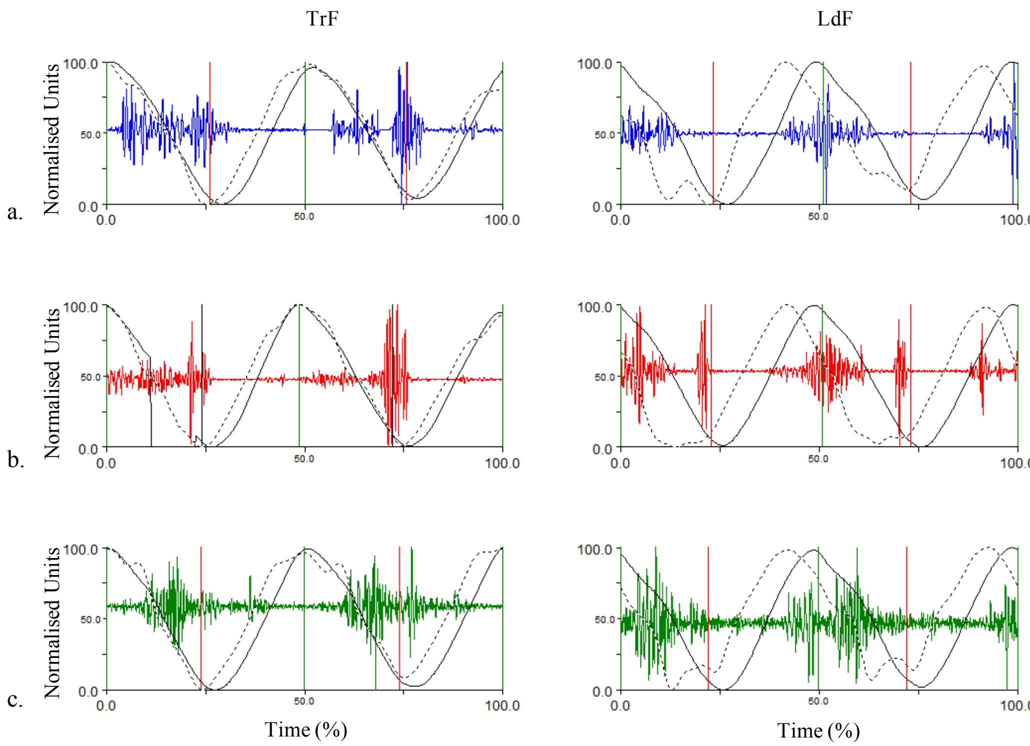


Figure 9.4 Time-angle curves for forelimb pro/retraction (black solid line) and scapula inclination (dashed line) overlaid over representative sEMG signals for the Trapezius muscle during canter. Signals from one horse from each group are represented: a.) elite, b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Signals presented are DC offset and high pass filtered at 80Hz. Signals are normalised between two canter strides. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

9.2.2(ii) Jump

EMG signal analysis revealed increases in muscle activity for all forehand muscles during jump. This is in accordance with Bobbert and Santamaria (2005), who describe the energetic demands of FL musculature during push-off before the fence (see Section 2.6.2(i)). The proportional changes in muscular activity between canter and jump were found to be much smaller for forehand muscles than HL muscles. This was especially true for the Splenius and Trapezius muscles. For the Triceps Brachii, the school group consistently displayed the lowest average normalised iEMG, ARV and PA values across all phases. Findings from the school group during A1 stride will not be discussed due to insufficient data. However, NC horses exhibited greater Triceps Brachii activity during A1. Average normalised iEMG values for A1 stride were found to increase by approximately 3.5 times and 5.5 times the average normalised canter values for elite and NC horses, respectively. This finding suggests that NC horses employ similar neuromuscular strategies to those observed in the

HL, which showed anticipatory increases in muscle activity during A1. At take-off, the lowest iEMG values were observed in the school group, with the Triceps Brachii of elite horses exhibiting the greatest muscle activity. Significant differences were not found between groups, but this is likely due to high SD in elite and NC groups. The proportional change for between canter and take-off for iEMG values from the Triceps Brachii, showed increases of 6.5 times, 5 times and 2 times canter values for elite, NC and school groups respectively, which is relatively similar to the percent change calculated for Biceps Femoris during take-off. The large increase in muscular work observed for Triceps Brachii is in accordance with previous studies, which have suggested that the energy required to increase $\dot{Z}_{CM}$ at take-off is not solely attributable to the pole-vault mechanism (Bogert et al., 1994; Santamaria et al., 2004a; Bobbert and Santamaria, 2005). Therefore, during jumping, the FL does not act as a mere passive spring and muscle shortening is required to generate the mechanical work required to lift and accelerate the CM at take-off (Roberts et al., 1997; Alexander, 2002; Santamaria et al., 2004a; Bobbert and Santamaria, 2005).

St. George and Williams (2013) is the only other study to examine activity of the Triceps Brachii during jumping. This study described similar phasic activity values for the jump stride, but reported that PA values were lowest for the jump stride, which is not in agreement with this study. Again, methodological constraints in the study by St. George and Williams (2013) are likely to explain these differences (see Section 9.2.1(ii)). Visual observation kinematic and sEMG data revealed that phasic activity of the Triceps Brachii was directly related to extension of the elbow and deceleration of the limb in late swing (Figure 9.5). Muscle activity onset during late swing occurred at the initiation of elbow extension and ceased in middle to late stance, indicating a muscular role in propulsion (Bobbert and Santamaria, 2005). Interestingly, activity bursts following take-off occurred in relation to increases in elbow flexion and limb protraction. At landing, muscle activity was again associated with elbow extension, which supports the antigravity function described in previous research (Robert et al., 2002; Hodson-Tole, 2006; Harrison et al., 2012).

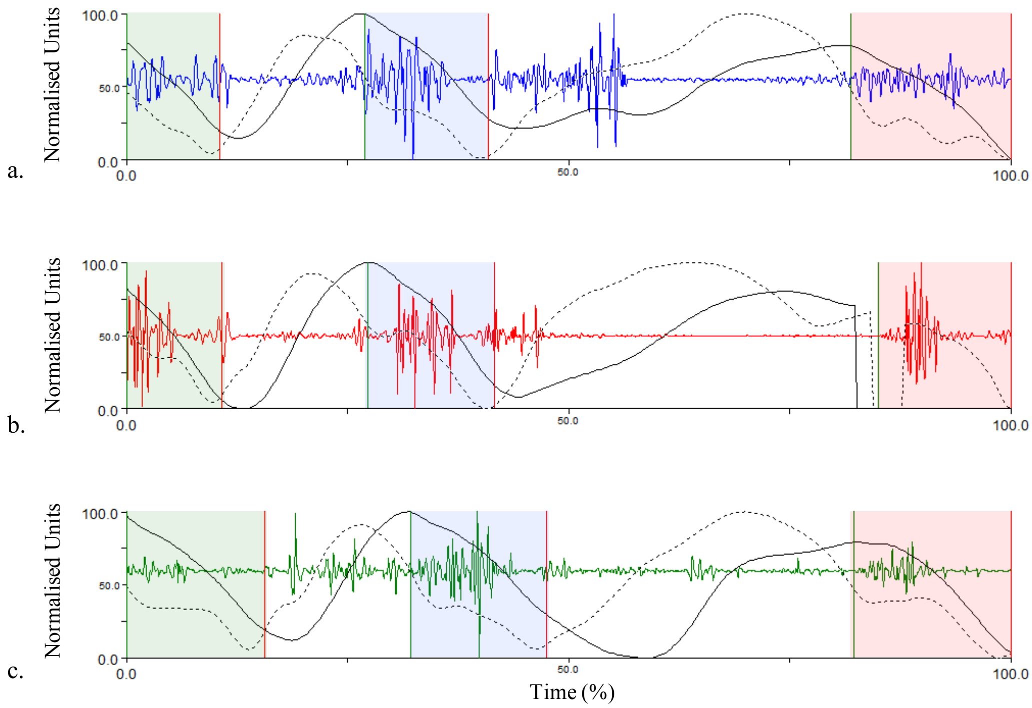


Figure 9.5 Time-angle curves for forelimb pro/retraction (black solid line) and elbow joint angle (dashed line) overlaid over representative sEMG signals for the Triceps Brachii muscle from LdF during A1, jump and departure strides. Signals from one horse from each group are represented: a.) elite b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Shaded areas represent fore stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80 Hz. Signals are normalised between hoof impact event at A1 and hoof off event at departure stride. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

During jump, phasic activity of the Splenius was found to be directly associated with its stabilising and extension role observed during canter. Muscle activity at take-off occurred between late swing and early stance and ended during middle to late stance phase. The double activity burst observed in canter was less prevalent and single bursts of activity were characterised by a more gradual increase in amplitude. This may suggest that MU recruitment or rate coding increased at a more constant rate during jump. Muscle activity at FL take-off and landing are in agreement with Denoix (2014), who describe Splenius activity for stabilisation of the head and neck, which are passively lowered by inertia during limb loading. In the second half of stance, the head and neck are elevated to reduce vertical impulse and to aid in propulsion (Denoix, 2014). Therefore, muscle activity extending into late stance may suggest that the Splenius contracts concentrically to elevate the neck. To the author’s knowledge, Giovagnoli et al. (1998) is the only other study to investigate Splenius activity during jumping. In their study, Giovagnoli et al. (1998) describe a similar phasic activity pattern to that observed in this study. Interestingly, Giovagnoli et al (1998) also describe Splenius activity during middle jump suspension, which was related to head and neck extension. Activity bursts during the airborne phase were also observed in this study, but the location of activity bursts varied within jump suspension.

Significant differences were not found between group and limb for EMG variables from the Splenius. iEMG values were found to be the lowest and least variable for the elite group during take-off and landing, but were relatively similar for NC and elite groups. Average normalised iEMG values for the Trapezius were slightly greater than the Splenius, but a similar trend was observed with the elite group displaying the lowest average values. Average iEMG values for the Trapezius during canter were found to increase by approximately 2 times, 3 times and 3.5 times during take-off in elite, NC and school groups, respectively. These findings reveal that the Splenius and Trapezius may play a greater role for stabilisation in non-elite horses. It is also possible that non-elite horses employed different HNP during take-off to assist with propulsion and vertical velocity. This may have effected findings as different HNP have been shown to affect Splenius and Trapezius muscle activity (Kienapfel, 2015). Kinematic data from the head and neck segments are required to explore these findings further.

The relatively low increase in work done by the Trapezius during jumping compared to pelvic limb muscles, appears to support Payne et al. (2004), who postulate that extrinsic muscles are less suited for power production and more suited to power absorption. This is also supported by the phasic activity patterns observed in this study, as visual observation of sEMG and kinematic data revealed that activity during middle-late stance at take-off and early-middle stance at landing was associated with stabilisation of the scapula during limb loading, which is likely due to muscle lengthening (Payne et al., 2004). Comparison of these results with other studies was not possible, as this is the first study to present muscle activity patterns for the Trapezius during jump. Therefore, similar to canter, kinematic data for FL pro/retraction and scapula inclination were used to explore its proposed functions (Figure 9.6).

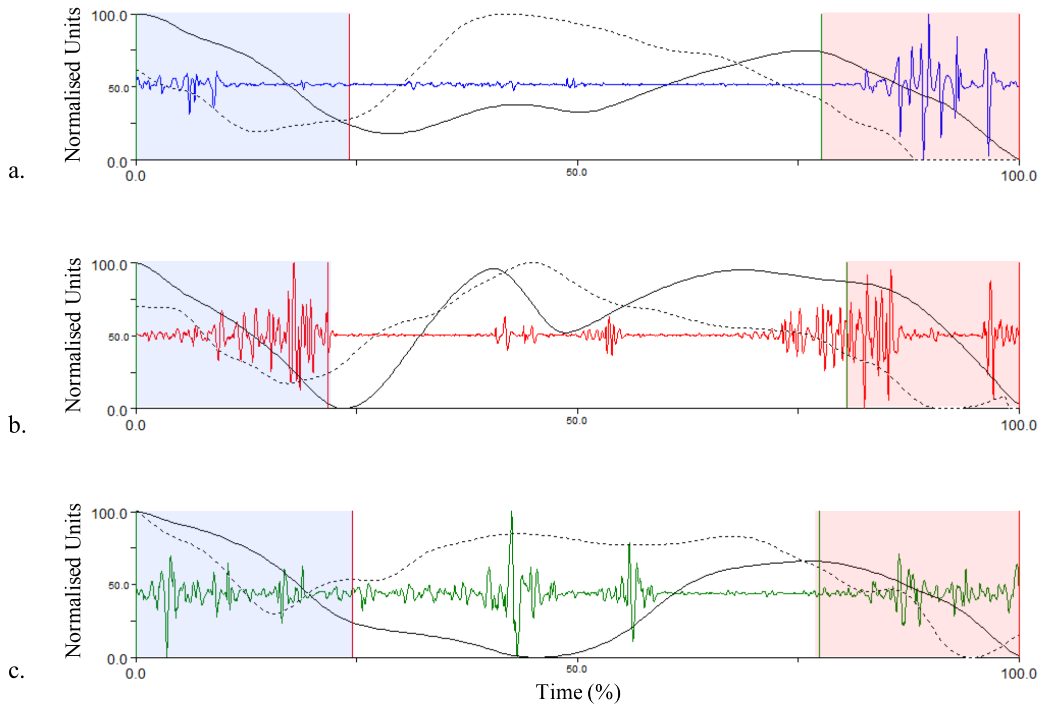


Figure 9.6 Time-angle curves for forelimb pro/retraction (black solid line) and scapula inclination (dashed line) overlaid over representative sEMG signals for the Trapezius muscle from LdF during jump stride. Signals from one horse from each group are represented: a.) elite b.) NC c.) school. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Shaded areas represent fore stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset and high-pass filtered at 80Hz. Signals are normalised between hoof impact event at take-off and hoof off event at landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

Although not quantified in this study, Figure 9.6 illustrates that Trapezius activity is related to scapula stabilisation and regulating retraction during limb loading. At take-off, this is observed where muscle activity occurs at maximum scapula retraction and ceases shortly prior to FL protraction. Bursts of activity during jump suspension were found to occur in relation to increases in scapula inclination. Interestingly, sEMG signal presented for the school horse (Figure 9.5c) did not exhibit protraction until middle jump suspension. Instead, the limb retracted under the horse’s body, which may be due to positioning the FL too close to the fence. Nevertheless, this resulted in Trapezius activity during the transition from retraction to protraction, further justifying this muscle’s role as a limb protractor. At landing the muscle became active during limb and scapula retraction, which is again suggestive of its stabilising role during limb loading. These findings offer the first insight into activity of the Trapezius muscle during jumping, and again reveal that this muscle may play a greater role in the jump technique of non-elite horses.

9.2.3 Summary of fundamental muscle activity patterns in elite and non-elite horses during jump and canter

Increases in muscular activity between canter and jump were observed in all muscles investigated. This is in accordance with previous studies that have described the fundamentally different mechanical function of skeletal muscles during activities such as jumping compared to level running (Roberts et al., 1997; Robert et al., 2000; 2001a, b, 2002; Hodson-Tole, 2006; Crook et al., 2010). Payne et al. (2004) state that the bulk of propulsive muscle required for accelerating and jumping activities is most likely located in the pelvic limb. Findings from this study support this claim, as pelvic limb muscles exhibited the greatest proportional change in work between canter and jump. This finding also concurs with previous studies that have described the HL muscles as being largely responsible for the production of mechanical work required for jump execution (Bogert et al., 1994; Barrey and Galloux, 1997; Bobbert and Santamaria, 2005). Apart from the Splenius and Trapezius, the school group consistently exhibited the lowest normalised EMG values during canter and jump. Studies suggest that the HL of poor jumpers produce a weaker force for push off than the ones of good jumpers (Barrey and Galloux, 1997) and findings from this study suggest that this is likely true for school horses. The Splenius and Trapezius muscles were found to function mainly as stabilisers and for fine-tuning of the largely passive movements generated by the thoracic limb. These muscles also exhibited a relatively low increase in muscular activity during jump compared to the other muscles investigated. However, large increases in iEMG values for the Triceps Brachii in elite and NC horses, revealed that this muscle makes an active contribution to generation of vertical velocity and elevation of the CM at take-off. Apart from the Biceps Femoris, muscle activity patterns and normalised EMG values were relatively similar across groups during canter, with no significant differences observed. Instead, differences in muscle activity for canter were mainly associated with the different mechanical functions of leading and trailing limbs, which provides original, objective evidence for working the horse equally on both canter leads.

Many of the muscles described in this section have not been previously investigated during canter and jumping. Previous anatomical (Payne et al., 2004, 2005; Watson and Wilson, 2007), histological (Gellman et al., 2012) and kinematic studies (Bogert et al., 1994; Bobbert and Santamaria, 2005) have offered suggestions for the functional roles of many of the muscles investigated. However, this study is unique, in that it provides quantitative reference information for the fundamental activity patterns of superficial muscles from the neck, pelvic limb and thoracic limb, which represents an original contribution to knowledge. This information may be used to advance our current understanding of equine locomotion and will be extrapolated to inform training methods in Section 9.4.

To the author's knowledge, this is the only study to explore muscle activity patterns and differences between groups of horses with varying levels of athletic ability and competition experience. In human research, muscle activation patterns for explosive movements have reported differences in muscle activation patterns between professional and amateur athletes (Cerrah et al., 2014). For example, in football players performing a countermovement jump, temporal and amplitude values from sEMG data were found to be similar between professional and amateur athletes, with significant differences in muscle activation strategies observed between groups during propulsion, push-off and flight phases (Cerrah et al., 2014). These findings are largely in accordance with this study, as differences in normalised EMG values were largely non-significant between groups. However, further exploration of fundamental activity patterns and signal amplitude variables in additional muscles is required. This may divulge further information for differences in movement patterns and underlying muscular control in elite and non-elite athletes. This information is vital for understanding how "quality" movement is facilitated by muscular action, which will be explored in the proceeding sections.

9.3 How do equine muscles facilitate "quality" movement in elite and non-elite jumping athletes?

A comprehensive understanding of specific locomotor activities is achieved when kinematic and sEMG data are combined to examine how the neuromuscular system facilitates movement. An understanding of discipline-specific movement and muscular activity patterns is essential for extrapolating these findings into the design of scientifically evidenced training programmes. Furthermore, no studies have obtained sEMG data from proven elite horses, which may highlight neuromuscular strategies for enhanced performance. This section will therefore focus on investigating differences observed in sEMG data between groups in relation to kinematic data obtained during jumping.

9.3.1 Hindlimb muscle activity and its effect on movement of the centre of mass during jumping

Previous studies have described the relationship between HL propulsion, Z_{CM} and $\dot{Z}_{CM}$ during jumping (Bogert et al., 1994; Powers and Harrison, 2000; Bobbert et al., 2005; Bobbert and Santamaria, 2005; Powers, 2005; Santamaria et al., 2004a, b, 2005). By combining sEMG and kinematic data, this study is able to offer insight into how HL and FL muscles facilitate changes in Z_{CM} and $\dot{Z}_{CM}$. This has not previously been explored and therefore offers and original contribution to knowledge. Figure 9.7 illustrates Superficial Gluteal and Triceps Brachii activity, which were found to exhibit the highest normalised iEMG values during take-off in the FL and HL, respectively. Data for Z_{CM} and $\dot{Z}_{CM}$ are also presented in Figure 9.7 to examine how their movement is influenced by muscular control strategies.

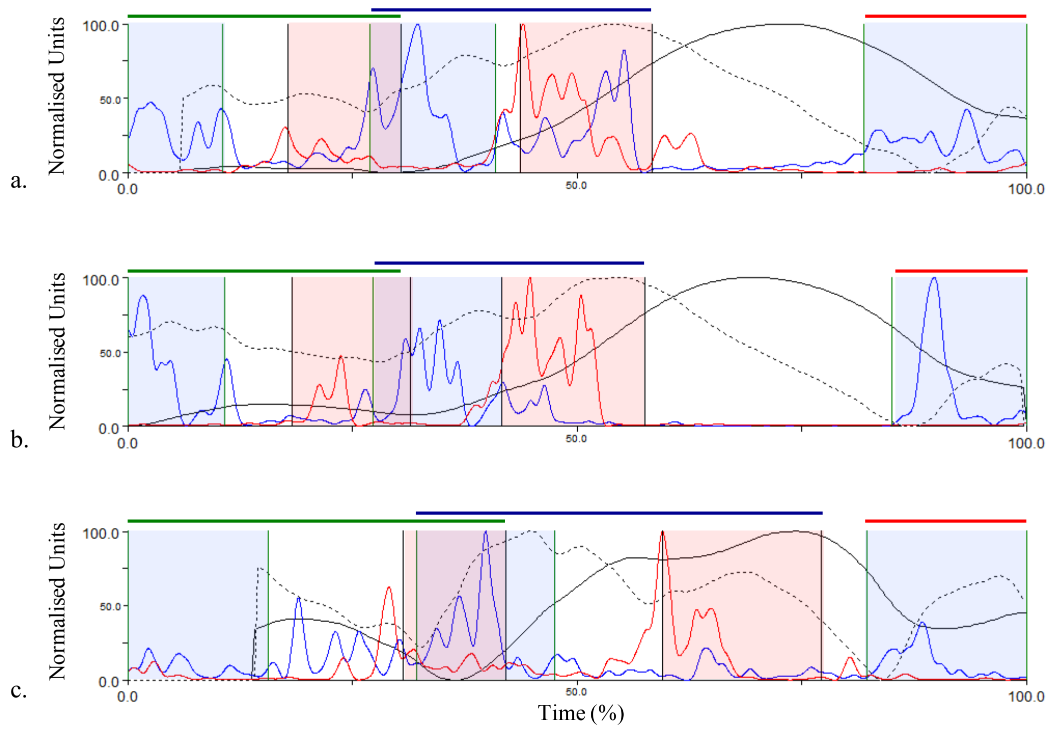


Figure 9.7 Time course curves for vertical displacement (black solid line) and vertical velocity (black dashed line) of the CM overlaid over sEMG signals for the Superficial Gluteal (red solid line) and Triceps Brachii (blue solid line) muscles from LdF and LdH during jump stride. Signals from one horse per group are represented: a.) elite b.) NC c.) school. Shaded areas represent fore (blue) and hind (red) stance phase during A1 (green horizontal line), take-off (blue horizontal line), and landing phases (red horizontal line). Signals presented are DC offset, high-pass filtered at 80 Hz and low-pass filtered at 25 Hz. Signals are normalised between FL hoof impact event at A1 and FL hoof off event at landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

Examination of Figure 9.7 reveals interesting differences in strategies employed by elite and non-elite horses. During A1, NC and elite horses exhibited muscle activity that was relatively similar to canter, but with prolonged muscle activity duration. Higher amplitude bursts of Superficial Gluteal and Triceps Brachii activity in NC horses during A1 stride are illustrated, providing further insight into the apparent anticipatory increases in FL and HL muscle activity prior to jump take-off. NC and elite horses displayed minimal Z_{CM} during A1 stride suspension, which provides further evidence for the more economical cantering technique suggested in Section 9.1.1(i). In contrast to elite and NC horses, school horses were found to exhibit relatively lower muscle activity and greater Z_{CM}, which accounts for the longer suspension phase observed between FL and HL stance.

