Strategies to optimise sled towing and acceleration in semi-elite rugby league players

by

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STUDENT DECLARATION FORM

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Type of Award **PhD via MPhil**

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Abstract

Sprint-specific training modalities may have a better transfer to performance compared to non-specific strength training. Resisted sprint training modalities such as sled towing (ST) are performed in a horizontal direction, and involve the relevant muscles, velocities and ranges of motion to those of uninhibited sprinting. Despite the widespread use of ST there is a lack of agreement in the optimal sled setup, loading strategies and programming variables. Therefore, the aims of this thesis were to provide new knowledge and practical applications for practitioners looking to incorporate ST into their training programme.

Study one aimed to investigate the kinetics and 3-D kinematics of different harness attachment points on ST during the acceleration phase of sprinting. Participants completed sprint trials under different conditions (uninhibited sprinting, shoulder and waist attachments). Results indicated that various kinetic differences were present between the normal and ST conditions. Significantly greater net horizontal mean force, net horizontal impulses, propulsive mean force and propulsive impulses were measured ($p < 0.05$). Interestingly, the waist harness also led to greater net horizontal impulse when compared to the shoulder attachment ($p < 0.01$). In kinematic terms, ST conditions significantly increased peak flexion in hip, knee and ankle joints compared to the normal trials ($p < 0.05$). Results highlighted that the shoulder harness had a greater impact on trunk and knee joint kinematics when compared to the waist harness ($p < 0.05$). In summary, waist harnesses appear to be the most suitable attachment point for the acceleration phase of sprinting. Sled towing with

these attachments resulted in fewer kinematic alterations and greater net horizontal impulse when compared to the shoulder harness.

Study two examined the kinetics and 3-D kinematics of different loadings on ST during the acceleration phase of sprinting. Semi-elite rugby league players performed a series of 6 m sprints in different conditions; uninhibited, 10, 15 and 20% velocity decrement (V_{Dec}). Results indicated that ST affected trunk, knee and ankle joint kinematics ($p < 0.05$). Peak knee flexion increased as sled loads increased ($p < 0.05$), which may enable athletes to lower their centre of mass and increase their horizontal force application. Net horizontal and propulsive impulse measures were greater in all sled conditions ($p < 0.05$), which increased significantly as sled loadings were heavier. In conclusion, this study highlights the effects of differential loads to help coaches understand acute kinetics and kinematic changes in order to improve the planning of sprint training.

Study three looked to determine the effectiveness of a ST intervention compared to an uninhibited sprint training (UST) intervention on semi-elite rugby league players during the competitive season. Baseline testing consisting of 5, 10, 20 m sprints as well as counter movement jumps (CMJ) was undertaken before, during (week 4) and after an 8-week training intervention consisting of 16 sessions (3 x 3 20 m sprints of either ST or UST). Both interventions significantly reduced sprint time over 5, 10 and 20 m ($p < 0.01$). CMJ height was increased significantly in the ST group ($p = 0.012$), there were no significant changes in CMJ height in the US group ($p > 0.05$). Differences between the ST and UST groups over 5, 10 and

20 m were non-significant ($p > 0.05$). The results indicated that the inclusion of ST in an 8-week training programme improves explosive power, but these adaptations did not transfer through to acceleration as distinctly as they did to executing a CMJ. In conclusion, for semi-elite rugby league players, ST appears to provide marginal benefits over UST when combined with a concurrent training programme.

The findings from this thesis have provided new insights into the optimal sled setup, loading strategies and programming variables affecting a training intervention. It is clear that ST should be individually loaded based on acceleration performance and incorporated into the periodised programme accordingly, thus allowing for performance benefits to be maximised.