During FL stance at take-off phase, elite horses showed higher-amplitude bursts of activity for the Triceps Brachii, which is in agreement with the relatively higher normalized iEMG values observed in this group. In human jumping athletes, lowering of the CM at take-off is known to be one of the main determinants for Z_{CM} during flight phase and $\dot{Z}_{CM}$ during take-off phase (Hay, 1993; Dapena, 2000; Grieg and Yeadon, 2000; Isolehto et al., 2007) (see Section 2.6.1(i)). Elite horses exhibited a similar technique, where the CM was lowered at FL take-off, resulting in significantly greater $\dot{Z}_{CM}$ during take-off and Z_{CM} during jump suspension. These findings indicated that elite horses show a better "gathering" technique. A similar trend was observed for NC horses at FL take-off, but this group showed lower-amplitude bursts of EMG activity in the Triceps Brachii and subsequently lower $\dot{Z}_{CM}$ at take-off. This may be related to a decreased ability to convert horizontal velocity to vertical velocity at take-off, as has been observed in previous studies of inexperienced jumping horses (Santamaria et al., 2004a; Powers and Harrison, 2000). School horses exhibited greater overlap of FL stance at take-off and HL stance duration during A1 stride, compared to elite and NC horses. This may represent a strategy for increasing Z_{CM} and $\dot{Z}_{CM}$ by combining muscular force production from the FL and HL muscles.

The most apparent differences between groups were found during HL stance at take-off. The higher-amplitude and longer duration activity bursts of the Superficial Gluteal muscle in elite and NC horses displayed a better ability to produce the force required to increase Z_{CM} and $\dot{Z}_{CM}$ during HL take-off. This was evidenced by peak $\dot{Z}_{CM}$ during HL stance phase, which is in accordance with Santamaria et al. (2004a). The angle of $\dot{Z}_{CM}$ curves was greatest in the elite group, revealing that these horses could generate $\dot{Z}_{CM}$ at a faster rate. Although not shown in Figure 9.7, elite horses also exhibited high $\ddot{Z}_{CM}$ at take-off over a shorter average HL stance duration, which is indicative of higher production of vertical push off forces (Santamaria et al., 2004a). This further supports the finding that HL muscles of elite horses were more effective for producing muscular force at take-off.

In contrast, the school horse illustrated in Figure 9.7 was found to initiate increases in Z_{CM} and $\dot{Z}_{CM}$ in HL stance during A1 stride, which showed a large overlap with FL stance at take-off. As a result, peak $\dot{Z}_{CM}$ was observed during FL take-off, which exhibited relatively high-amplitude activity bursts for the Triceps Brachii. The school horse also exhibited a prolonged duration between FL stance and HL stance at take-off, where $\dot{Z}_{CM}$ decreased at faster rate than was observed in elite and NC horses. During HL take-off Z_{CM} and $\dot{Z}_{CM}$ increased. However, Superficial Gluteal activity was relatively low, resulting in decreased generation of Z_{CM} and $\dot{Z}_{CM}$ compared to NC and elite horses.

Contrary to NC and elite horses, which exhibited peak Z_{CM} around mid-jump suspension, the peak in school horses was observed earlier in the suspension phase. In all horses, Z_{CM} and $\dot{Z}_{CM}$ decreased during in the later half of jump suspension, however NC and school horses showed more rapid declines than elite horses. Decreasing Z_{CM} and $\dot{Z}_{CM}$ was most abrupt in school horses and is in accordance with the significantly shorter jump stride length observed in this group. This finding illustrates that decreased power production from the FL and HL muscles in school horses, results in inability to elevate the CM and generate adequate $\dot{Z}_{CM}$ for jump execution. This is further illustrated by the fact that FL impact at landing occurred shortly after the HL take-off event.

Differences in height between equine subjects were accounted for by normalising data. However, it is important to note that the school horse used in Figure 9.7 represented the largest horse in the group (165.3 cm) and required less CM elevation to clear the fence. Interestingly, the majority of elite horses examined in this study were of a similar height and the submaximal fence was considered to be a relatively easy task for these horses, particularly for those that had competed up to 1.40 m. It was therefore postulated that elite horses would display the least amount of muscular effort to clear the fence, but the opposite trend was observed. Irrespective of height, this particular school horse (Figure 9.7) was used to illustrate an extreme example of the poor jumping technique observed in the school group. Although less exaggerated, a similar jump technique was also observed in smaller school horses (Figure 9.8). Therefore, height of the horses was found to have minimal influence on the movement and neuromuscular strategies observed. Nevertheless, data from three different school horses, including the smallest horse (152.4 cm) (9.8a), are presented in Figure 9.8 to provide a full overview of the jump technique observed in the school group. Unfortunately, data from A1 were not available for all horses and Figure 9.8 is therefore normalised between FL take-off and landing.

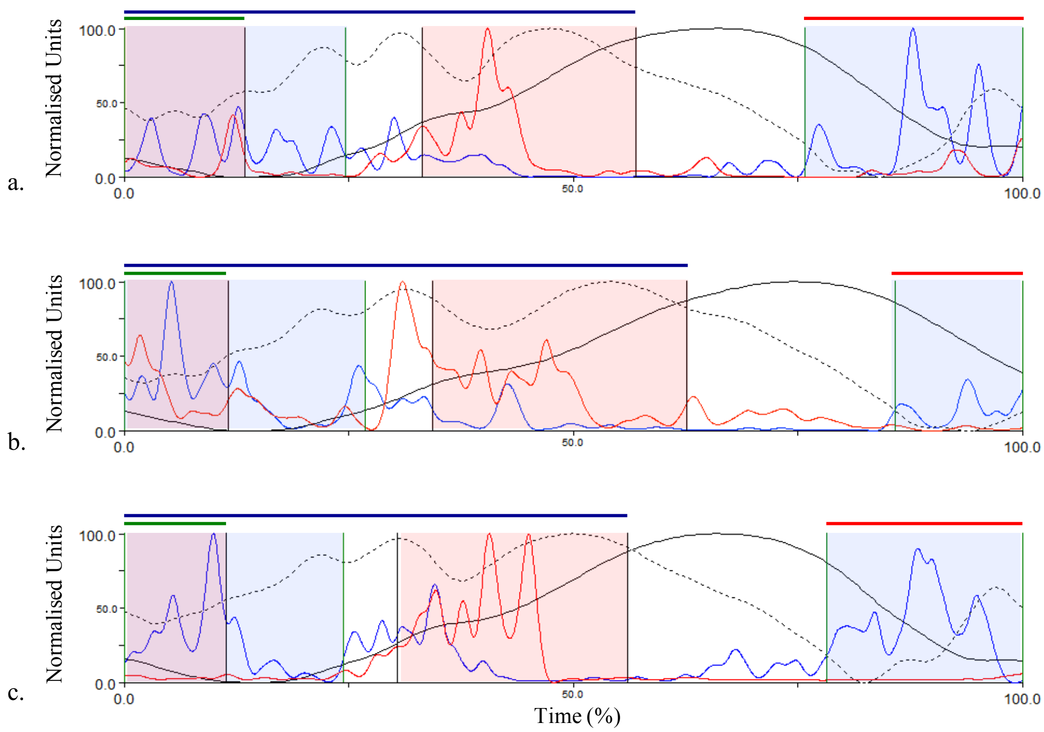


Figure 9.8 Time course curves for vertical displacement (black solid line) and vertical velocity (black dashed line) of the CM from overlaid over sEMG signals for the Superficial Gluteal (red solid line) and Triceps Brachii (blue solid line) muscles from three school horses. Signals are for TrF and TrH during jump stride. Shaded areas represent fore (blue) and hind (red) stance phase during A1 (green horizontal line), take-off (blue horizontal line), and landing phases (red horizontal line). Signals presented are DC offset, high-pass filtered at 80 Hz and low-pass filtered at 25 Hz. Signals are normalised between FL hoof impact event at take-off and FL hoof off event at landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

Irrespective of height differences, school horses in Figure 9.8 also display a decreased ability to produce optimal increases in $\dot{Z}_{CM}$ and Z_{CM} at take-off due to decreased muscle activity. This is illustrated by lower-amplitude and shorter duration muscle activity bursts, particularly for the Superficial Gluteal, and by a more gradual increase in both $\dot{Z}_{CM}$ and Z_{CM} and at HL take-off. School horses also showed a relatively larger decrease in $\dot{Z}_{CM}$ at the beginning of HL take-off, which coincides with decelerative forces experienced by the HL at the beginning of stance (Schamhardt et al., 1993). Elite and NC horses exhibited a more consistent increase in $\dot{Z}_{CM}$, with a minimal decrease observed during initial HL stance phase. A relatively abrupt drop in $\dot{Z}_{CM}$ following peak Z_{CM} was also observed during jump suspension, resulting in the characteristically shorter jump stride length observed in this group. These findings are representative of the significantly lower $\dot{Z}_{CM}$

at take-off and Z_{CM} during jump suspension found for school horses. The differences observed between groups for $\dot{Z}_{CM}$ and Z_{CM} are very similar to those presented by Santamaria et al. (2004a). However, this study has offered original insight into how differences in muscle activity patterns contribute to the good jumping technique of elite horses and the poor technique of school horses.

9.3.2 Activity patterns of forehand muscles and their effect on forelimb joint articulation during jump suspension

The perceived importance of FL joint articulation and "tucking" action for evaluation of quality jump technique has been previously described. Sufficient FL clearance during jump suspension is undoubtedly important for decreasing the risk of obtaining faults for knock-downs. However, non-significant differences between groups for kinematic and sEMG data suggest that, this may not be a primary indicator of jump technique, particularly over submaximal fences. Furthermore, school horses were found to exhibit the greatest average percent decrease in FL length during jumping. Nevertheless, these traits could not be overlooked due to their relevance for the selection processes of equine jumping athletes. An examination of sEMG and kinematic data from the forehand revealed that different neuromuscular strategies were apparent outside of the temporal domains evaluated in this study. These were therefore investigated to determine whether each group exhibited characteristic neuromuscular control strategies.

It was found that, in the majority of assessment trials, two FL lengthening/ shortening cycles occurred during HL take-off and are illustrated in Figure 9.9. Observation of kinematic data revealed that this pattern coincided with muscle activity of the forehand muscles. Muscle activity onset of the Triceps Brachii occurred at take-off, just prior to HL impact, and continued until middle-late stance phase during HL take-off (Figure 9.9a). This muscle activity was found to coincide with the initial lifting and shortening of the FL and with increases in elbow flexion during take-off. Muscle activity in the Trapezius and Splenius muscles occurred during middle to late HL stance at take-off, and coincided with the second maximum shortening event. Splenius activity during the second FL shortening cycle appears to be in accordance with Giovagnoli et al. (1998), who state that activity during jump suspension facilitates extension of the head and neck. These findings suggest that the Triceps Brachii, which functions as an antagonist to elbow flexors such as Biceps Brachii, becomes active to limit elbow flexion during initial elevation of the FL at take-off. This is in agreement with Harrison et al. (2012), who reported co-contraction between Triceps Brachii and Biceps Brachii to stabilise the elbow. Similar to canter, the Trapezius appears to play an important role for adjusting movement of thoracic limb during jumping, as muscle activity coincided with peak scapula inclination. Findings reveal that the Trapezius is likely to perform concentric contractions to elevate the scapula during HL take-off and jump suspension. These findings are in agreement with equestrian preference for “good use of shoulder” during jumping.

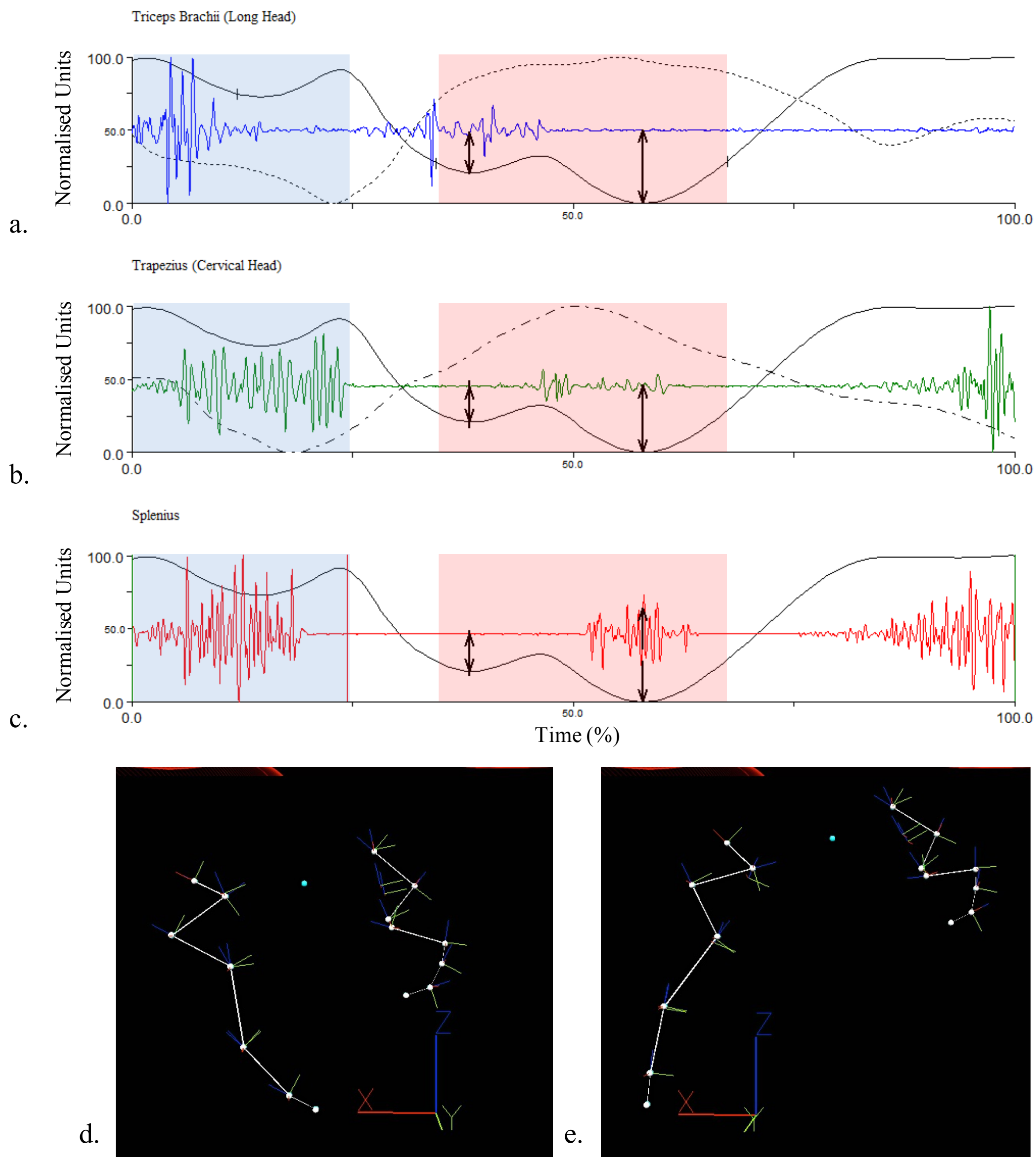


Figure 9.9 Time-course data for FL segment length (black solid line) overlaid over sEMG signals for a.) Triceps Brachii b.) Trapezius c.) Splenius muscles from the TrH during jump in one NC horse. Time-angle curves are also presented for: a.) elbow joint (dotted line), b.) scapula inclination (dash-dot line). Vertical arrows represent maximum shortening events of the fore distal spring segment. Visual representations of maximum FL shortening events are illustrated by corresponding snapshots of the model in d.) and e.). Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Shaded areas represent fore (blue) and hind (red) stance phase during take-off. EMG signals presented are DC offset and high-pass filtered at 80 Hz. Signals are normalised between for hoof impact event at take-off and landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

The double FL shortening cycle occurred most frequently in the school horse group and was observed in 27.3%, 30.6% and 31.0% of all trials for elite, NC and school groups, respectively. Interestingly, changes in FL muscle activity and signal amplitude were found to be directly related to differences in kinematic patterns for elevating and “tucking” the FL. Some horses exhibited only one FL shortening event, which was most frequently observed in elite horses. In these trails, one burst of muscle activity was observed, which was characterised by a higher-amplitude and longer duration burst. This is illustrated in Figure 9.10, which presents sEMG and kinematic data from one elite horse. These findings may suggest that horses with a better jumping ability achieve sufficient FL joint flexion during HL take-off, which is facilitated by the production of greater muscular force to elevate the forehand. These horses appear to be capable of maintaining the degree of FL flexion without altering movement via additional muscular contractions during HL take-off. These observations provide further evidence for the fact that elite horses exhibit greater muscular effort than NC and school horses during jumping, even over submaximal fences. Interestingly, horses that showed decreased FL shortening also exhibited high-amplitude, long duration bursts of muscular activity. as evidenced in Figure 9.11. This highlights the importance of analysing sEMG data in accordance with kinematic data.

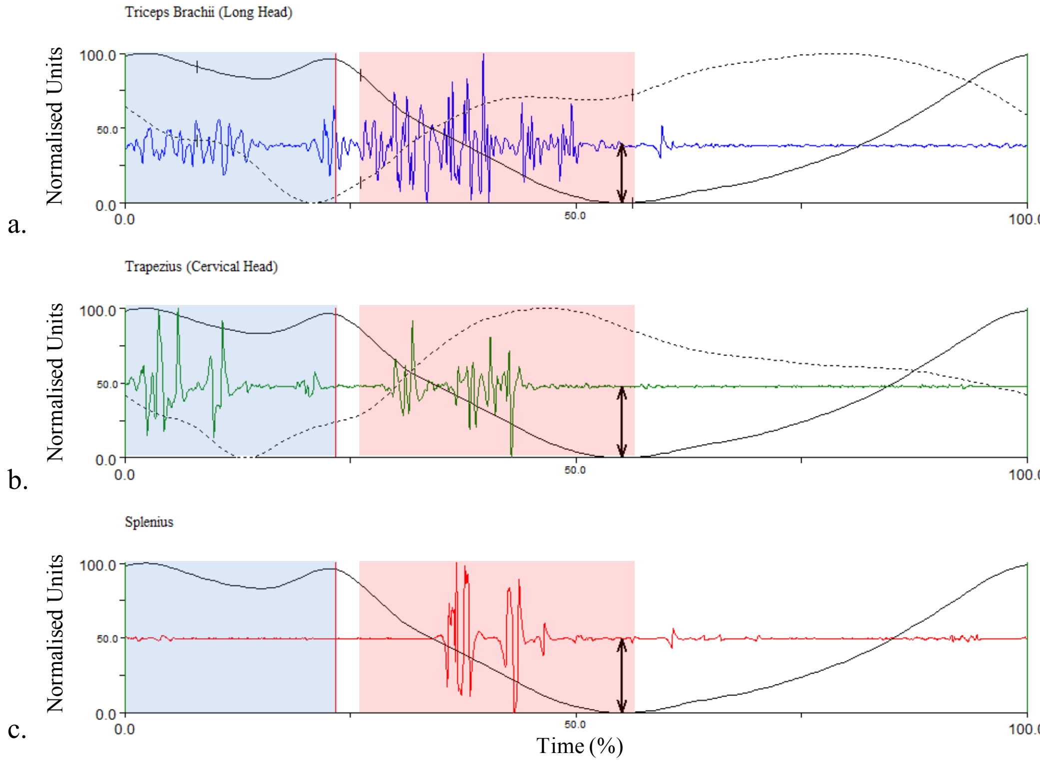


Figure 9.10 Time-course data for FL segment length (black solid line) overlaid over sEMG signals for a.) Triceps Brachii b.) Trapezius c.) Splenius muscles from the TrH during jump in one elite horse. Time-angle curves are also presented for: a.) elbow joint (dotted line), b.) scapula inclination (dash-dot line). Vertical arrows represent the maximum shortening event of the fore distal spring segment. Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Shaded areas represent fore (blue) and hind (red) stance phase during take-off. EMG signals presented are DC offset and high pass filtered at 80 Hz. Signals are normalised between for hoof impact event at take-off and landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve. Note: sEMG data for Splenius is included for phasic analysis only, and is an example of a signal that would not be included in magnitude analysis.

This is the first time that the relationship between forehand muscle activity and movement patterns has been examined. Although these relationships were not quantified in this study, the patterns observed in kinematic and sEMG data suggest that differences in neuromuscular strategies for FL "tucking" and elevation are most likely to be found during HL stance at take-off. This was not explored in this study and represents an area for future exploration. However, this may explain why significant differences were not found between groups. Future research may also consider analysing sEMG data from knee flexors, as the resultant signal for FL lengthening/ shortening was found to mimic the time-angle curve for the knee joint. The observed differences in neuromuscular strategies and non-significant differences in kinematic data between groups, provides further evidence for the fact that movement alone may not be an accurate indicator of quality jump technique.