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Contents

Abbreviations

2-D – Two dimensional

3-D – Three dimensional

ANOVA – Analysis of variance

ASIS – Anterior super iliac spine

BM – Body mass

CAST - calibrated anatomical system technique

Coefficients of variance – CV

GPS – Global positioning system

GRF – Ground reaction force

Hz – Hertz (the number of times an even occurs in one second)

ICC – Intraclass correlation coefficient

Kg – Kilograms

N - Newtons

$N.kg^{-1}$ – Newtons per kilogram

$m.s^{-1}$ – Metres per second

PSIS – Posterior super iliac spine

Rel ROM – Relative range of motion (the angular displacement from foot-strike to peak angle)

ROM – Range of motion (the angular displacement from foot-strike to toe-off during stance)

RST – Resisted sprint training

S - Seconds

ST – Sled towing

UST – Uninhibited sprint training

V_{DEC} – Velocity decrement

Glossary of terms

Backs – one of two basic positional groups in rugby league. Backs are usually smaller in size, their roles require speed and greater ball playing skills to take advantage of the field position gained by the forwards.

Coefficient of friction – a value that shows the relationship between the force of friction between two objects and the normal reaction between the objects that are involved.

Concurrent training – the combination of resistance and endurance training in a single periodised programme.

Coronal plane – an anatomical plane dividing the body into dorsal and ventral parts.

Team-sports – team sports which require a large range of fitness abilities and are not continuous in nature. The different fitness abilities are specific to each sport and their rules.

Forwards – one of two basic positional groups in rugby league. Forwards are typically larger in size, they are generally expected to help gain field position and make more tackles than the backs.

Gait cycle – a method for identifying biomechanical abnormalities in the gait cycle.

Ground reaction force – the reaction to the force a body exerts on the ground.

Kinematics – the study of describing movement.

Kinematic waveforms – a curve graphed with time highlighting joint angle.

Kinetics – the study of force that cause motion.

Lower-extremities – refers to the lower part of the body including the hips, knee and ankles joints as well as the bones of the thigh, shank and foot.

Motion analysis – techniques that allow the observation and definition of human movement.

Non-specific strength training – exercises that are designed to improve general strength.

Periodisation - the systematic planning of the training programme.

Resisted sprint training – performing overloaded sprints.

Rugby League – one of the two codes of rugby, it is a full-contact sport played by two teams of thirteen players.

Sagittal plane – an anatomical plane which divides the body into left and right parts.

Semi-elite – athletes whose highest level of participation is below the top standard possible in their sport.

Sled towing – a form of resisted sprint training which involves dragging a sled via a harness and attachment cord.

Sprint-specific training – exercises that are designed to improve sprint performance.

Step frequency – the frequency of strides during the gait cycle.

Step length – the distance between two successive placements of the same foot during the gait cycle.

Targeting – the altered gait pattern observed when instructed to contact a force platform.

Transverse plane – an anatomical plane dividing the body into superior and inferior parts.

Uninhibited sprinting – sprinting which is not restricted in any way.

Publications

Journal Articles

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2014) A review of resisted sled training: Implications for current practice. Professional Strength & Conditioning, 34, 23-30.

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2016) Impact of harness attachment point on kinetics and kinematics during sled towing. Journal of Strength and Conditioning Research, 30 (3) 768-776.

Bentley, I., Sinclair, J., Atkins, S., Metcalfe, J., and Edmundson, C. (In Press) Effect of velocity-based loading on acceleration kinetics and kinematics during sled towing. Journal of Strength and Conditioning Research.

Published Abstracts

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) The impact of force plate striking on lower body kinematics during sprinting. Journal of Sports Sciences, 33, S21-24.

Conference Poster Presentations

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) Influence of different harness attachment points on kinetics and kinematics during sled towing. Poster Presentation at the UKSCA Annual Conference, Chesford Grange, UK.

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) The impact of force plate striking on lower body kinematics during sprinting. BASES Annual Conference, St George's Park, UK.

Conference Oral Presentations

Bentley, I., Sinclair, J., Atkins, S., Metcalfe, J., and Edmundson, C. (2018) The effect of in-season velocity-based sled towing on acceleration in semi-professional rugby league players. European Congress of Sport Science, Dublin, Ireland.

List of tables and figures

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1. Introduction

This chapter will introduce the key thesis topic areas and provide an overview of the general aims of the thesis. The thesis structure will also be presented.

1.1. Background

Strength and conditioning is widely acknowledged as a major contributor to the progress of sport. Historically, important milestones and ideas regarding training theory have been documented as far back as Ancient Greece. Since then training has progressed greatly, the general concept of periodised training was proposed in the 1960s and has been adopted by generations of coaches since (Issurin, 2010). Today strength and conditioning is an integral part of the training programme for most athletes. Team-sports such as rugby league require a range of different fitness abilities, as such, the issue of how best to train and prepare for athletic competition remains challenging and debatable. Programming variables such as volume, frequency of training and choice of exercise are often debated by coaches looking to maximise performance (Bruce-Low & Smith, 2007).

Sprint running is a popular athletic event that has entertained audiences since the Olympics began. Sprinting is not only an athletic event but is essential for success in many sports (Duthie, et al., 2006; Frost, et al., 2008; Murphy, et al., 2003). For example, in team-sports the player that gets to the ball first has an advantage over any of the opposition players. The acceleration phase is of importance in team-sports because sprint efforts are generally of short duration (e.g. 10 – 20 m) (Cronin, et al., 2008; Kawarmori, et al., 2013). Sprint performance may be improved in different ways, and practitioners can implement non-specific or sprint-specific strength exercises into the programme. It is widely accepted that non-specific strength training can be utilised to improve sprint performance, particularly for those with a lower training age (James, et al., 2018; Young, 2006). However, because most sports involve activities performed through high velocity muscle contractions research has suggested that resistance exercises performed at high velocities will better prepare athletes for performance (Bruce-Low & Smith, 2007).

The development of resisted sprint training (RST) methods such as sled towing (ST), parachute and uphill running are providing practitioners with alternatives to the more common strategies e.g. Olympic lifting or plyometric training (Keogh, et al., 2010). RST exercises are performed in a horizontal direction and are uniplanar in nature that involve the relevant muscles, velocities and ranges of motion similar to those of uninhibited sprinting (Keogh, et al., 2010; Kristensen, et al., 2006). During ST, the external resistance is provided by the mass of the sled and the coefficient of friction between the sled and the surface (Cronin & Hansen, 2006). Generally, the mass of the sled is adjusted using additional loading which enables practitioners to alter the resistance provided. However, sled loading strategies as well as the sets and repetitions used to implement ST sessions remain equivocal (Alcaraz, et al., 2008; Cronin, et al., 2008; Lockie, et al., 2003; Maulder, et al., 2008; Murray, et al., 2005). Despite the lack of agreement around the optimal sled setup and loading strategies ST is integrated into training across many different sports. This uninformed approach may limit performance gains or has the potential to prove detrimental to sprint performance, e.g. such as negatively affecting sprint kinematics (Clark, et al., 2010; Lockie, et al., 2003; Murray, et al., 2005).

1.2. Thesis structure

This thesis consists of eight different chapters. Succeeding this brief introductory chapter is a comprehensive literature review. This chapter will provide an overview of the different biomechanical analysis techniques, the kinetics and kinematics of sprinting, ST, and the concurrent training programme for team-sport athletes. Chapter three details and provides a rationale for the different methods utilised throughout the thesis. Chapter four details all the different developmental studies that were undertaken to allow validity and reliability in the main studies. Chapters five, six and seven consist of the main studies, each providing an introduction, method, results, discussion and conclusion section. Chapter five comprises of a study examining the impact of harness attachment point on kinetics and kinematics during sled towing. Chapter six is an investigation into the effect of velocity-based loading on acceleration kinetics and kinematics during sled towing. Chapter seven provides the final intervention study examining the effect of in-season velocity-based sled towing on acceleration in semi-elite rugby league players. Chapter eight summaries the important findings of the thesis as well as providing recommendations for practitioners and future research.