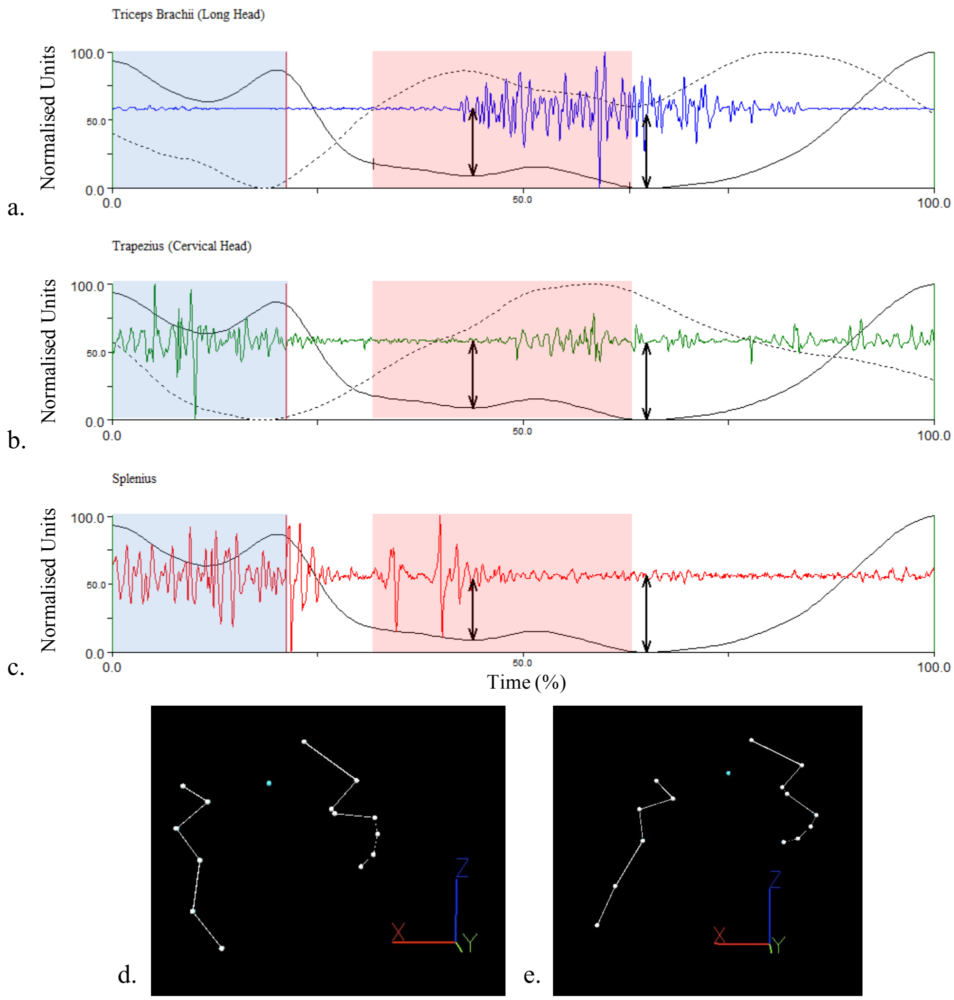


Figure 9.11 Time-course data for FL segment length (black solid line) overlaid over sEMG signals for a.) Triceps Brachii b.) Trapezius c.) Splenius muscles from the TrH in one NC horse exhibiting decreased FL shortening. Time-angle curves are also presented for: a.) elbow joint (dotted line), b.) scapula inclination (dash-dot line). Vertical arrows represent the maximum shortening event of the fore distal spring segment. Visual representations of maximum FL shortening events are illustrated by corresponding snapshots of the model in d.) and e.) Green and red vertical lines represent fore hoof impact and hoof off events, respectively. Shaded areas represent fore (blue) and hind (red) stance phase during take-off. EMG signals presented are DC offset and high pass filtered at 80 Hz. Signals are normalised between for hoof impact event at take-off and landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

9.3.4 Activity patterns of hindlimb muscles and their effect on hindlimb joint articulation during jump suspension

Equestrians describe the HL as the most important contributor to quality jump technique, which has been illustrated throughout the discussion. However, joint articulation in the HL was also found to be important to equestrians, particularly the ability to "open out behind". This was kinematically investigated using HL retroflexion, which Bobbert et al. (2005) found to be a characteristic trait of horses with good jump technique. However, findings from this study found no significant differences between groups, with school horses displaying the greatest average degree of HL retroflexion. sEMG data from HL muscles were therefore evaluated in relation to HL retroflexion and shortening in order to determine whether neuromuscular strategies offered a possible explanation for differences between studies.

Figure 9.12 and 9.13 illustrate muscle activity from Superficial Gluteal and Biceps Femoris, respectively, together with data for HL retroflexion and HL shortening. For the Superficial Gluteal (Figure 9.12), maximum protraction observed at HL impact during take-off, was observed to coincide with peak EMG amplitude. In elite and NC horses, the HL then retracted at a gradual rate throughout HL stance and jump suspension, reaching a peak just prior to landing. In contrast, the school group exhibited greater rate of HL retraction, which was likely necessitated due to lower Z_{CM} and decreased jump suspension duration. A similar pattern was observed for HL pro/retraction in all groups in Figure 9.13, however peak EMG amplitude was found to correspond with maximum HL shortening during HL stance at take-off. Figure 9.12 also illustrates the higher-amplitude, longer duration muscle activity bursts of Superficial Gluteal activity exhibited by elite and NC groups in comparison with the school group. Increased activity of the Superficial Gluteal during A1 in NC horses is also highlighted and is indicative of anticipatory muscle activation patterns that have been previously described.

The most noticeable difference between groups was observed for shortening of the HL segment during HL take-off and jump suspension phases. Elite horses generally exhibited two lengthening/ shortening cycles during jump suspension, with the first occurring around middle-jump suspension and the second just prior to HL landing, when the HL began to protract under the horse's body in preparation for impact. Peak HL shortening at the end of jump suspension phase was found to coincide with HL muscle activity onset prior to HL impact at landing. NC horses were also found to exhibit this HL shortening pattern (Figure 9.12b), but more commonly exhibited one maximum shortening event, as seen in Figure 9.13b.

In contrast, school horses showed a faster rate of HL shortening during jump suspension and one major HL shortening event prior to HL landing. Interestingly, school horses also exhibited generally less HL shortening during HL stance phase at take-off, which is especially evident in Figure 9.12. As previously stated, the amount of positive work generated by the HL at jump take-off is directly related to the increase in total length of the limb during stance (Bobbert and Santamaria, 2005). Greater HL shortening during stance is likely to produce greater lengthening contractions in the Biceps Femoris, which results in increased storage of elastic strain energy (Biewener and Roberts, 2000). As discussed in Section 9.2.1(ii), there is likely some degree of muscle shortening in the Biceps Femoris during jump take-off, as muscle activity was found to occur during late stance phase, when the HL exhibits retroflexion and lengthening. It is generally accepted that increased force production occurs when a concentric contraction is preceded by an eccentric contraction (see Section 2.3.3(ii)). This finding therefore provides further evidence for increased force and power production by the HL muscles of elite and NC horses during jump take-off.

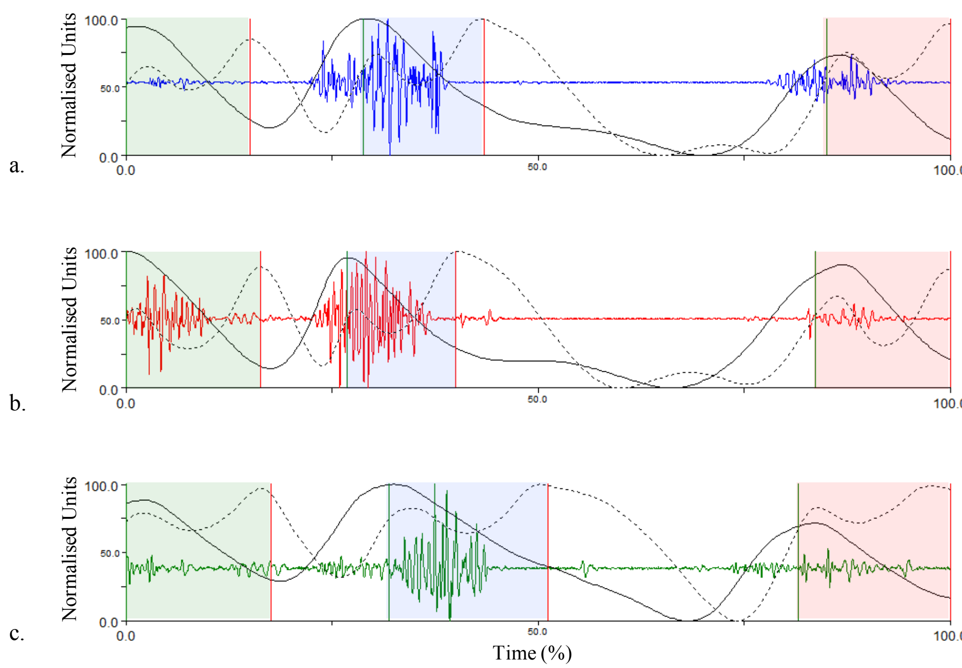


Figure 9.12 Time-angle curve for HL pro/ retraction (black solid line) and time course data for HL segment length (black dashed line) overlaid over sEMG signals for the Superficial Gluteal from TrF during A1 and jump strides. Signals from one horse from each group are represented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80 Hz. Signals are normalised between HL hoof impact event at take-off and HL hoof lift off event at landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

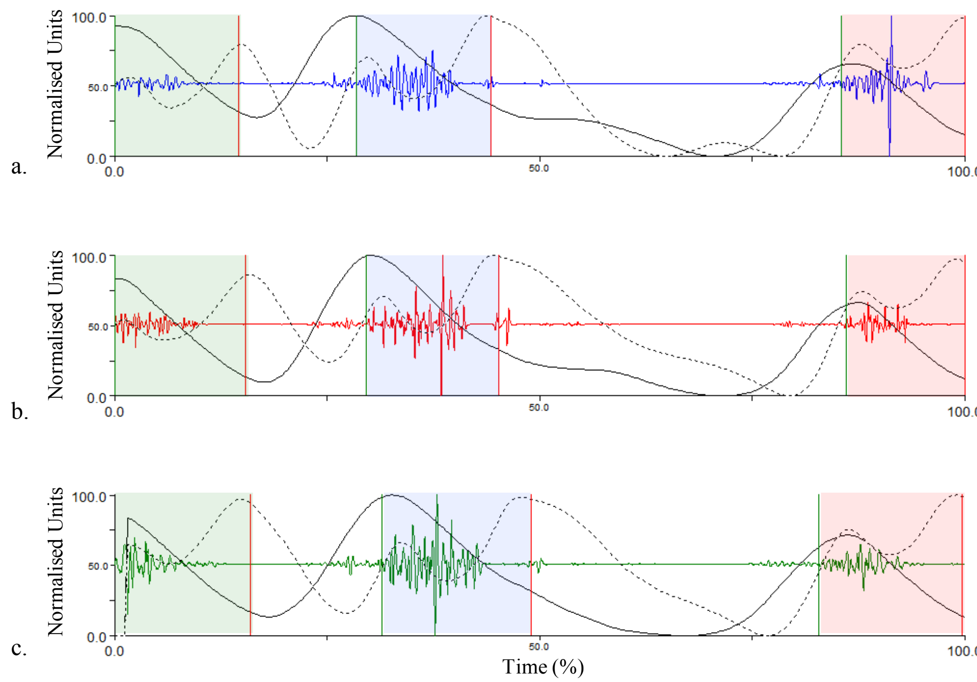


Figure 9.13 Time-angle curve for HL pro/ retraction (black solid line) and time course data for HL segment length (black dashed line) overlaid over typical sEMG signals for the Biceps Femoris from TrF during A1 and jump strides. Signals from each group are represented: a.) elite b.) NC c.) school. Green and red vertical lines represent hind hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset and high pass filtered at 80Hz. Signals are normalised between HL hoof impact event at take-off and HL hoof lift off event at landing. Note: x axis is normalised as 0-100% to permit scaled presentation of sEMG and time-angle curve.

Contrary to FL joint articulation, no major differences in phasic activity patterns were found between groups in relation to HL joint articulation during jump suspension. This is mainly due to the fact that HL muscles exhibited quiescent activity where differences in HL kinematics were observed. It appears that HL shortening and retroflexion during jump suspension are passive events for the Superficial Gluteal and Biceps Femoris muscles. It is suggested that future research investigate muscular activity of larger hip flexor musculature, such as the Tensor Fascia Lata, which was found to be active during early swing phase (Wentink, 1978; Tokuriki and Aoki, 1995; Robert et al. 1999, 2000; Deban et al., 2012; Deniox, 2014). Exploration of additional HL muscles may therefore reveal how muscles facilitate differences in HL retroflexion and shortening observed in this study. Furthermore, Section 9.1.1(ii), highlighted the effect of fence height on the degree of HL retroflexion observed in elite horses. Therefore, the use of higher fences in future research may expose differences in muscle activity patterns for the production of desirable HL joint articulation.

9.3.5 Summary of muscular contribution to "quality" jump technique in the jumping horse

Findings from this section reveal that the main difference in neuromuscular strategies between groups was related to the ability of the HL muscles to produce muscular power for elevating the CM and lifting the forehand during HL take-off and jump suspension. HL muscles of elite horses were found to exhibit the greatest capability for force and power production, which was evidenced by greater iEMG values and higher-amplitude, longer-duration bursts of muscle activity. These differences were exhibited kinematically by increased generation of Z_{CM}, $\dot{Z}_{CM}$, and jump stride length in elite horses. It was also found that the degree of FL and HL joint articulation were largely dependent on Z_{CM} and $\dot{Z}_{CM}$ generation at take-off, where elite horses were found to exhibit less FL shortening and HL retroflexion than school horses. This finding is in accordance with Santamaria et al. (2004a, 2005) and Bobbert et al. (2005) and suggests that increased Z_{CM} during jump suspension results in a decreased requirement for "tucking" the FL and "opening out behind", especially over submaximal fences. Elite horses were more inclined to elevate the FL during early HL stance at take-off. This was accomplished via increased activity of the forehand muscles, specifically the Triceps Brachii. This neuromuscular strategy mitigated the need for alterations to FL positioning through additional muscular activity during jump suspension, which was observed in NC and school horses. In the HL, no obvious differences in muscle activity were apparent for the facilitation of kinematic differences during jump suspension. Again, this is postulated to be largely related to Z_{CM}, as higher Z_{CM} in elite horses did not necessitate increased HL retroflexion for HL clearance. It is postulated that significant increases in HL shortening in elite horses is related to an increased ability to effectively decrease the moment of inertia during jump suspension.

There is a degree of conjecture between authors for the kinematic definition of optimal jump technique (See Section 2.6.3). Findings from this study suggest that, based on the technique of established elite athletes, a good jump technique is represented by muscular strength and subsequent ability to generate large Z_{CM}, even over submaximal fences. An extreme degree of FL shortening and HL retroflexion may not be apparent in these horses over submaximal fences. In younger horses, it has been argued that the ability to execute the jump with relatively low Z_{CM} is indicative of a more economical jump technique (Bobbert et al., 2005; Santamaria et al., 2004a, 2005). However, findings from this study indicate that the ability to generate high Z_{CM} and $\dot{Z}_{CM}$ is likely to be indicative of a horse's capacity for executing larger fences. This is therefore more indicative of quality jump technique and suggests that greater emphasis should be placed on muscular strength and the generation of Z_{CM} and $\dot{Z}_{CM}$, or "scope", when evaluating equine jumping athletes. These findings also reveal that desirable movement traits, such as FL joint articulation, are secondary to the neuromuscular strategies that determine the ballistic flight of the CM during the jump stride.

9.4 Practical application of knowledge to training and selection processes for the equine jumping athlete.

9.4.1 Practical application to training

Recommendations for scientifically evidenced jump training programmes have been previously described in research and are discussed in detail in Section 2.3. It is imperative that the exercises comprising any training programme mimic the duration and intensity of skills required during competition (Clayton, 1996; Müller et al., 2000; Keteyian and Schairer, 2010; Bompa and Buzzichelli, 2015; Bompa and Carrera, 2015). In the SJ horse, these skills have been described as both aerobic and anaerobic in nature (Art et al., 1990a, Barrey and Valette, 1993). However, studies investigating the training programmes of professional SJ trainers found that aerobic exercise represented the largest proportion of training regimes, with strength (anaerobic) training representing the lowest proportion (Lönnell et al., 2010, 2014; Sommer et al., 2015). Professional trainers also reported low intensity levels during training (Sommer et al., 2015), which further highlights a trend for predominantly aerobic exercise in SJ training programmes. These findings are in accordance with results from the questionnaire study, which found flatwork and hacking to represent the largest component of training programmes. Admittedly, exercise intensity, duration and frequency were not explored in the questionnaire and represent an area for further research. However, there was a clear trend for aerobic training, and analysis of open-ended questions revealed no explicit mention of anaerobic strength training or fitness work. Results from previous research and the questionnaire study are in agreement with Barrey and Valette (1993), who state that conditioning work to improve aerobic capacity and anaerobic power are generally overlooked for training the SJ horse. This is not to say that this is the case for all trainers, however an obvious trend has been demonstrated.

Findings from this study have shown that muscular strength, and subsequent power production represent the main difference between elite and non-elite jumping horses. This finding suggests that strength training and conditioning should represent a more predominant role in training programmes for the equine jumping athlete. An ideal training programme will induce beneficial adaptations to the physiological systems. However, this section will focus on how findings may be practically applied to induce beneficial muscular adaptations in the SJ horse. As previously described, equine skeletal muscles are highly adaptable to training, which has a considerable influence on strength (power production), stamina (fatigue resistance) and speed (velocity of shortening) (Rivero, 2007). The remodelling transition of muscle fibres from fast-to-slow type has been reported in previous studies that have evaluated equine muscular adaptations to endurance training (Tyler et al., 1998; Serrano et al., 2000). These findings suggest that prolonged endurance training results in decreased velocity of muscle shortening (Tyler et al., 1998; Serrano et al., 2000), which represents a key component to muscular power production. Prolonged aerobic training may therefore have a negative effect on the SJ horse's ability to produce the power required for generation of Z_{CM} and $\dot{Z}_{CM}$ at take-off.

The school horses employed for this study were used almost daily for riding lessons with riders of varying ability levels. This type of work largely limited their workload to aerobic exercise, which predominantly consisted of walk and trot. These horses were rarely jumped over fences greater than 1.0 m in height and generally did not partake in work above the anaerobic threshold. Muscular adaptation to prolonged aerobic exercise in school horses may therefore suggest that these horses exhibit decreased velocity of muscle shortening. This may offer a valid explanation for why decreased muscular activity during jumping was observed in these horses. In contrast to this, three of the horses in the elite group regularly competed in both SJ and eventing competitions, with one horse having competed up to three-star eventing level. Elite horses that were only used for SJ competitions were competed regularly, which act as strength training sessions in themselves (Clayton, 1994a). These horses therefore received a well-rounded training programme, comprised of aerobic and anaerobic exercises. The differences in training regimes experienced by the different groups of horses, highlights the importance of training methods on quality jump technique and performance.

As previously described in Section 2.3.3(ii), the maximum force that can be generated by skeletal muscles is directly related to PCSA and fibre-type composition (Rivero and Letelier, 2000; Rietbroek et al., 2007; Rivero et al., 2007), while power production is the product of force generated and shortening velocity (Kearns et al., 2002). With this in mind, Rivero (2009) suggest that strength training in the equine athlete should aim to increase hypertrophy, recruitment and contraction velocity of type II fibres. However, trainers are faced with difficulty when it comes to strength training in horses, due to the inherent locomotor strategies, which minimise the contribution of muscular work (Roberts et al., 1997; Biewener, 1998; Alexander et al., 2002; Rivero, 2009). The equine jump has been described as an inherent form of plyometric training (Rivero, 2009), which is characterised by high-intensity eccentric contractions, followed immediately by rapid concentric contraction (Malisoux et al., 2006). Results from this study provide objective support for this claim, as muscle shortening was apparent due to prolonged FL and HL muscle activity, which continued into late stance phase at take-off. This is in accordance with previous studies that have shown that muscle shortening is required to generate the force required for jumping or inclined running (Roberts et al., 1997; Alexander, 2002). Jumping has also been reported to induce significant hypertrophy of type IIA fibres in HL muscle of jumping horses (Rivero and Letelier, 2000), further supporting its application as a strength training exercise.

Interestingly, questionnaire results showed that equestrians prioritised the development of quality canter through flatwork, placing less emphasis on actual jump training. This was especially true for more competent jumping horses, which were also less likely to train over larger fences. It was postulated that this was likely due to the increased injury risks associated with jumping (Schamhardt et al., 1993; Bailey et al., 1998; Meershoek et al., 2001a; Williams et al., 2001; Murray et al., 2006; Parkin et al., 2006) (see Section 2.3.4). Injury risks have also been found to increase with fence height (Shamhardt et al., 1993; Meershoek et al., 2001a; Dyson et al., 2006). However, findings suggest, that even submaximal fences increased the amount of work performed by active muscle. In fact, the proportional change between canter and jump was found to be relatively large in elite horses, which was surprising considering the heights that these horses were used to competing at. This finding provides quantitative support for equestrian trainers who employ submaximal fences for jumping exercises. Dissemination of these findings to non-elite riders is will be important, as these riders were found to display a tendency for exercising over larger fences, which may increase the risk of injury (Shamhardt et al., 1993; Meershoek et al., 2001a; Dyson et al., 2006). sEMG data also revealed that horses exhibited largely economical locomotor strategies during canter, which resulted in minimal increases in muscular work. This finding therefore suggests that an emphasis on aerobic canter work may not represent an adequate strengthening exercise, especially when conducted on level ground (Roberts et al., 1997).