2. Literature Review

This chapter will review the literature on the kinetics and kinematics of sprinting, sled towing, biomechanical analysis techniques and the training programme for team-sport athletes.

Journal Articles

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2014) A review of resisted sled training: Implications for current practice. Professional Strength & Conditioning, 34, 23-30.

2.1. The training programme

Irrespective of whether ST is implemented to target the acceleration or maximum velocity (MV) phase of sprinting, in the first instance practitioners should examine all the different aspects of the training programme. Periodisation, concurrent training and the sport itself need to be analysed and understood. Failure to consider all the elements of the programme may result in an ineffective training intervention and no performance enhancement.

2.1.1. Team-sports

Although, all team-sports (e.g. rugby, football and hockey) are unique in certain aspects they share a few common fitness characteristics and focus on the goal of winning the match. Effectively, while ensuring the defence of its own goal each team must coordinate its actions to recapture, conserve and move the ball to effectively score in the opposition's goal (Grehaigne, et al., 1997). There are many possible determinants of performance, such as anthropometric variables (e.g. body size and composition), physiological factors (e.g. muscle strength, power, anaerobic and aerobic capacity), biomechanical variables (e.g. mechanical efficiency) and psychological aspects (Reilly, 2001; Reilly & Gilbourne, 2003). The complex nature of these sports is apparent and to be successful intricate teamwork is often required, as such the link between an athlete's individual characteristics and performance capability is not a straightforward relationship (Reilly, 2001).

The physical and physiological demands of match play have been investigated in football (Reilly & Gilbourne, 2003), rugby (Sirotic, et al., 2011) and hockey (Spencer, et al., 2004). Research shows that demands are sensitive to positional role, fatigue, aerobic fitness, style of play and environmental factors. Activity profiles include time spent at different intensities (e.g. walking, jogging and sprinting), movements in different directions (e.g. sideways and backwards), static pauses and key actions (e.g. tackling and kicking) (Reilly & Gilbourne, 2003). Much of the movement is 'off the ball' and the ability to perform short maximal sprints throughout the game is an integral fitness component of all team-sports (Spencer, et al., 2004). Thus, it is important for practitioners to investigate and understand the demands of the sport in which their athletes perform.

2.1.2. Rugby league

Rugby League is an intermittent team-sport played over two halves of 40 minutes. The objective of the game is to advance the ball down the field into the opposing team's territory and score a try. The ball must be passed backwards but can be carried or kicked down into the opposing teams half within six tackles (Gabbett, 2005). The same set of 13 players are involved in attack and defence. As such, the game involves bouts of high-intensity activity (e.g. running, sprinting and tackling), interspersed by periods of low-intensity activity (e.g. standing and walking) (Gabbett, 2005). The match-play demands of rugby league are complex; as a result, players require a variety of physical attributes depending on their playing position (Wilson, et al., 2012). Playing positions can be broadly categorised into two different groups, the forwards (involved in more tackles and collisions) and the backs (involved in more running activities) (Gabbett, 2005; Sirotic, et al., 2011).

The running demands of rugby league match-play have been investigated using different time-motion analysis tools, video and global positioning systems (GPS) analysis are two of the most common. GPS is a satellite-based navigational technology used determine the position and subsequent movement of a unit through a process called ‘triangulation’ (Cummins, et al., 2013). This process relies on the position of three satellites with a fourth acting as a correction factor. Velocity is calculated using a Doppler Shift estimation of the carrier frequency (typically sampling at 10 to 15 Hz) and the satellite, which is subject to change through movement. The devices also have triaxial accelerometers and gyroscopes (sampling at 100 Hz) built in to quantify accelerations, player load and collisions (measured in G-Force) (Cummins, et al., 2013; Varley & Aughey, 2012). The data provided by this technology can be used to inform training practices, programming, prevent injuries and monitor the demands of match-play (Waldron, et al., 2011). Several studies have used GPS technology to investigate the match-play demands of rugby league (King, et al., 2009; Sirotic, et al., 2011; Waldron, et al., 2011). Some studies focussed on the Australian based National Rugby League competition (King, et al., 2009; Sirotic, et al., 2011), whereas Waldron et al., (2011) examined the European based Super League competition. Many different factors are thought to influence the running demands of rugby league match-play e.g. competition, playing level, team tactics and playing position (Gabbett, 2005; Waldron, et al., 2011).