Strength training has been associated with decreased risk of musculoskeletal injury in human athletes (Knapik et al., 1991; Orchard et al., 1997; Tyler et al., 2001; Hunt, 2003) Furthermore, increased understanding of the functional activity of equine locomotor muscles has been suggested as an important tool for the development of training programmes, which decrease injury risks (Crook et al., 2010). However, it is important to note that, although anaerobic strength training is advocated in this study, high-intensity training must be accompanied by adequate systematic recovery periods for tissue repair (Clayton, 1994a; Seene and Kassik, 2013). Findings from this study largely support the training recommendations for SJ horses put forth by Clayton (1991, 1994a), who suggests high-intensity strength training, with a small number of repetitions and a frequency of 2-3 times per week to allow sufficient time for rest and minor tissue repair. Gymnastic jumping, slope training and step gradients are suggested as exercises, which mimic the SSC and joint ROM required for jumping competition (Clayton, 1991, 1994a). Although not explicitly examined in this study, previous research has shown increases in muscular work during inclined running (Roberts et al., 1997), trotting (Robert et al., 2000; 2001a, b, 2002; Crook et al., 2010) and cantering (Hodson-Tole, 2006; Harrison, 2012), suggesting that these exercises would induce desirable muscular adaptations for jumping.

This represents the first study to provide scientifically evidenced suggestions for improving the largely anecdotal state of training for the SJ horse. This is also the first study to offer objective suggestions for training, which are based on the direct relationship between optimal movement and neuromuscular strategies observed in established, elite sport horses. These suggestions may be used to inform the training of young or non-elite horses, by developing similar neuromuscular control strategies to improve performance. It is also important to note that breeding, temperament and conformation are among many factors that will influence the performance level of a horse. However, well-informed training practices will undoubtedly allow a horse to perform to the best of its inherent ability, whilst decreasing the risk of training-related injuries. Although this study has provided scientific evidence for the importance of anaerobic strength training in SJ horses, further work is required to investigate the optimal volume of work required for inducing beneficial muscular adaptations.

9.4.1 Practical application to the selection of the equine jumping athlete

This study has demonstrated that characteristic traits of quality movement, as defined by equestrians, can be quantified using kinematic methods. Kinematic results were found to support the opinions and preferences described by equestrian professionals for the selection of equine jumping athletes. Desirable movement traits, namely collection, impulsion and engagement, were observed in "quality" canter and jump exhibited by elite horses. However, this study is unique in that it has provided insight into the underlying muscular control strategies, which facilitate preferred movement traits. Results revealed that primary emphasis should be placed on a horse's ability to raise the CM during jump suspension and at take-off when evaluating jump technique, as this was found to be indicative of muscular strength. This is also likely to be an indicator of the horse's capacity for executing larger fences, or its "scope". Although aesthetically pleasing and functionally important for reducing the risk of faults, findings from this study suggest that FL and HL joint articulation should be considered as secondary factors to "scope". This is especially relevant, as equestrians described an ability to alter FL and HL technique with proper training. As previously stated, these traits are also likely to be influenced by fence height (Powers, 2005), which should be considered when evaluating technique over submaximal fences.

It was not possible to discern inherent movement from the effects of training, as all horses were in regular work at the time of the study. Previous research has demonstrated that jump training at a young age had no long-term effect on jumping capacity at 5 years of age (Santamaria et al., 2005). However, the effects of long-term training in older, more established horses are not known. Further work is therefore required to explore the link between muscular activity and movement traits in young horses as they progress through training. This information would provide further insight into the development of jump technique, which may provide additional suggestions for scientifically evidenced training programmes.

9.4.3 Potential impact and dissemination of findings to the Equine Industry

As highlighted in Section 2.5, an emphasis on scientific advancement in equine training programmes is lacking in the equine industry. This has been linked to lack of marked improvement in winning race times in recent decades (Gaffey and Cunningham, 1988; Rose and Evans, 1990; Smith et al., 1999) and is in contrast to human athletes, whose performance has undoubtedly benefited from advances in sport science. In both equine and human sport, the boundaries of performance are continually rising and as such, a winning performance is dependant on the smallest of margins (Smith, 2003). As discussed in Section 2.1, modern SJ has seen increases in the physical demands and calibre of equine athletes, which often means that a winning performance can be based on milliseconds. As such, programmes like the British Equestrian Federation's "Equestrian World Class Programme" (EWCP) have been developed with the aim of optimising Team GBR podium success at Olympic and Paralympic Games through intensive selection, development and performance programmes for equine and human athletes (British Equestrian Federation, 2014). The EWCP cites Research and Development as a key area of programme support and aims to identify where science may inform performance development (British Equestrian Federation, 2014). The EWCP also seeks to include state-of-the-art technology to develop a better understanding of equine locomotion, fitness, strength and conditioning and training methods (British Equestrian Federation, 2014).

As described in Sections 9.4.1 – 9.4.2, quantitative and qualitative findings from this study offer original suggestions for the development of objective selection and training practices for the equine jumping athlete. As discussed, certain findings suggest scientifically evidenced alterations to current anecdotal training and selection methods, including placing greater emphasis on strength training. The practical application of these suggestions may therefore have beneficial implications for the equine industry. However, the impact of findings on equine performance is difficult to determine at this point and is not only dependant on further research being conducted, but also implementation of findings in equestrian practice. It is therefore imperative that findings are not only disseminated through peer-reviewed scientific journals, but also through direct dissemination to equestrian organisations and programmes. This is especially true for programmes, such as the EWCP, which express a direct interest in research and have embraced objective feedback to improve the marginal gains that may constitute a winning performance. Findings from this study have also illustrated the potential practical applications of sEMG, which would fit within the remit of such programmes. This is discussed further in Section 9.5.

The intrinsic gap and lack of knowledge transfer between equine science and equestrian practice has been discussed in Section 2.5. However, if research is to inform practice in the equine industry, findings must be accessible to equestrian practitioners of all levels. This is especially important, as findings from this study are not restricted to elite horses and riders. The suggestions put forth in this study for training and selection processes, were largely based on optimal movement and neuromuscular strategies observed in elite horses. However, these suggestions are generalisable to horses and riders of all skill levels for developing similar neuromuscular control strategies and improved performance. Furthermore, findings from this study support the strength training practices put forth by Clayton (1991, 1994a), which can be implemented by riders of all skill levels and for all horses, irrespective of breed, conformation, inherent talent and jumping ability. It is therefore vital that findings from this study are disseminated through layperson articles in popular equestrian publications and websites, which will reach equestrians of all skill levels. Ideally, both layperson and scientific articles will also place emphasis on the integration of equine industry opinion and preferences into the methodology employed in the study. It is hoped that placing emphasis on the collaborative aspects of this research will have a beneficial impact on how the equine industry views research and its relevance to practice. It is also hoped that this will influence equine researchers to employ equestrian opinion and tacit knowledge to inform research design, which may help bridge the gap between science and practice in the equine industry.

9.5 Practical application and limitations of sEMG in equine research

This study has illustrated the potential applications of sEMG for informing the largely anecdotal training methods for the equine athlete. sEMG has the advantage of being telemetric, non-invasive and relatively user friendly. Sensors were not found to restrict or influence the natural movement and jump technique of the horses used in this study. However, the use of sEMG is not without limitations, especially when equine subjects are studied. The major challenges faced in this study were related to the lack of standardised methods described for sEMG data acquisition and analysis techniques in equine research. These limitations are described in detail in Chapter 5 and by Valentin and Zsoldos (2016). However, these challenges were overcome through the development of protocols for: sensor placement, signal filtering and data analysis, which were tailored to sEMG data from the equine subject. The methods described in Chapter 5 offer an original contribution to knowledge, but also represent a starting point for researchers to develop further on a wider number of equine subjects. Standardisation of sEMG methods in equine research may lead to more widespread use in biomechanics research, which will lead to a more comprehensive understanding of equine locomotion and neuromuscular control.

Practical challenges for sEMG data collection were mainly associated with adherence of the sensors during highly dynamic movements, which was especially challenging when horses began to sweat. However, these limitations were relatively easily mitigated by the use of heavy duty adhesive tape and consistent inspection of sensor adherence between trials. The requirement for removing all hair from sensor locations posed challenges for recruiting elite horses, as turnout is an important aspect in high level competition. This represents a consideration for future work, as recruitment of elite riders who are willing to have their horses clipped proved to be a time-consuming process.

9.5.1 Limitations and further work

Limitations and further work have been described throughout the discussion and this section will therefore offer a brief summary. Perhaps the greatest limitation associated with analysis of sEMG data was the inability to conclusively discern between eccentric and concentric contractions (see Section 9.2.1(i)). Although kinematic data offered evidence for contraction type, future research is required to quantitatively measure changes in muscle fibre length. This has been done in previous equine (Hoyt et al., 2005; Wickler et al., 2005) and animal research (Roberts et al., 1997; Carroll et al., 2008; Lee et al., 2011, 2013) using implanted sonomicrometer crystals and strain gauges, and will provide conclusive evidence for defining contraction type during the equine jump technique.

As previously discussed, increased muscular strength is related to PCSA and type II muscle fibre composition (Rivero and Letelier, 2000; Rietbroek et al., 2007; Rivero et al., 2007). Furthermore, trained jumping horses are reported to exhibit increased CSA of type II fibres and increased IIA/B fibre isoforms (Rivero and Letelier, 2000). It is therefore tempting to make inferences regarding the effect of muscle ultrastructure on sEMG data. However, the sEMG signal represents the interference pattern of MUAPs from a number of MUs located within the detection area of the surface electrodes (Basmajian and De Luca, 1985). Therefore, the sEMG signal cannot provide direct evidence for the muscle fibre-type composition of muscles investigated (Kupa et al., 1995). This highlights an area for future research, as sEMG research may incorporate histological analysis to investigate the relationship between muscle activity and ultrastructure. This could offer further insight into muscular adaptation to training in jumping horses.

This study has provided a comprehensive description for the functional roles of five superficial muscles. As previously stated, this is the first known study to present overlaid kinematic and sEMG data, offering original insight into how equine movement is facilitated by selected superficial muscles. However, as described throughout the discussion, associations between the timings of events within kinematic and sEMG data were largely based on visual interpretation and were not quantified, as this was beyond the scope of the current study. This is therefore an area requiring further investigation. Further research is also required to examine additional muscles to advance our understanding of how equine muscles facilitate locomotion. Furthermore, the role of antagonist muscles and co-contraction has been highlighted as an important factor for joint stability and positional control (Harrison et al., 2012). It is therefore recommended that future research examine antagonistic muscle function, as measurement of these muscles may further elucidate the role of pelvic and thoracic limb muscles during canter and jump. In this study, data were only collected from the right side of horses and an examination of both left and right sides may offer insight into muscle symmetry, as has previously been explored in racehorses (Williams et al., 2013).

Kinematic data were not collected from the neck and back, and the muscle activity patterns of back musculature were not investigated in this study. This represents an essential area for future research, as the importance of back movement for the jumping effort has been previously described (Cassiat et al., 2004). Furthermore, equestrians described bascule as the most desirable trait for evaluating quality of jump technique. Unfortunately, examination of the movement and muscle activity of the back segment was restricted by the presence of the rider. However, questionnaire data revealed that equestrians displayed a preference for evaluating quality movement from the ridden horse and methodology was therefore tailored to emulate these circumstances for data collection.

As previously discussed, the effect of a rider on jump technique has been highlighted as an area requiring further investigation (Powers and Harrison, 1999). In this study, horses were ridden by their normal rider. Therefore, a two-stride jump combination was used in an effort to minimise rider effect by standardising the approach strides. Although it is not possible to determine the effect of different riders, the low SD values presented for kinematic and sEMG data within groups suggests that riders had a minimal influence on findings reported in this study. Future research may consider the use of one rider for standardisation purposes.

The relatively small sample size represents a limitation for this study, as recruitment of horses proved to be difficult. However, kinematic and sEMG data were found to agree with previous equine research, suggesting that the data presented in this study provides a good representation of the movement and muscle activity patterns in elite, NC and school horse populations. It is hoped that further work will be undertaken in this area to examine a larger sample of horses. It is also hoped that future research will employ sEMG to examine of the effects of commonly used exercises on movement and muscular activity patterns. Exercises may include, but are not limited to: pole work, cavaletti work and slope training (in the field), which may provide objectively-evidenced alternatives for strength training with reduced injury risks.

9.6 Conclusion

This study has demonstrated the applications of sEMG in equine research, which can be practically applied to inform the largely subjective selection and training methods for equine jumping athletes. In this study, sEMG data offered original insight into fundamental muscle activity patterns of selected superficial muscles during jump and canter. Muscle activity patterns agreed with literature on the functional role of muscles and the biomechanical demands of the equine jumping effort. However, this represents the first study to demonstrate how neuromuscular strategies differ between elite and non-elite jumping athletes using 3D kinematic and sEMG data. This is also the first known study to incorporate the tacit knowledge and opinions of equine industry professionals to produce research that has “real world” applications.

Findings from this study have demonstrated that movement alone does not provide an ideal method for differentiating between elite and non-elite equine jumping athletes. Differences in “quality” movement during jumping were found to be largely related to differences in neuromuscular strategies, with elite horses displaying a greater ability to generate muscular force and power, particularly in the HL during jump take-off. This finding had a direct influence on “quality” of jump technique, as increased muscular power resulted in the generation of increased vertical displacement and vertical velocity of the CM trajectory. These findings have offered objective evidence for greater emphasis to be placed on strength training exercises within jump training programmes, which will support the development of “quality” movement and jump technique in non-elite horses. Findings from this study also have practical applications for the selection of potential jumping athletes. It is suggested that equestrians place greater emphasis on the evaluation of traits that are indicative of muscular strength and power (i.e. increased vertical displacement of CM during the airborne phase). Equestrians expressed preference for FL and HL joint articulation traits and although these traits have functional relevance, findings from this study suggest that they should be considered as secondary to the ability to elevate the CM during jump suspension, especially over submaximal fences.

This study represents an original contribution to the study of equine locomotion and has provided suggestions for the development of scientifically evidenced training and selection processes for the equine jumping athlete. It is hoped that further research in this area will continue to develop the original methods described for sEMG data acquisition and analysis in equine subjects, in an effort to progress equine sEMG research towards a more standardised state. Further research is also required to explore the functional role of additional muscles for facilitating "quality" movement and to explore how scientifically evidenced training practices can be further developed across different equestrian disciplines. Finally, it is hoped that future research will incorporate the opinions and preferences of equine industry professionals, in order to bridge the gap between equestrians and researchers. In doing this, research is more likely to influence equestrian training and management strategies towards a more scientifically evidenced state.

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APPENDICIES

Appendix A: Questionnaire

Training and Performance Evaluation of the Equine Jumping Athlete

Welcome

Thank you for your interest and participation. Your qualifications and ability to provide expert/ informed answers to questions are invaluable to the relevance of this work.

This questionnaire aims to uncover what equestrian experts look for when evaluating movement and performance in the sports horse. We are also hoping to gather information regarding professional training strategies used to maximise performance in the show jumper.

The questionnaire can be saved part way through and takes around 15 minutes to complete 18 questions. Questions are multiple choice or rating questions, with the option to expand answers based on personal opinions and experiences.

All data collected in this survey will be held anonymously and securely. No personal data is asked for or retained. Ethical approval has been obtained from UCLan's Animal Projects Committee and there is no known risk to your participation in this questionnaire

Coach and Rider/Trainer Qualifications

*** 1. Please indicate your highest coaching level and highest level competition level.**

	Coaching Qualification	Highest Competition Level
Qualification		

Other (please specify)

Image: British Showjumping, (2010), 2010 British Showjumping Coaches Conference [ONLINE]. Available at: http://www.britishshowjumping.co.uk/training/news/2010-british-showjumping-coaches-conference [Accessed 11 March 14]

Evaluating Quality Movement and Performance in the Equine Jumping Athlete

Please answer all questions based on your personal experiences and opinions.

Page 1

Training and Performance Evaluation of the Equine Jumping Athlete

***2. Select the most appropriate response for the following statement:**

"The following criteria play a critical role as indicators of performance when evaluating sport horse prospects"

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
Conformation	○	○	○	○	○
Pedigree	○	○	○	○	○
Movement	○	○	○	○	○

Image: South Lane Farm, (2002), Lacantus Warmblood Stallion [ONLINE]. Available at: http://www.southlanefarm.com/otherhorses/Lacantus.htm [Accessed 11 March 14].

Determining Quality Canter in the Equine Jumping Athlete

***3. Please rate the following criteria based on their importance and contribution to evaluating quality of canter.**

	Very Important	Important	Neither Important nor Unimportant	Unimportant	Very Unimportant
Hindlimb	○	○	○	○	○
Fore Limb	○	○	○	○	○
Neck and Back	○	○	○	○	○
Stride Length	○	○	○	○	○

Training and Performance Evaluation of the Equine Jumping Athlete

4. Use spaces to provide a short description of desired traits within each criteria

Hindlimb	
Fore Limb	
Neck and Back	
Stride Length	

Image: Dawson, D. Practical Horseman , (2011), Rodrigo Pessoa [ONLINE]. Available at: http://equisearch.com/article/olympic-show-jumper-rodrigo-pessoa-dont-settle-for-just-ok [Accessed 12 March 14].

Determining Quality of Jump Technique in the Equine Jumping Athlete

***5. Please rate the following criteria based on their importance when evaluating quality of jump technique.**

	Very Important	Important	Neither Important nor Unimportant	Unimportant	Very Unimportant
Hindlimb					
Fore Limb					
Neck and Back					

6. Use spaces to provide a short description of desired traits within each criteria.

Hindlimb

Fore Limb

Back and Neck

Image: Ramos, D., Getty Images Europe, (2014), Grand Prix Hermes Of Paris At the Grand Palais : Day 3 (Marcus Ehning) [ONLINE]. Available at: http://www.zimbio.com/pictures/jY4JC0rORpO/Grand+Prix+Hermes+Paris+Grand+Palais+Day+3/jLcLryTlcrv/Marcus+Ehning [Accessed 12 March 14].

Determining Quality of Jump Technique in the Equine Jumping Athlete Cont'd

***7. Please rate each phase of the equine jumping technique based on its level of importance when evaluating jump quality.**

	Very Important	Important	Neither Important nor Unimportant	Unimportant	Very Unimportant
Take Off	○	○	○	○	○
Jump Suspension	○	○	○	○	○
Landing	○	○	○	○	○

8. Use spaces to provide a short description of desired traits for each phase

Take Off

Jump Suspension

Landing

Image: Chéhu, F., Jensen, T. , (2014), Marcus Ehning [ONLINE]. Available at: http://www.ridehesten.com/en/Heste-nyheder/SeNyhed/?ID=26251 [Accessed 20 March 14].

Sportfot/GCT, , (2012), Laura Kraut & CEDRIC (USA) [ONLINE]. Available at: http://clean-round.com/cedric-laura-kraut/ [Accessed 20 March 14].

Evaluating Quality Movement and Performance in the Equine Jumping

Training and Performance Evaluation of the Equine Jumping Athlete

Athlete C...

9. Please answer based on your personal opinion and experiences. Select the most appropriate response for the following statement:

"Quality of canter is irrelevant to quality of jump technique in the jumping horse"

- Strongly Agree
- Agree
- Neither Agree nor Disagree
- Disagree
- Strongly Disagree

Fence Type and Arrangement for the Evaluation of Jump Technique

We are interested to know the type of fence and arrangement you would employ when evaluating jump technique. For example: when buying horses.

We recognise that answers will vary greatly depending on individual horses. However, please answer based on methods which you would most frequently use under ideal circumstances (ie. ideal facilities and availability of jump equipment

***10. Which method do you use most commonly when evaluating quality of jump technique?**

- Under Saddle/ Ridden
- Free Jumping/ Unridden
- Both

Training and Performance Evaluation of the Equine Jumping Athlete

Image: Houghton, K., FEI, (2012), Ben Maher and Tripple X [ONLINE]. Available at: http://www.an-eventful-life.com.au/showjumping-news/london-2012-olympic-games-showjumping-news/london-2012-olympic-games-jumping-team [Accessed 13 March 14].

***11. Please indicate the proportion of time (i.e. 30% Under Saddle/ 70% Free Jumping) you would use each method to evaluate jump technique.**

Under Saddle/ Ridden

Free Jumping/ Unridden

12. Please indicate whether you would use a single fence or multiple fences in a grid line to evaluate jump technique. (select all that apply)

☐ Grid Line

☐ Single Fence

***13. Please indicate the type of fence you would most commonly use when evaluating quality of jump technique. Rate each fence based on its effectiveness for demonstrating jump technique (5-most, 1-least). (Assuming each fence is constructed with a ground line placed at the base)**

	1	2	3	4	5
Square Oxer	○	○	○	○	○
Ascending Oxer	○	○	○	○	○
Vertical	○	○	○	○	○
Triple Bar	○	○	○	○	○

Please specify any other fence type you feel best demonstrates the quality of a horses jump.

Image: McMurdo, K., Horse Junkies United , (2011), Ian Millar (CAN) and 'Star Power' in the 1.50m Prairie Mines Cup. They finished third. [ONLINE]. Available at: http://horsejunkiesunited.com/?p=1590 [Accessed 13 March 14].

Training Methods for the Equine Jumping Athlete

The aim of this section is to gather information regarding professional training strategies used to maximise performance in the show jumper.

All questions from this section should be answered in relation to a horse training at a minimum competition level of BS Discovery. We recognise that answers will vary greatly depending on individual horses. However, please answer based on methods which you would most frequently use under ideal circumstances (ie. ideal facilities, availability of jump equipment and soundness of horse)

Training and Performance Evaluation of the Equine Jumping Athlete

***14. In your professional opinion, please rate the following based on the importance of their role in training to improve overall jumping performance.**

	Very Important	Important	Neither Important not Unimportant	Unimportant	Very Unimportant
Quality Canter	◯	◯	◯	◯	◯
Jump Technique	◯	◯	◯	◯	◯
Stride Adjustability	◯	◯	◯	◯	◯

Indicate any additional components which play an important role in a jump training program

Image: Cabrera, J., Weisselberg, K. , (2013), Tip of the Day: The "Nellie the Elephant" Canter! [ONLINE]. Available at: http://e-venting.co.uk/2013/02/tip-of-the-day-the-nellie-the-elephant-canter/ [Accessed 15 March 14].

Training Methods for the Equine Jumping Athlete Cont'd

***15. What exercises do you employ most often when training the jumping horse?**

Please indicate as a proportion of time spent using each exercise (ie. 0 - 100%). Answers must add up to 100, but are not required for each option. Input "0" for exercises which you would not use.