Positional differences exist between the forwards and backs when exploring sprint distances, durations and frequencies (Gabbett, 2005; King, et al., 2009; Sirotic, et al., 2011). This is not surprising given that the backs often receive the ball in more space, thus allowing them to sprint further before contact. In comparison the forwards generally receive the ball much closer to the opposition line (approximately 10 m) (Waldron, et al., 2011). On average across playing positions, players typically complete 30 sprints with few exceeding 50 m in distance (King, et al., 2009; Sirotic, et al., 2011; Waldron, et al., 2011). Waldron et al., (2011) reported significantly greater peak speeds of 31 km.h^{-1} for the backs compared to 25.2 km.h^{-1} for the forwards. Although, it has been reported that overall the backs complete more high-intensity accelerations than the forwards, when adjusted relative to playing minutes there is no significant difference between positions or playing level (Dempsey, et al., 2017). King et al., (2009) separated playing positions differently (e.g. forwards, adjustables and outside backs) and investigated typical sprint distances. They reported that forwards would typically cover less distance during sprints (typically 5 - 6 m), whereas the adjustables would sprint further on average (8 - 12 m) and the outside backs even more so. Given the brief duration of sprints (approximately 2.3 s) across positional groups in rugby league competition, acceleration appears to be a critical component for performance (Sirotic, et al., 2011).

2.1.3. Acceleration in rugby league

The importance of the acceleration phase is further highlighted by studies showing that differences exist between different playing levels (Gabbett, et al., 2009). This appears particularly important at the junior levels, which may in turn have an impact on players progressing to a professional playing level. Gabbett et al., (2009) reported that junior elite players were faster when compared to sub-elite players across all distances tested (10, 20 and 40 m). They suggested greater acceleration would contribute in the development of larger impact forces and physical collisions resulting in superior performance. Although results at senior level indicate that physical attributes do not discriminate between playing level, they were related to playing ability and do contribute to the transfer of effective playing ability in these athletes also (Gabbett, et al., 2007). It is recommended that most sprint sessions should focus on the development of the acceleration phase (e.g. 0 - 20 m). Therefore, practitioners need to consider where in the training week such sessions fit and be mindful of the concurrent training programme.

2.1.4. Concurrent training

Sports such as rugby league require strength, power, endurance and muscular size (Gabbett, 2005). As such, a range of training modalities need to be utilised to prepare these athletes for competition. The combination of resistance training (e.g. strength, power or hypertrophy) and endurance training (e.g. long, slow continuous endurance, threshold type work or high intensity interval training) in a single programme is known as concurrent training. Research suggests that practitioners can implement concurrent training without fear of interference with aerobic capacity and some studies have reported enhanced endurance adaptations (Wilson, et al., 2012). In contrast, concurrent training may have a detrimental effect on resistance training adaptations (Fyfe & Loenneke, 2018). The cause of this interference with resistance adaptations (e.g. increases in maximal strength, muscle hypertrophy and enhanced power/rate of force development) remains unclear. There are a few possible explanations, such as the endurance training compromising resistance training stimuli due to enhanced residual fatigue, and/or an attenuated post-exercise anabolic response to individual resistance training sessions (Fyfe & Loenneke, 2018). While the underlying mechanisms remain unclear, evidence supports the existence of an interference effect and it is clear that the manipulation of the programming variables (e.g. endurance and resistance training volume, intensity, modality, order of concurrent exercise bouts, length of between-mode recovery) appears important to minimise interference and maximise adaptations (Wilson, et al., 2012; Coffey & Hawley, 2017).