Gridwork

Flatwork

Polework

Groundwork/ Lunging

Hacking

Coursework

Other

16. Please specify any other training exercises you would use.

Training and Performance Evaluation of the Equine Jumping Athlete

Training Methods for the Equine Jumping Athlete Cont'd

***17. What is the range of fence height you would use during a typical jump training session?**

Answer all that would apply to you

	Please specify range of fence height for horses training at each competition level
British Novice	
Discovery	
Newcomer	
Foxhunter	

Other (please specify)

Image: Jaffer, N., (2012), Margie Engle and Indigo [ONLINE]. Available at: http://equisearch.com/article/final-2012-olympic-show-jumping-trial_032512 [Accessed 16 March 14].

Training Methods for the Equine Jumping Athlete Cont'd

***18. Which exercises would comprise a typical training session before the day of competition?**
Please specify typical training session for horses training at each competition level. (Check all that apply)

	Groundwork	Flatwork	Polework	Groundwork/lunging	Hacking	Course work	Rest/ Day off
British Novice	☐	☐	☐	☐	☐	☐	☐
Discovery	☐	☐	☐	☐	☐	☐	☐
Newcomer	☐	☐	☐	☐	☐	☐	☐
Foxhunter	☐	☐	☐	☐	☐	☐	☐
Classes Exceeding 1.20m	☐	☐	☐	☐	☐	☐	☐

Other (please specify)

Thank You

Your participation in this questionnaire is greatly appreciated. As a token of our appreciation, we will be happy to provide a description of questionnaire results upon request. We can also provide information regarding further participation in this exciting new area of equine research upon request.

Results from this questionnaire will be used to develop methods and explore areas which are relevant to members of the equine industry. Questions related to the evaluation of quality movement will be used to inform future research, as it will allow us to objectively examine areas of equine movement, which are relevant to the industry professional. Questions related to fence type and arrangement will help replicate industry practice in our research. Similarly, questions related to training will be used to ensure research explores and replicates aspects of professional training strategies used to maximise performance in the jumping horse. Your answers to this questionnaire are greatly appreciated as they will help us ensure results are relevant to equine industry professionals.

Please do not hesitate to contact me at LBSt-george@uclan.ac.uk. I will be happy to answer any questions you may have regarding the questionnaire or any aspect of the broader research project. Your participation represents a valuable contribution to the equine science field, and I thank you again for your help and cooperation.

Appendix B: Ethical Approval

uclan

MEMORANDUM

To: Sarah Hobbs
Division of Sport, Exercise & Nutritional Sciences

Date: 5th February 2014
Ref: RE/13/04/SH

From: Louise Price
Committee Secretary
Research Development & Support Team
☎ 3486
✉email: lmprice1@uclan.ac.uk

Animal Projects

The Animal Projects Committee which met on 5th February 2014 **has approved** the following project:

- **RE/13/04/SH** Electromyographic evaluation of muscle firing patterns in the sport horse jumping as an objective method of informing current jump training programs

Please note that this is also to notify you of the reference number allocated to your project (as stated above). Please use this reference number whenever your projects are returned to the Committee for renewal, closure etc.

Regards

Louise Price

Appendix C: Additional Kinematic Data

Table C1. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.1 (page 215).

	Elite	NC	School	Total
Stride velocity	66	128	68	262
Stride length	65	118	67	250
Stride duration	65	114	62	241
FL stance duration	70	137	63	270
HL stance duration	65	114	62	241
Duty factor	65	114	62	241

Table C2. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.2 (page 216).

	Elite	NC	School	Total
Stride velocity	19	37	15	71
Stride length	19	37	14	70
Stride duration	14	34	14	62
FL stance duration	10	23	2	35
HL stance duration	14	34	15	63
Duty factor	14	34	14	62

Table C3. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.3 (page 217).

	Elite	NC	School	Total
Stride velocity	21	34	29	84
Stride length	21	34	26	81
Stride duration	19	34	28	81
FL stance duration	22	35	28	85
HL stance duration	23	38	28	89
Duty factor	19	34	28	81

Table C4. Number of strides used to calculate group mean (± SD) values for sEMG data presented in Tables 8.4 – 8.7 (pages 221, 224 – 225).

	Elite	NC	School	Total
Canter	79	101	52	232
Approach	12	20	7	39
Take Off	24	21	16	61
Landing	11	16	16	43

Table C5. Number of strides used to calculate group mean (± SD) values for sEMG data presented in Tables 8.8 – 8.11 (pages 227, 229 – 231).

	Elite	NC	School	Total
Canter	80	115	47	242
Approach	13	13	11	37
Take Off	20	13	26	59
Landing	12	7	24	43

Table C6. Number of strides used to calculate group mean (± SD) values for sEMG data presented in Tables 8.12 – 8.15 (pages 233, 235 – 236).

	Elite	NC	School	Total
Canter	85	133	54	272
Approach	8	10	1	19
Take Off	17	15	12	44
Landing	8	11	10	29

Table C7. Number of strides used to calculate group mean (± SD) values for sEMG data presented in Tables 8.16 – 8.19 (pages 237, 240).

	Elite	NC	School	Total
Canter	32	70	41	143
Approach	2	10	1	13
Take Off	6	18	10	34
Landing	3	14	11	28

Table C8. Number of strides used to calculate group mean (± SD) values for sEMG data presented in Tables 8.20 – 8.23 (pages 242, 245).

	Elite	NC	School	Total
Canter	67	93	43	203
Approach	2	6	1	9
Take Off	8	14	11	33
Landing	7	10	12	29

Table C9. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.24 (page 246).

	Elite	NC	School	Total
Tracking up	85	112	74	271
Max Hock Angular Velocity	66	116	68	250

Table C10. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.25 (page 248).

	Elite	NC	School	Total
HL protraction	82	167	72	321
HL retraction	82	167	72	321
HL pro/re ROM	82	167	72	321
Prox Scap displacement	61	108	66	235
CM displacement	58	97	44	199

Table C11. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.26 (page 250).

	Elite	NC	School	Total
FL protraction	85	164	86	335
FL retraction	85	164	86	335
FL pro/re ROM	85	164	86	335
Elbow ROM	69	128	63	260
Shoulder ROM	71	126	66	263
Hock angle	87	153	87	327

Table C12. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.27 (page 252).

	Elite	NC	School	Total
FL shortening	22	41	29	92
Max elbow flexion	23	27	27	92
Carpus flexion	20	30	27	77
Radius inclination	11	19	28	58
Shoulder flexion	23	36	29	88
Scapula inclination	24	37	29	90

Table C13. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.28 (page 254).

	Elite	NC	School	Total
HL shortening	27	38	28	93
HL retroflexion	24	37	26	87

Table C14. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.29 (page 255).

	Elite	NC	School	Total
CM vertical displacement	25	41	26	92

Table C15. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.30 (page 256).

	Elite	NC	School	Total
Shoulder angular velocity	24	33	24	81
Elbow angular velocity	23	26	26	75
Carpus angular velocity	23	26	26	75

Table C16. Number of strides used to calculate group mean (± SD) values for kinematic data presented in Table 8.31 (page 258).

	Elite	NC	School	Total
Scapula vertical displacement	24	37	29	90
Max hock flex	25	38	28	91
Tracking up	13	26	22	61

Appendix D: Additional Electromyography Data

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Superficial Gluteal

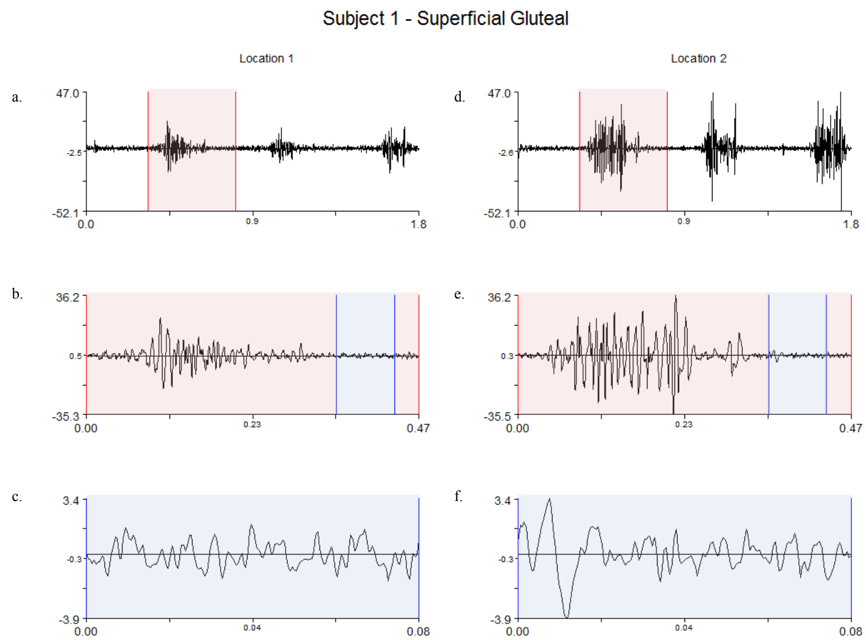


Figure D1. Time domain and spectral characteristics of baseline noise and sEMG signals from Superficial Gluteal from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 1.

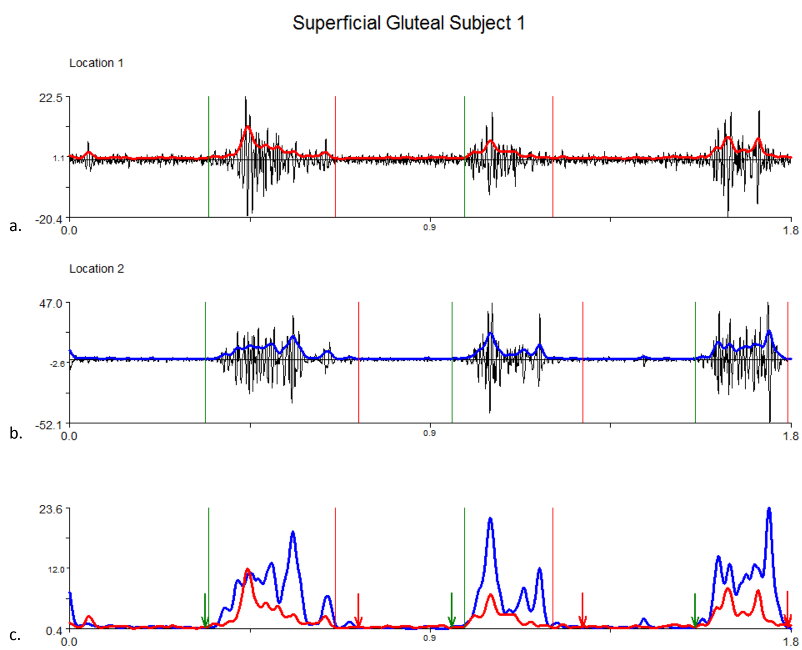


Figure D2 Onset and offset events from Superficial Gluteal sensor locations from subject 1.

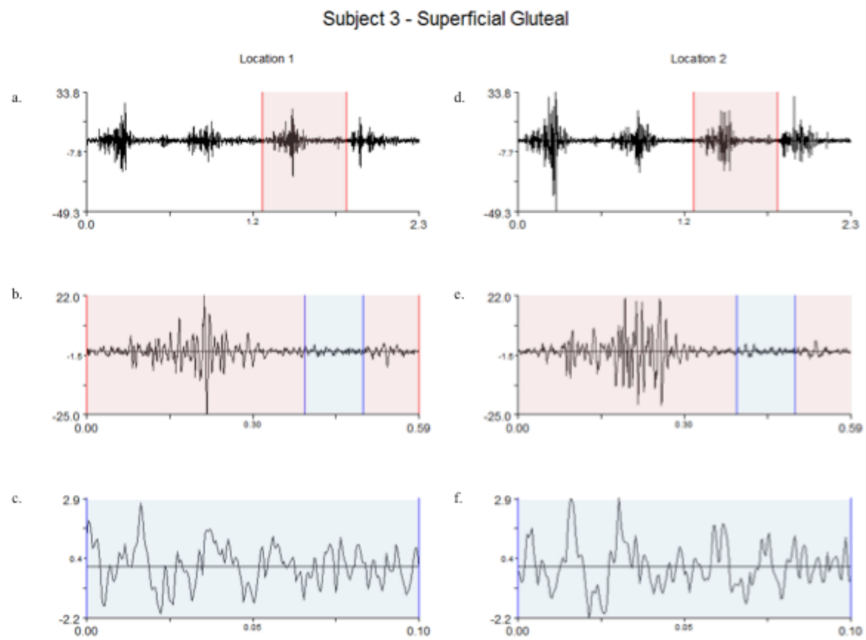


Figure D3. Time domain and spectral characteristics of baseline noise and sEMG signals from Superficial Gluteal from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 3.

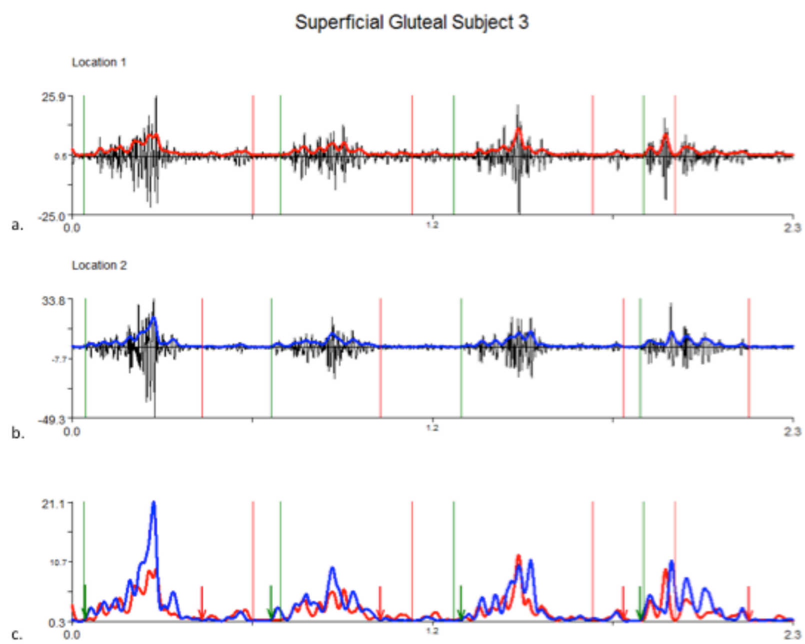


Figure D4. Onset and offset events from Superficial Gluteal sensor locations from subject 3.

Biceps Femoris (vertebral head)

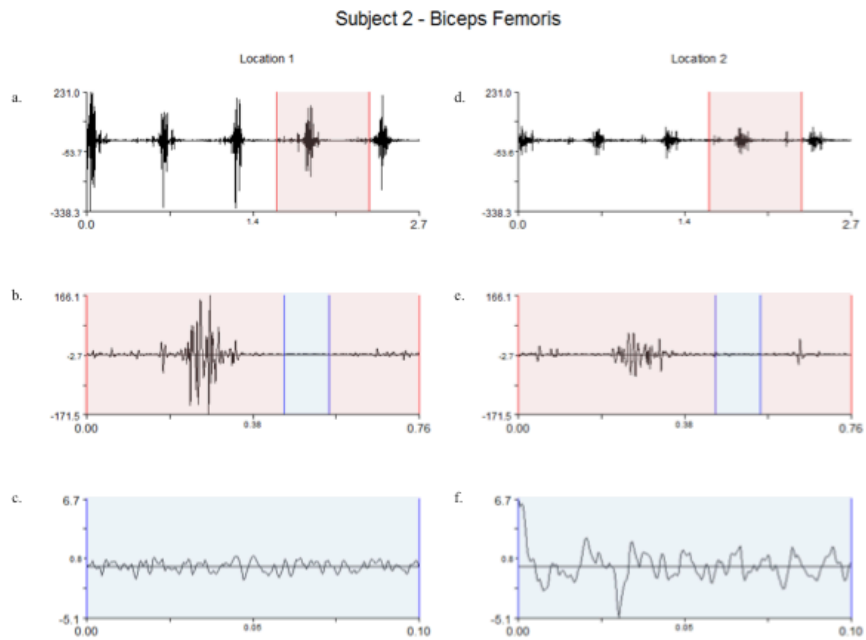


Figure D5. Time domain and spectral characteristics of baseline noise and sEMG signals from Biceps Femoris from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 2.

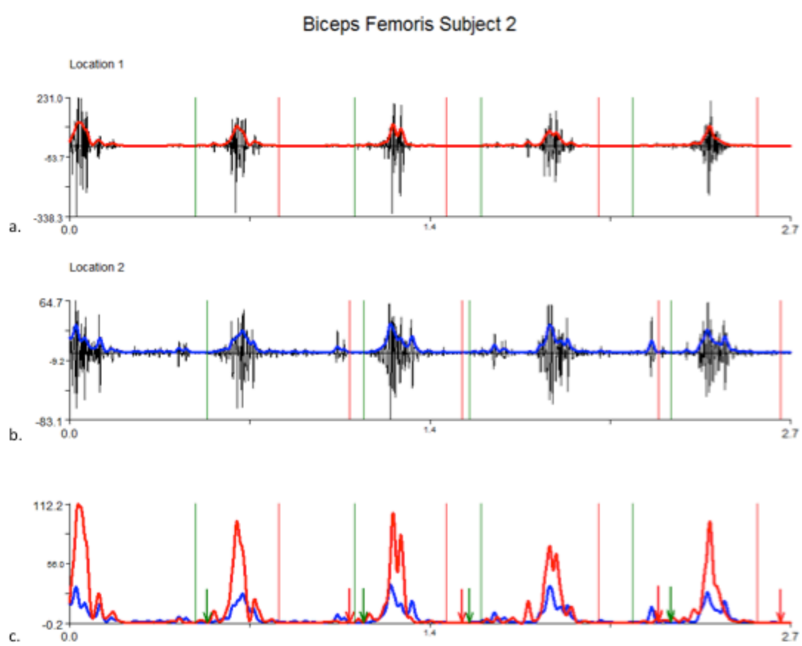


Figure D6. Onset and offset events from Biceps Femoris sensor locations from subject 2.

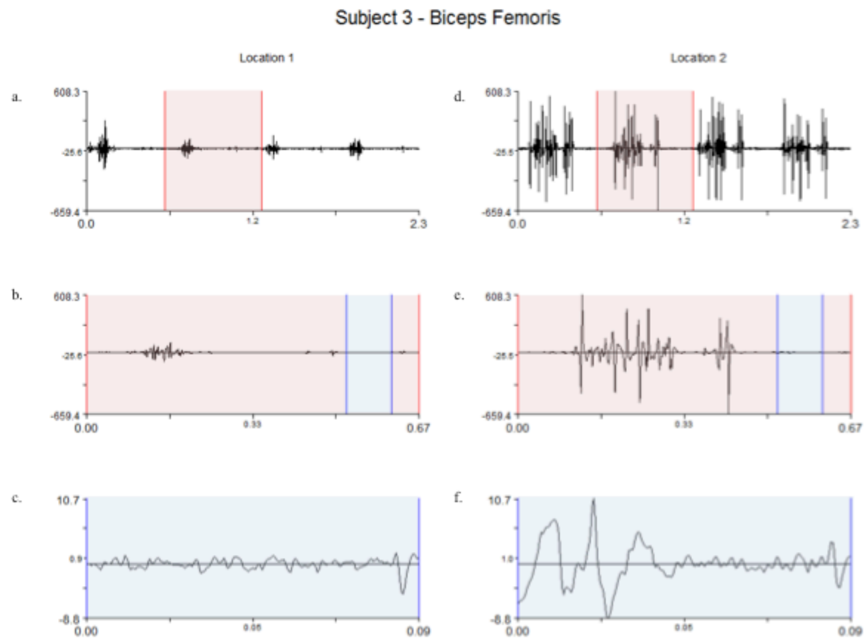


Figure D7. Time domain and spectral characteristics of baseline noise and sEMG signals from Biceps Femoris from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 3.

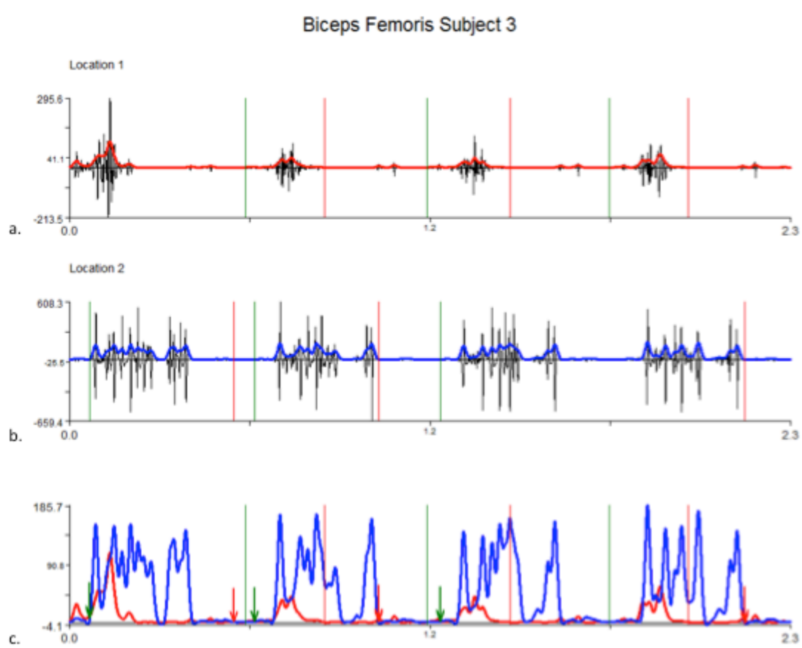


Figure D8. Onset and offset events from Biceps Femoris sensor locations from subject 3.

Triceps Brachii (long head)

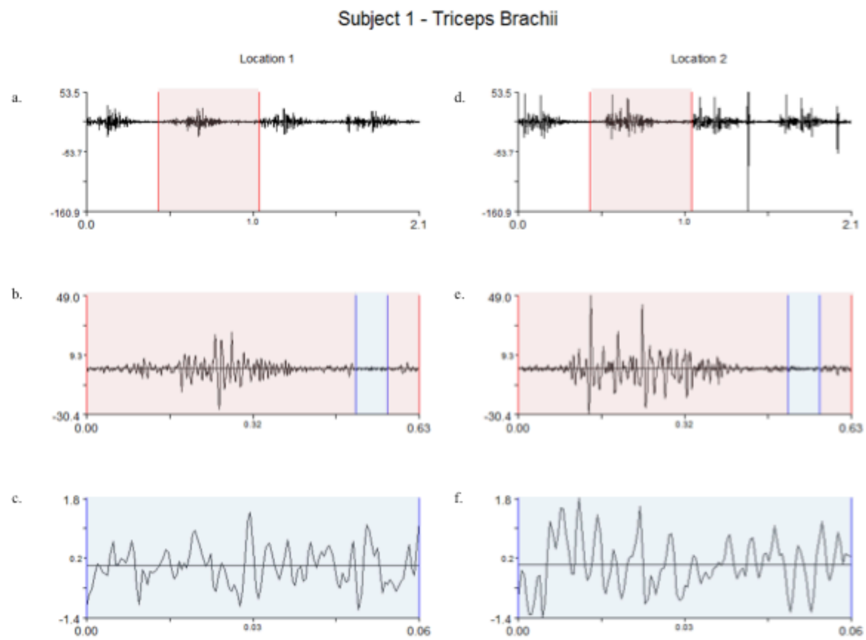


Figure D9. Time domain and spectral characteristics of baseline noise and sEMG signals from Triceps Brachii from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 1.

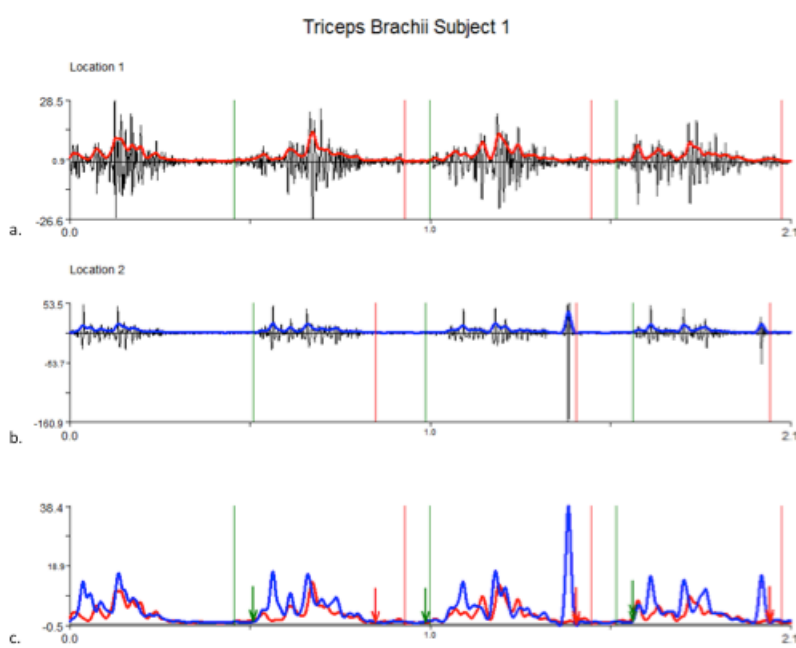


Figure D10. Onset and offset events from Triceps Brachii sensor locations from subject 1.

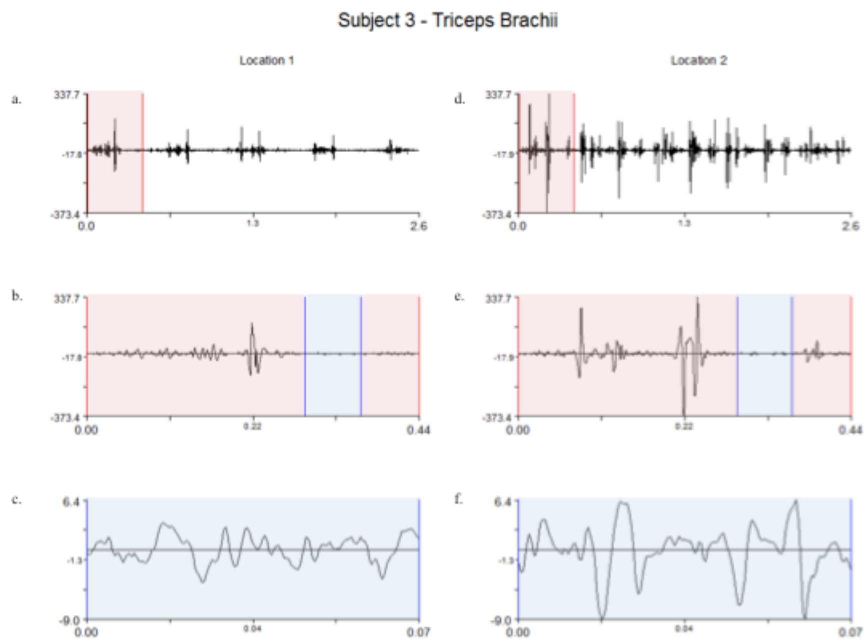


Figure D11. Time domain and spectral characteristics of baseline noise and sEMG signals from Triceps Brachii from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 3.

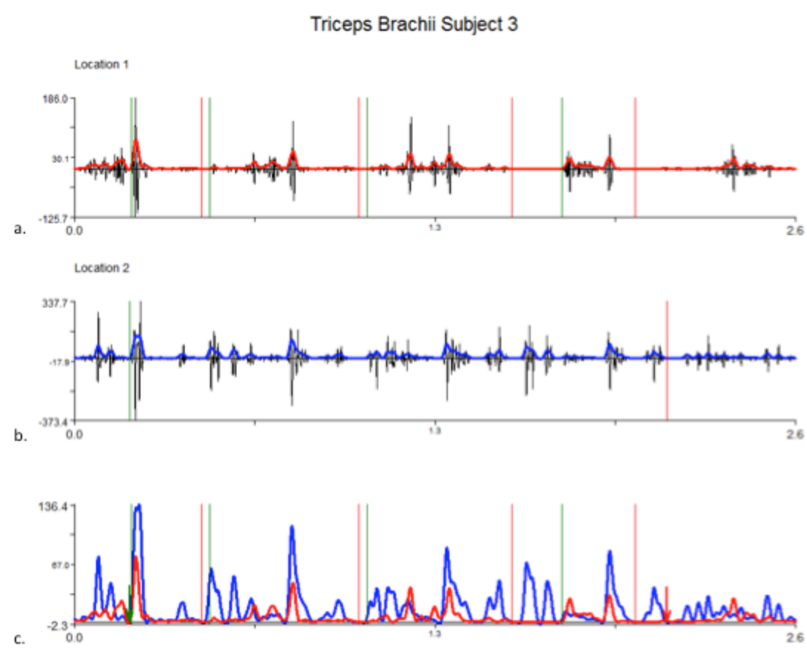


Figure D12. Onset and offset events from Triceps Brachii sensor locations from subject 3.

Trapezius (cervical head)

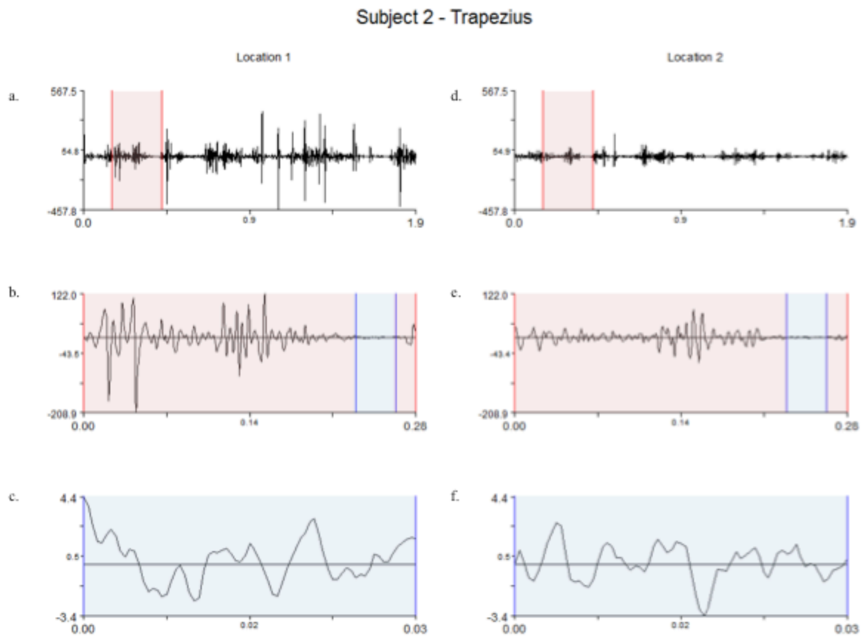


Figure D13. Time domain and spectral characteristics of baseline noise and sEMG signals from Trapezius from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 2.

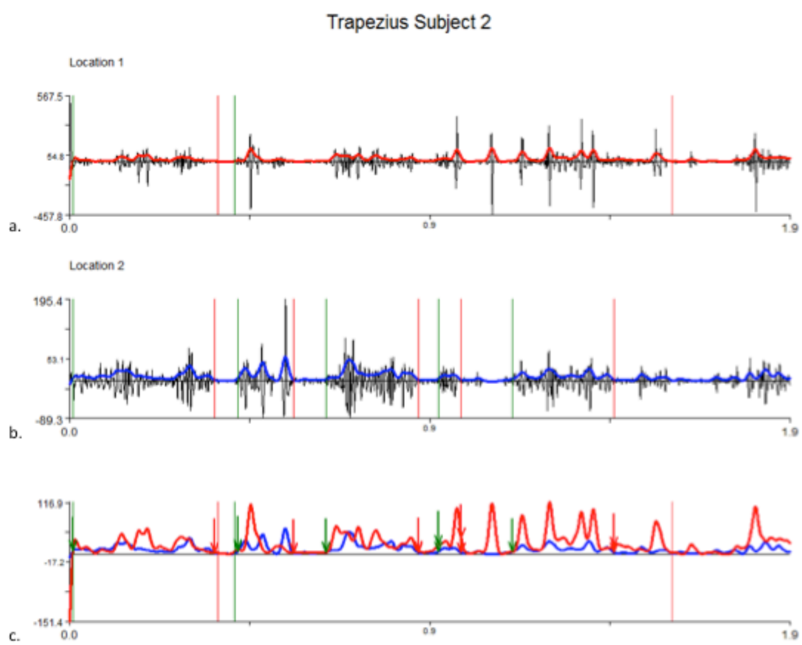


Figure D14. Onset and offset events from Trapezius sensor locations from subject 2.

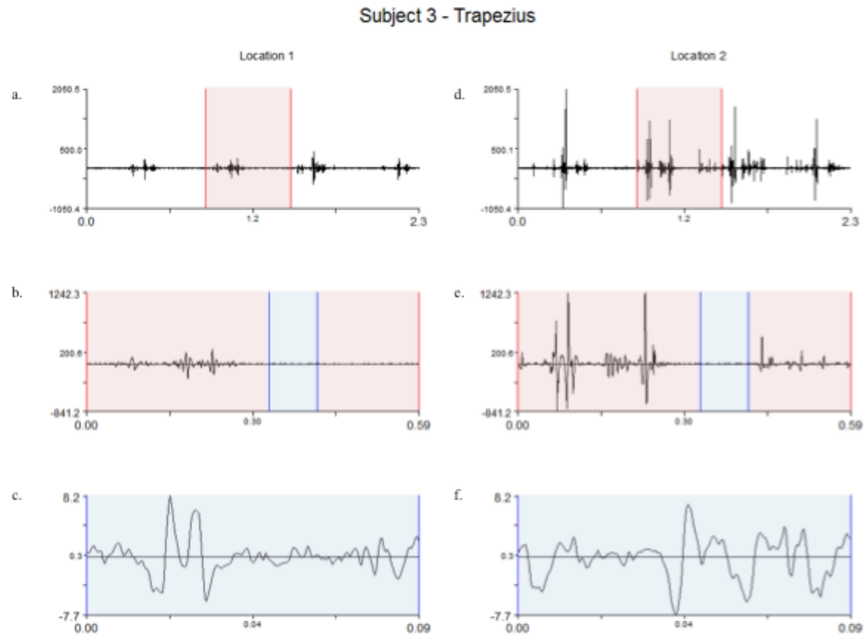
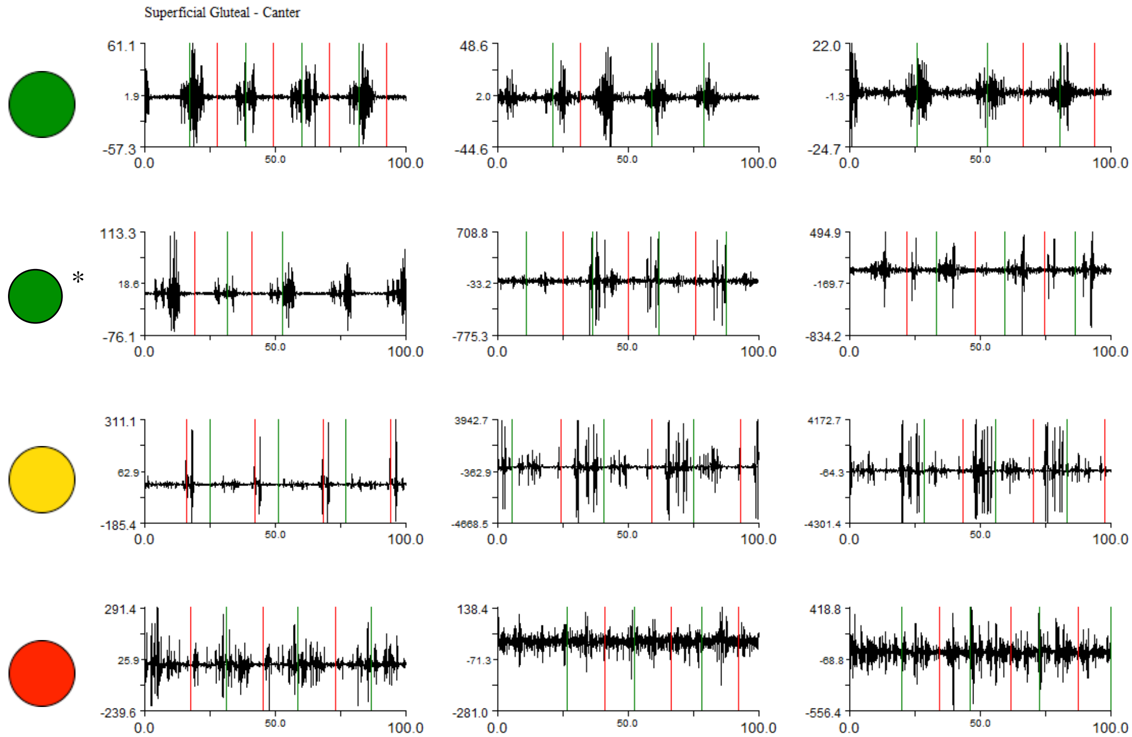
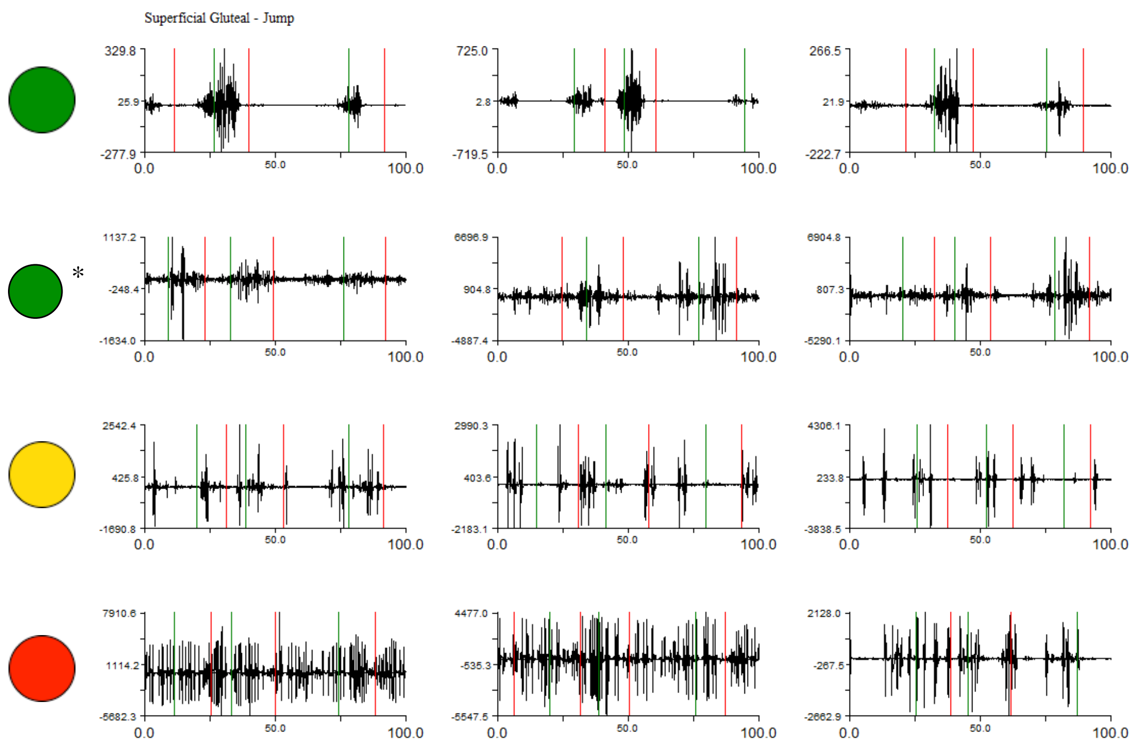


Figure D15. Time domain and spectral characteristics of baseline noise and sEMG signals from Trapezius from electrode site 1 (a, b, c) and Site 2 (d, e, f) in subject 3.

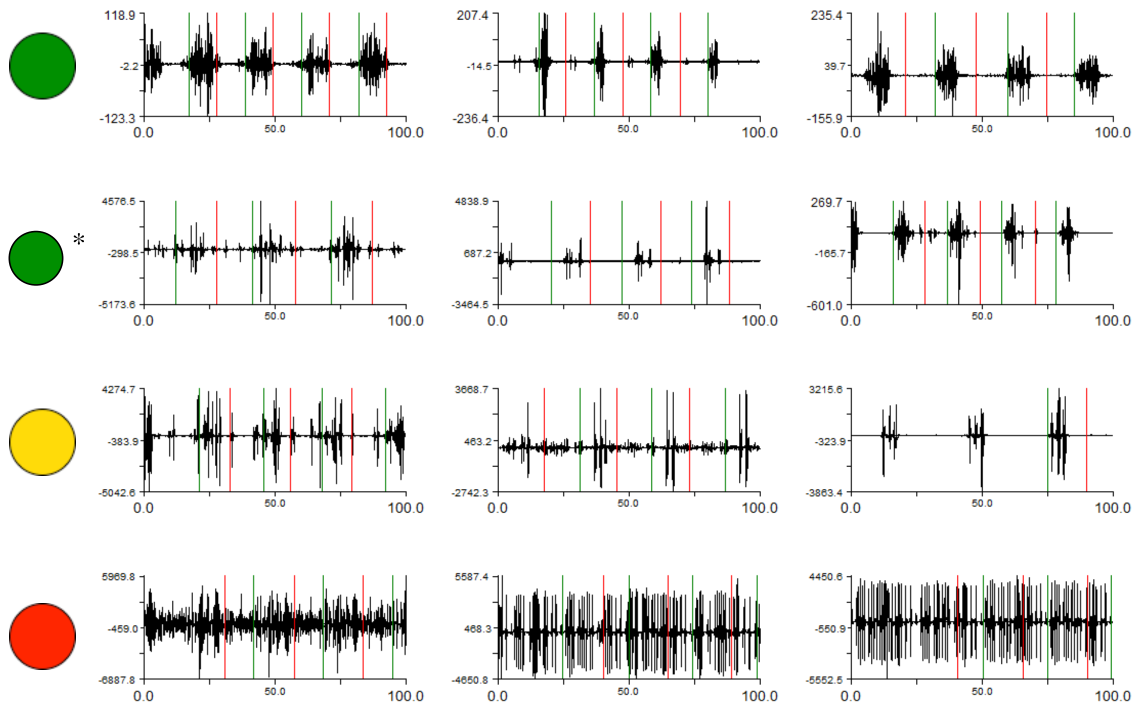
Superficial Gluteal



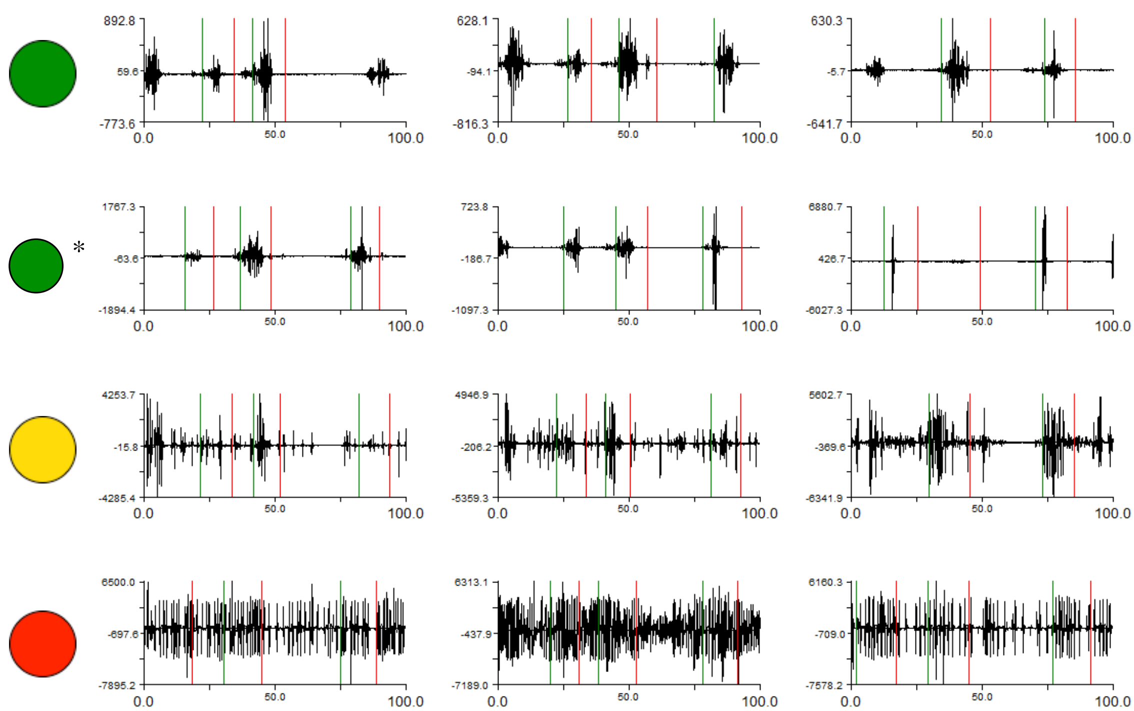


Biceps Femoris (vertebral head)

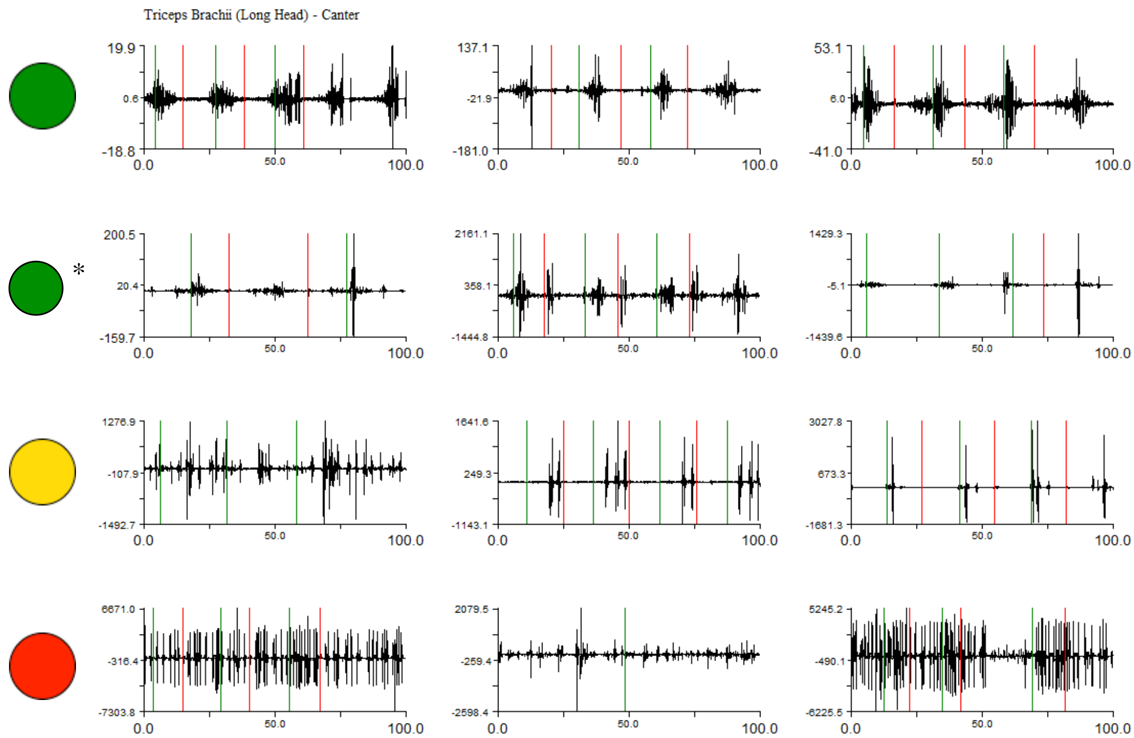
Biceps Femoris (vertebral head) - Canter

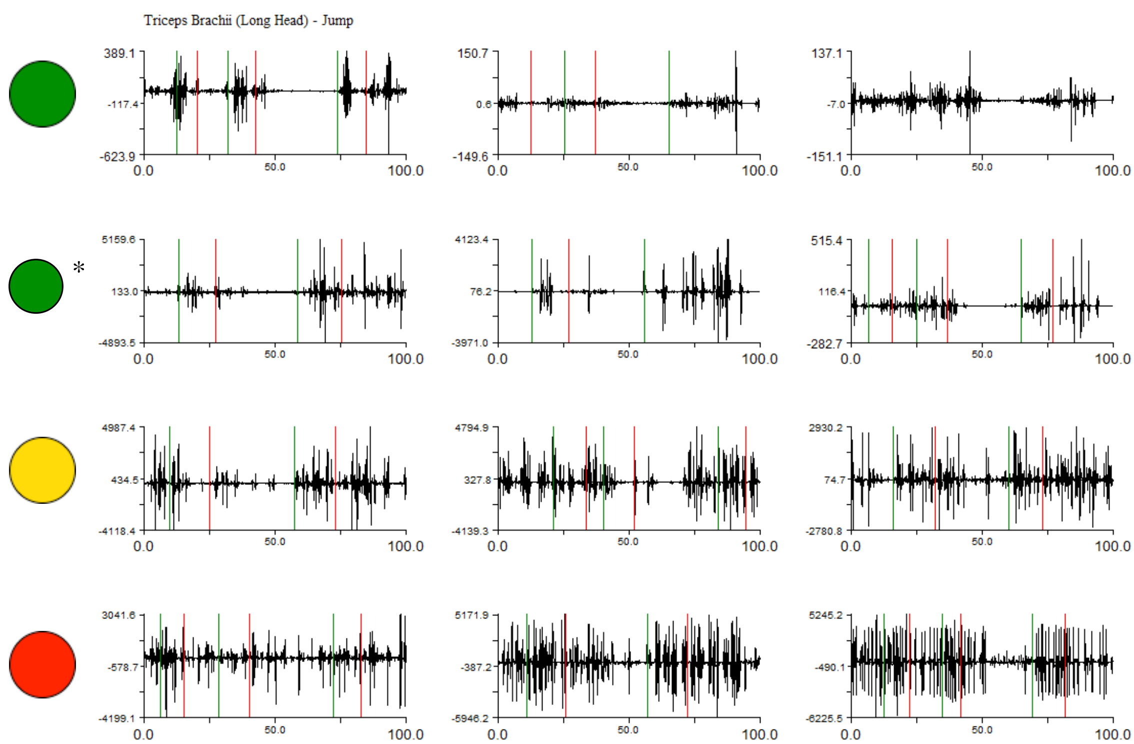


Biceps Femoris (vertebral head) -Jump

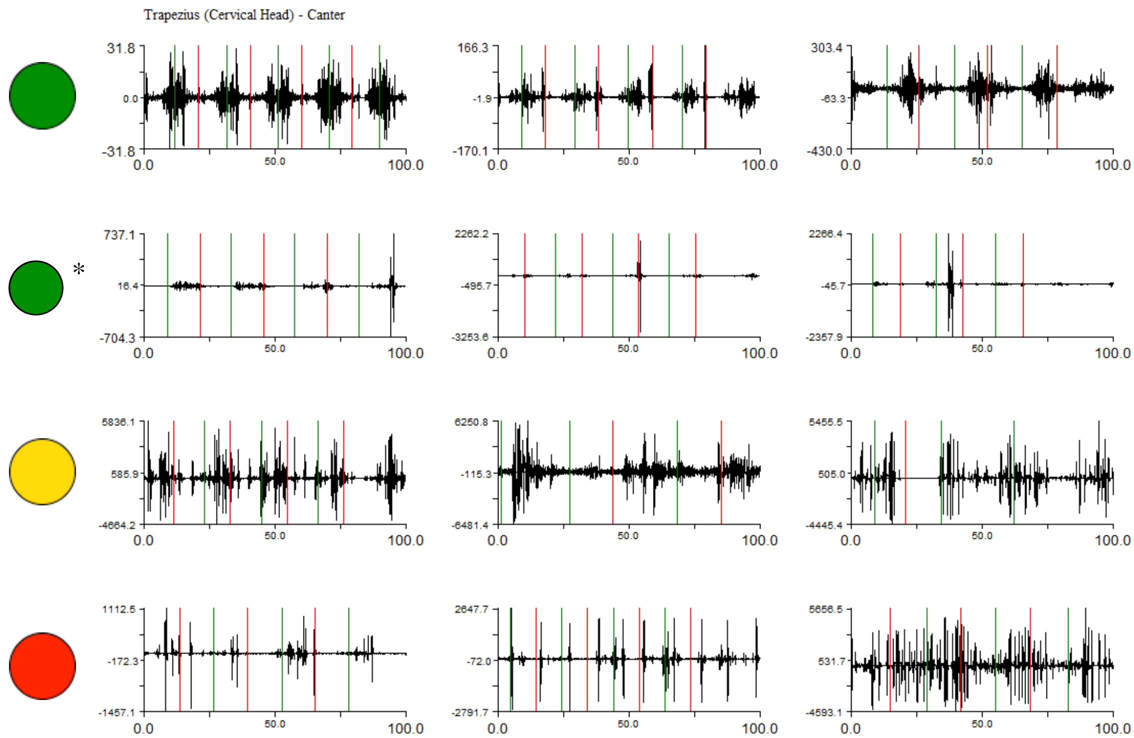


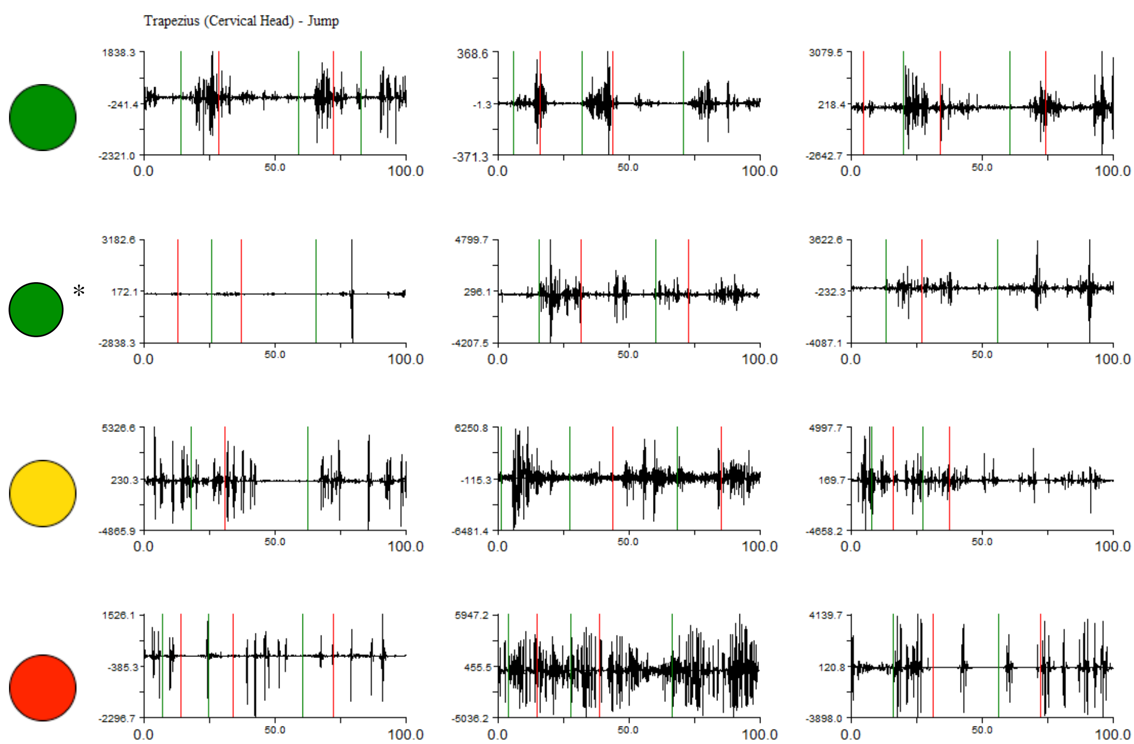
Triceps Brachii (long head)



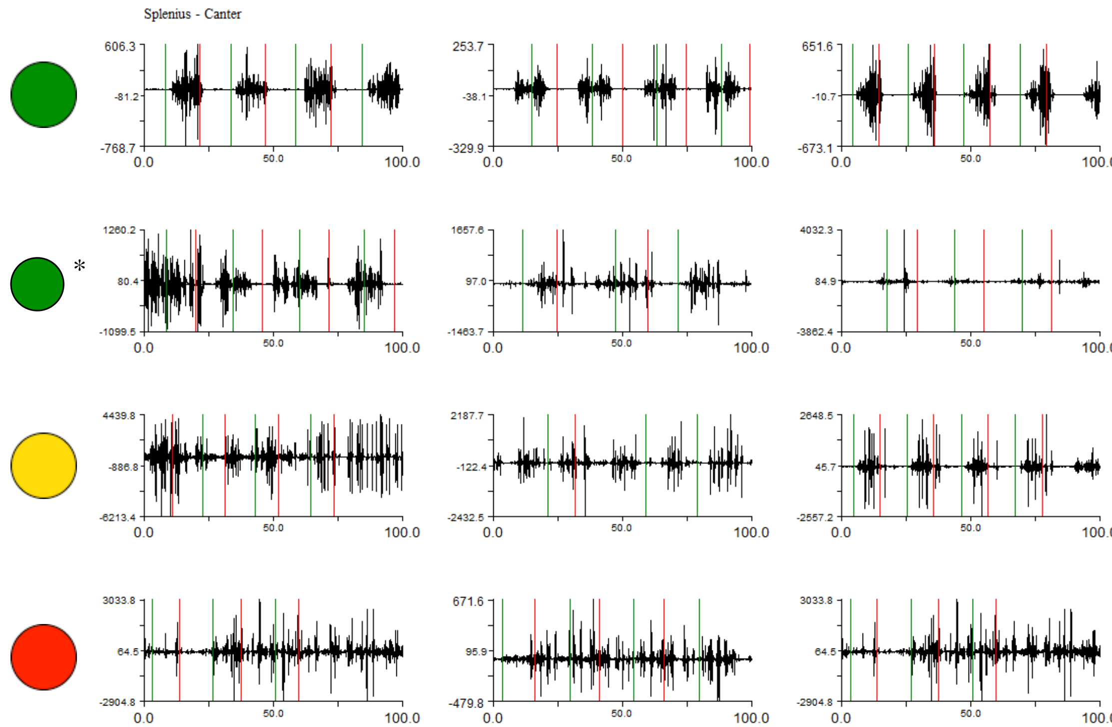


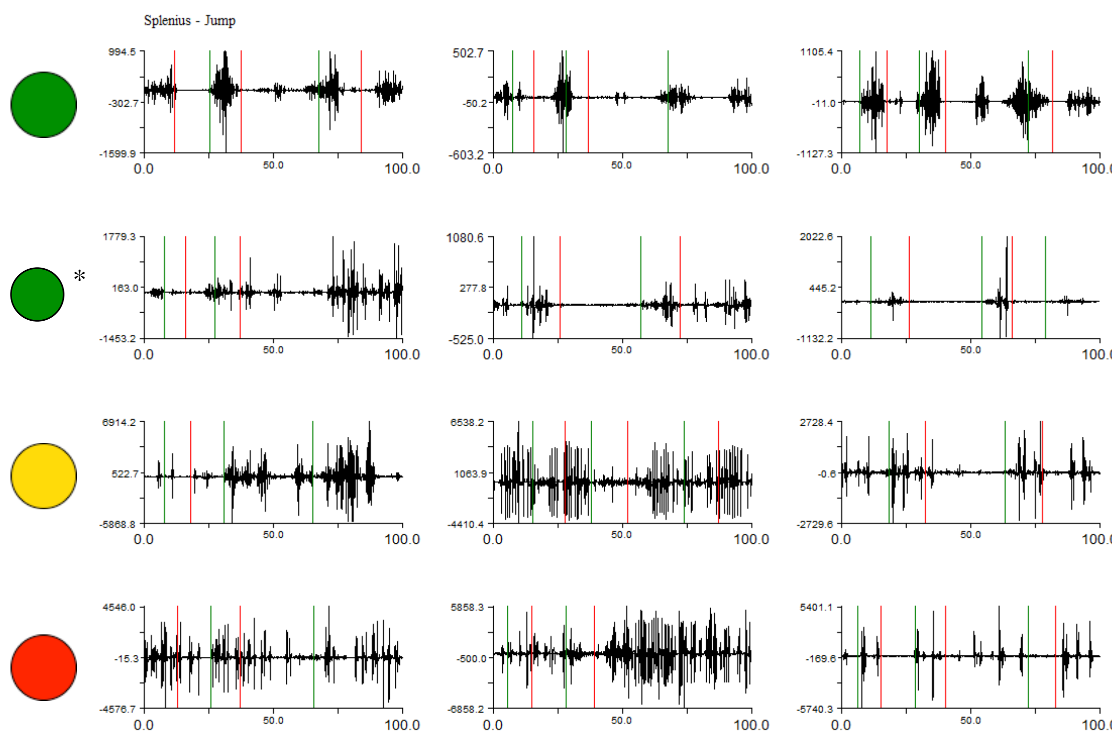
Trapezius (cervical head)





Splenius





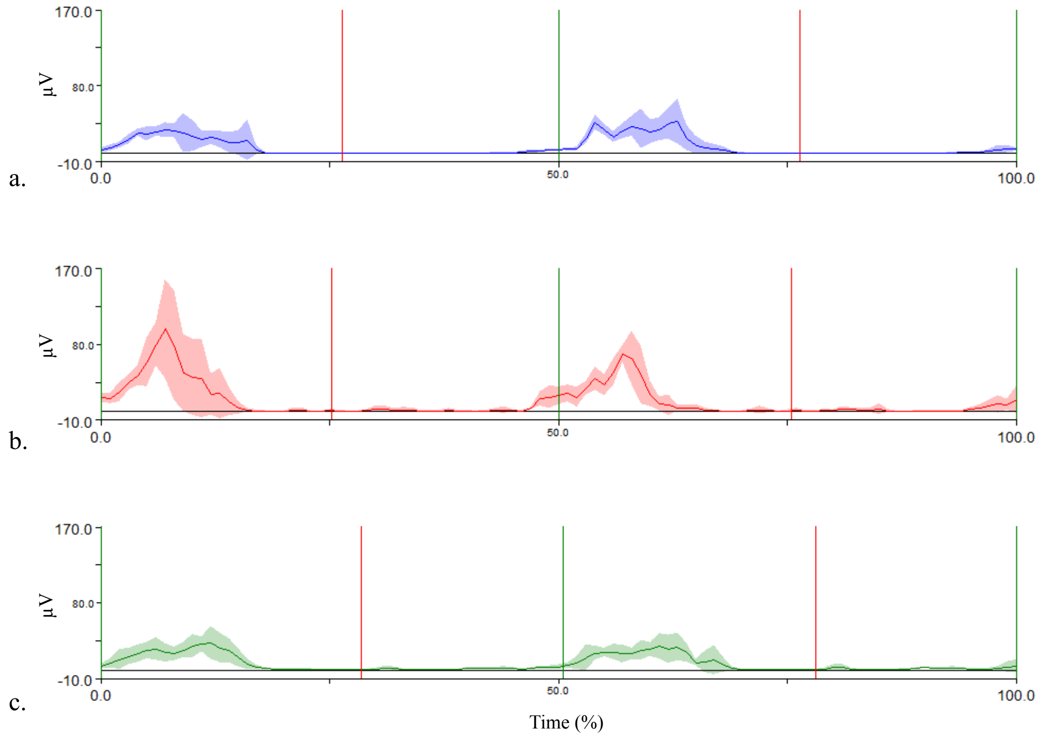


Figure D16. Representative linear enveloped sEMG signals from one horse per group for the Biceps Femoris muscle from LdH and TrH, time-normalised across two canter strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent HL hoof impact and hoof off events, respectively. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised across two canter strides.

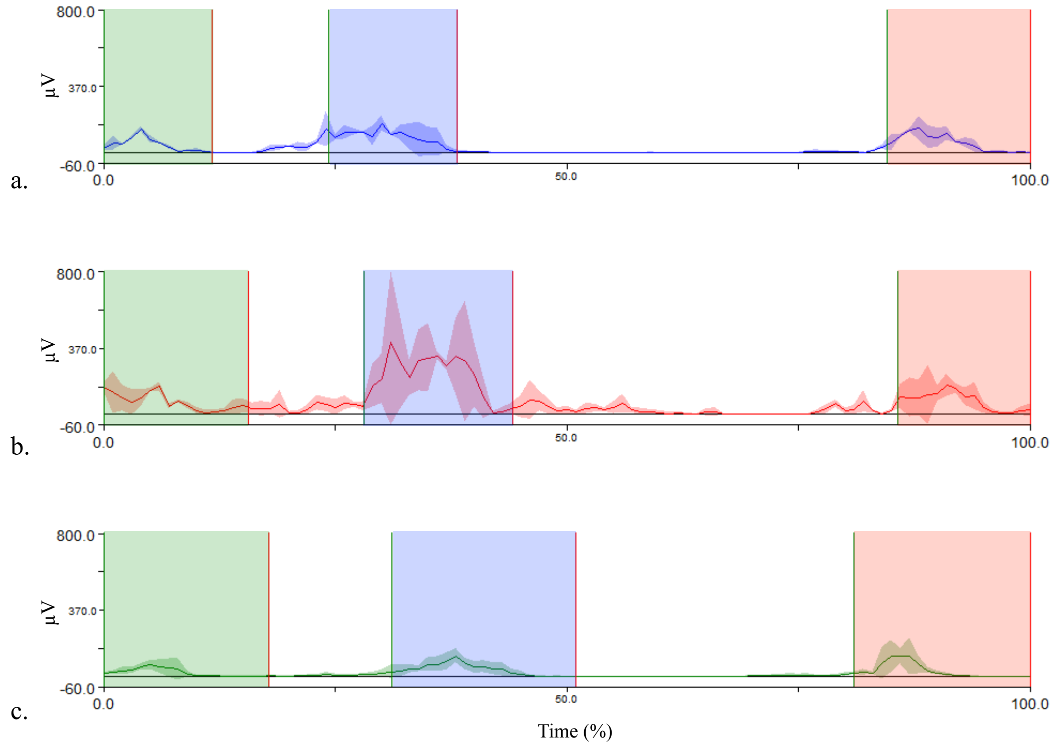


Figure D17. Representative linear enveloped sEMG signals from one horse per group for the Biceps Femoris muscle from LdH and TrH during approach (A1) and jump strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent HL hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase druing A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

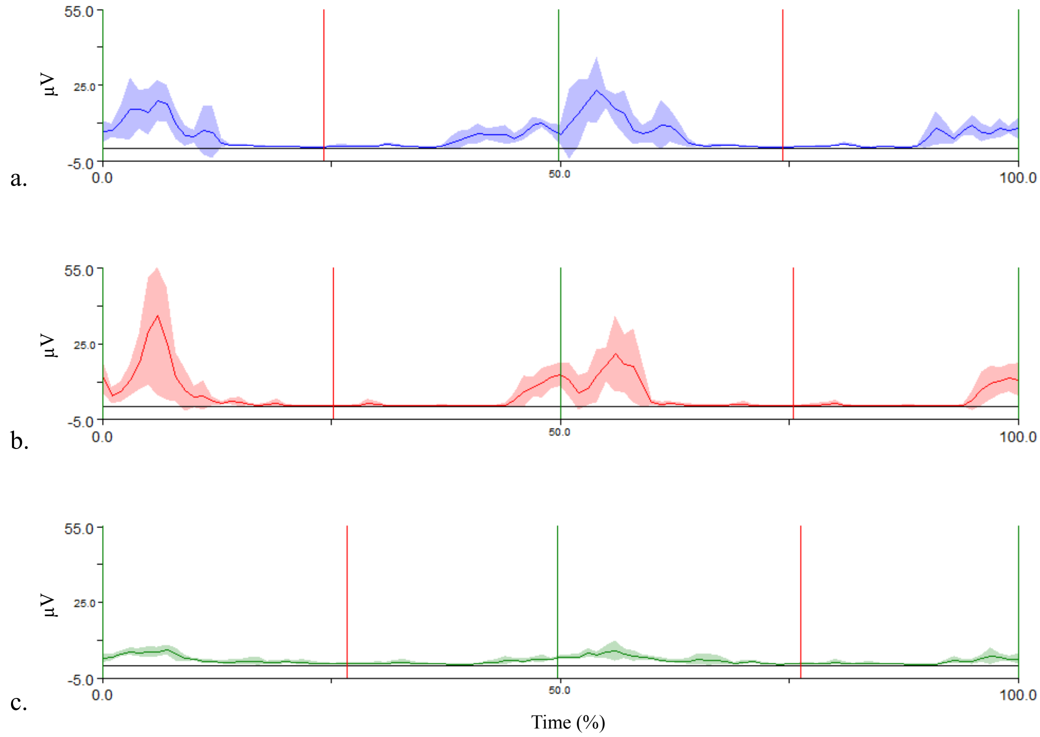


Figure D18. Representative linear enveloped sEMG signals from one horse per group for the Superficial Gluteal muscle from LdH and TrH, time-normalised across two canter strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent HL hoof impact and hoof off events, respectively. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised across two canter strides.

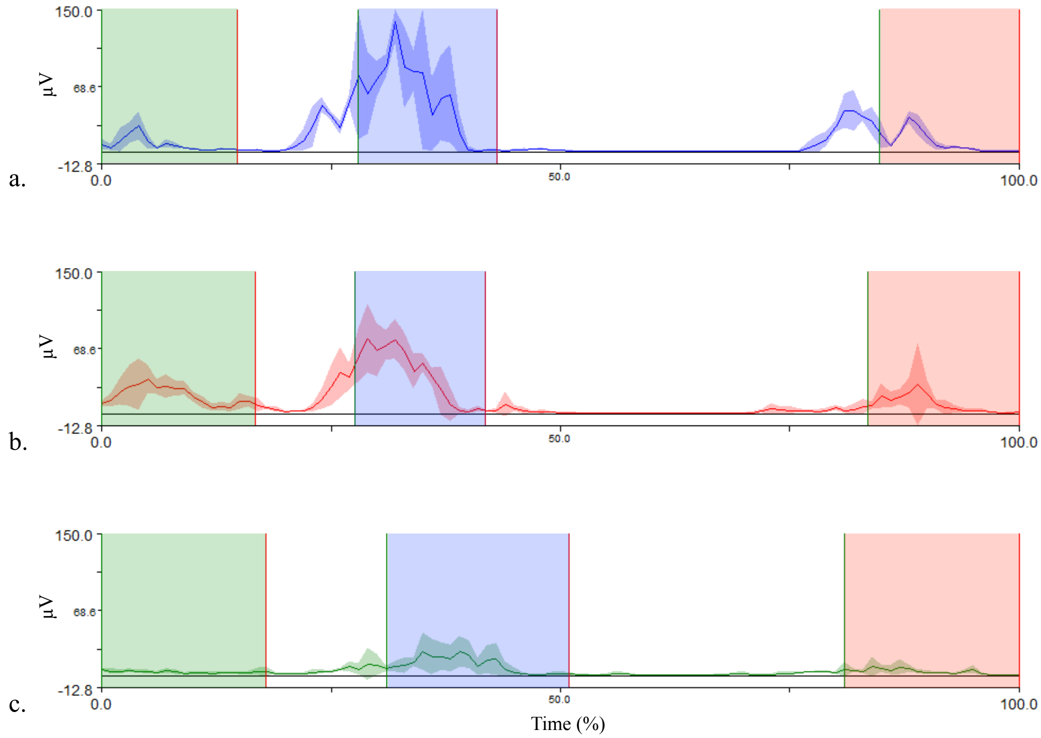


Figure D19. Representative linear enveloped sEMG signals from one horse per group for the Superficial Gluteal muscle from LdH and TrH during approach (A1) and jump strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent HL hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase druing A1 (green), jump (blue) and departure (red) strides. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised between hoof impact event at A1 and hoof off event at departure stride.

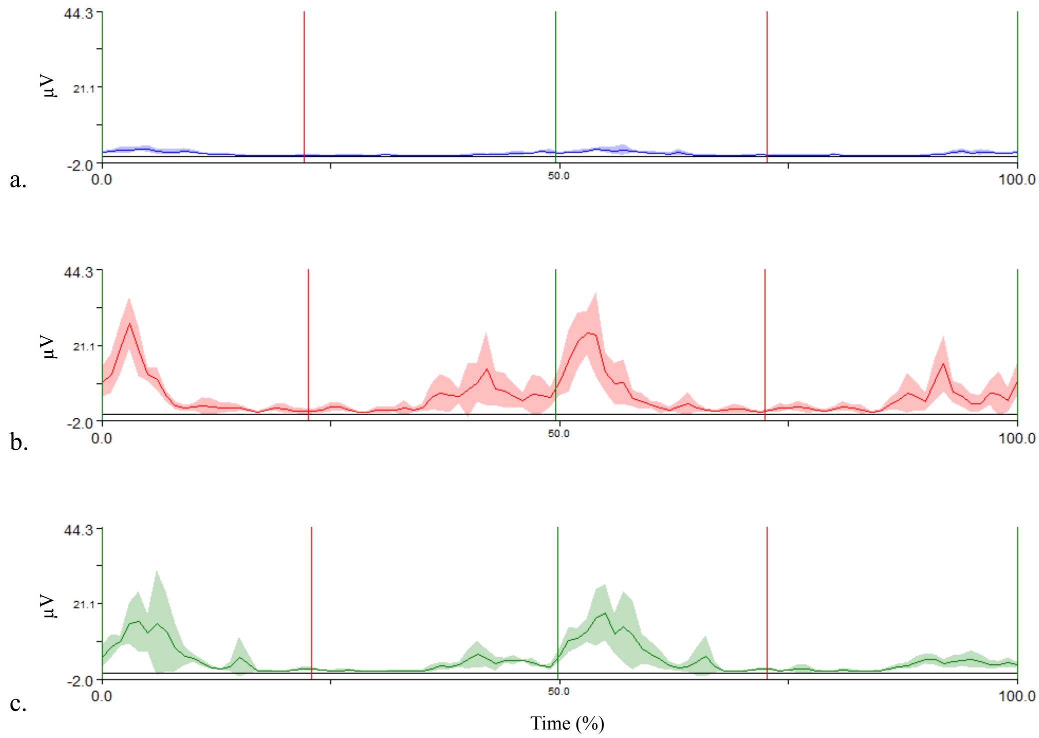


Figure D20. Representative linear enveloped sEMG signals from one horse per group for the Triceps Brachii muscle from LdF and TrF, time-normalised across two canter strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised across two canter strides.

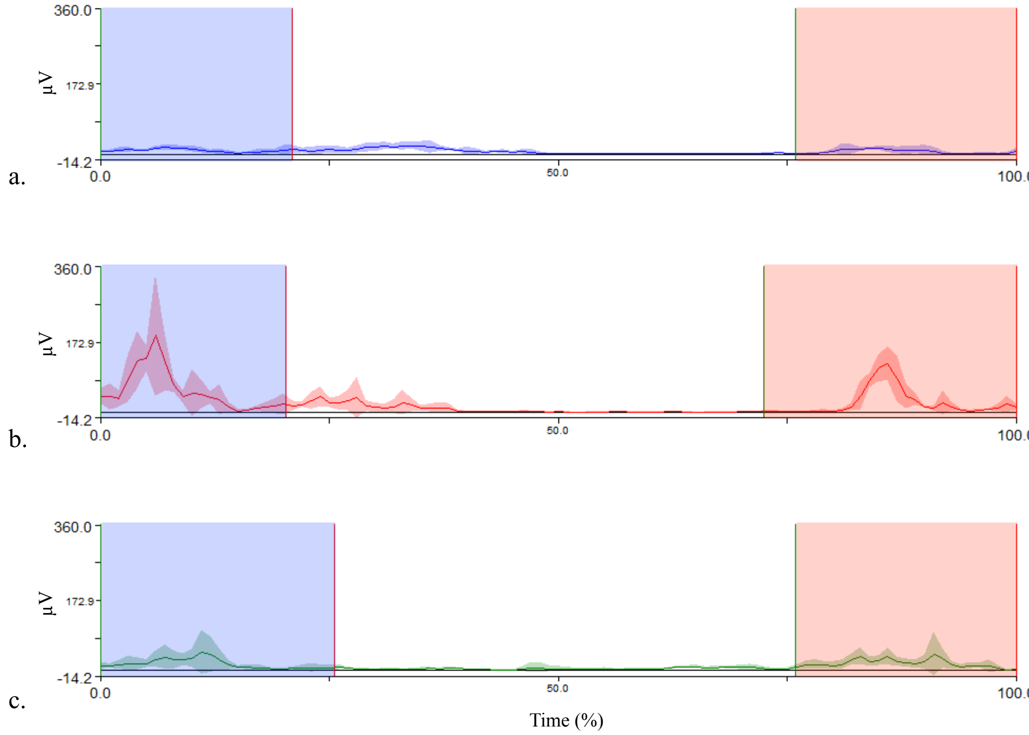


Figure D21. Representative linear enveloped sEMG signals from one horse per group for the Triceps Brachii muscle from LdF and TrF during jump stride. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised between hoof impact event at take-off and hoof off event at landing.

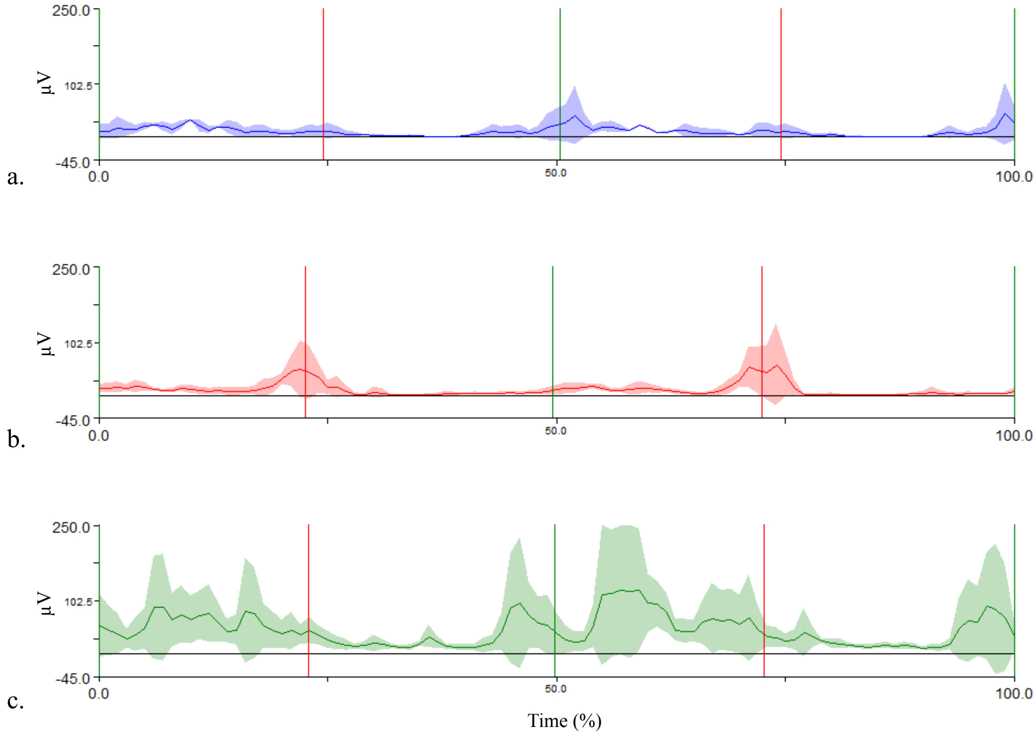


Figure D22. Representative linear enveloped sEMG signals from one horse per group for the Trapezius muscle from LdF and TrF, time-normalised across two canter strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in μV and graphs are normalised across two canter strides.

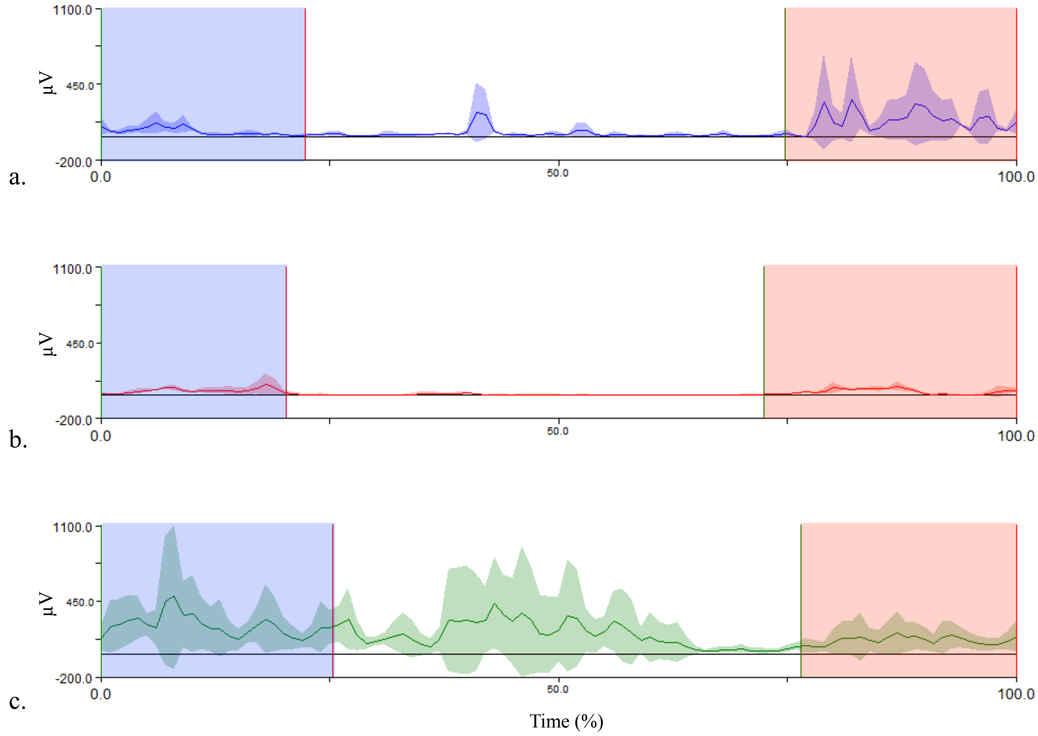


Figure D23. Representative linear enveloped sEMG signals from one horse per group for the Trapezius muscle from LdF and TrF during jump stride. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised between hoof impact event at take-off and hoof off event at landing.

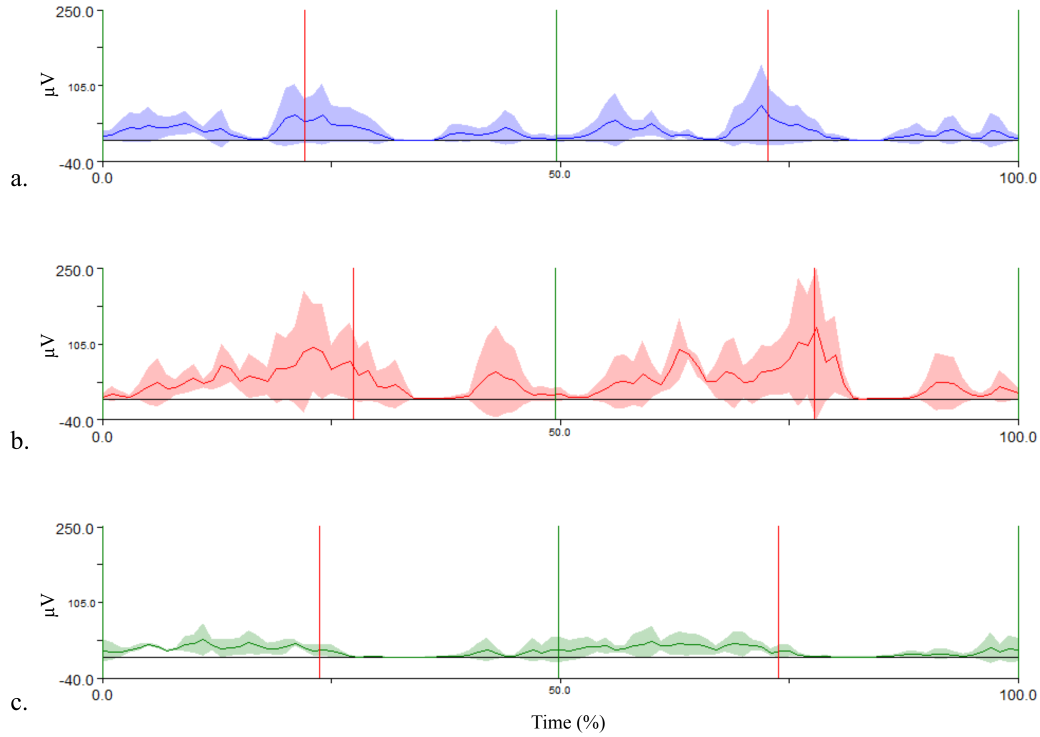


Figure D24. Representative linear enveloped sEMG signals from one horse per group for the Splenius muscle from LdF and TrF, time-normalised across two canter strides. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised across two canter strides.

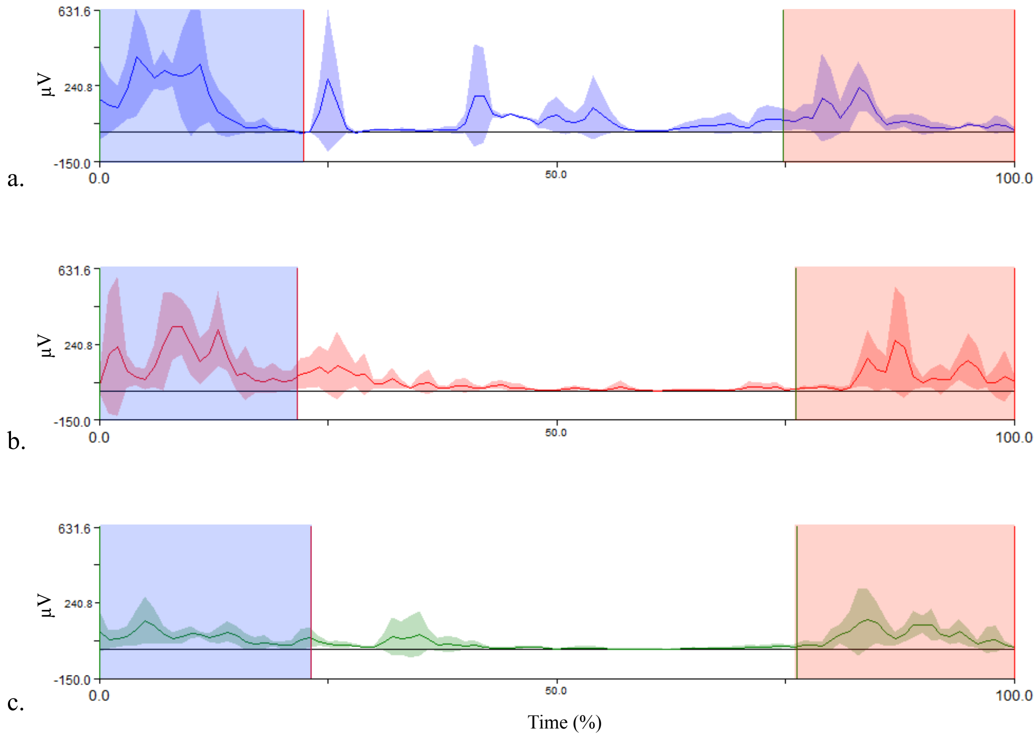


Figure D25. Representative linear enveloped sEMG signals from one horse per group for the Splenius muscle from LdF and TrF during jump stride. Data are presented as mean (± SD) time-normalised, linear enveloped sEMG data from one horse per group a.) elite, b.) NC, c.) school. Green and red vertical lines represent FL hoof impact and hoof off events, respectively. Shaded areas represent hind stance phase during take-off (blue) and landing (red) phases. Signals presented are DC offset, high-pass filtered (80 Hz cut-off), and low-pass filtered (25 Hz cut-off). EMG activity is presented in µV and graphs are normalised between hoof impact event at take-off and hoof off event at landing.

Appendix E: Publications and Conference Presentations

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