2.1.4. Periodisation

Periodisation can be defined as the purposeful sequencing of different training units so that athletes can attain a desired state and planned results (Issurin, 2010). Although the optimal strength and power training programme design is yet to be agreed upon it is generally accepted that some form of periodisation is important (Rhea, et al., 2002). Periodisation is based on the overload principle and attempts to maximize the use of physical stress and recovery time by manipulating volume and intensity to facilitate important neuromuscular adaptations (Apel, et al., 2011). There are many different models of periodisation, such as linear and weekly undulating programmes. When undertaking a linear periodisation programme strength training is typically divided into three different periods, over time intensity is increased while volume is decreased (Rhea, et al., 2002). In contrast, weekly undulating periodisation relies on the manipulation of volume and intensity over a one-week period (Apel, et al., 2011). Both strategies have their benefits and they may be utilised during the same yearly training programme e.g. a linear training programme during the pre-season period and a weekly undulating programme during the competition phase of the season.

Akin to any training exercise ST needs to be carefully scheduled into a periodised training plan. This type of training is suited to the specific preparation and competition phases, benefitting from the strength, co-ordination and postural stability qualities developed in the earlier general preparation phases (Issurin, 2010). This method of training may be an ideal transitional exercise between the high-force low-velocity strength exercises and the more specific low-force high-velocity plyometric exercises. Strength exercises of this nature are often neglected, therefore, incorporating ST exercises should enhance the transfer to performance. To understand and programme exercises effectively a detailed analysis is generally undertaken, in this instance the biomechanics of the sporting action may provide a valuable insight.

2.2. Biomechanical analysis

Biomechanical advances over the last 25 years have been considerable. Researchers can investigate sporting actions using specially designed motion analysis laboratories (Richards, 2008). Such laboratories allow researchers to study the kinematics and kinetics of walking, running, sprinting actions and multiplanar movements. As discussed previously, there are many different determinants of performance in sports such as Rugby League. Therefore, it is important to remember that the biomechanical analysis of a sporting action (e.g. sprinting) may form a small element of the training programme.

2.2.1. Kinematic measurements

Kinematics are a description of movement and do not consider the forces that ultimately cause the movement (Novacheck, 1998). Motion analysis systems utilise either single or multiple cameras to reconstruct two-dimensional (2-D) or 3-D movement data. This allows researchers to quantify the kinematics of different actions (Harris & Wertsch, 1994). 2-D motion analysis systems are popular and offer a much cheaper alternative to the 3-D motion systems. However, single camera setups will limit the researcher to single plane analysis (e.g. sagittal or coronal) and have several risks that are associated with the quality of data as participants move out of that plane (Richards, 2008). 3-D motion analysis systems are much more expensive but do reduce the risks associated with 2-D setups, as such researchers are able to investigate complex sporting actions (Richards, 2008). In this instance camera speeds of 200 to 2000 Hz systems are available compared to the 50 or 60 Hz available with the standard 2-D video technology (Harris & Wertsch, 1994).

When undertaking 2-D motion analysis, markers are placed on bony landmarks on the lateral aspect of the joint. Although, this is not the actual joint they can provide estimates and information on joint angular motion (Richards, 2008). 3-D motion capture analysis systems rely on the accurate placement of passive reflective or actively illuminated optoelectric markers on anatomical landmarks (Harris & Wertsch, 1994). Although the 3-D coordinates of a marker can be determined when seen by two cameras, more cameras are generally required. Motion analysis systems normally require at least four cameras, in this instance marker dropout is reduced (e.g. markers not in view of at least two cameras) (Harris & Wertsch, 1994). The link segmental model and the method of calculating joint centres determine marker placement on anatomical landmarks, which in turn allows for the reconstruction of the skeletal system in 3-D space (Cappozzo, et al., 2005). Kinematic data can then be presented in terms of sagittal, coronal and transverse planes at various joints (e.g. hip, knee and ankle joints) as well as allowing an analysis of temporal, stride events and the gait cycle (Harris & Wertsch, 1994).

2.2.2. The gait cycle

The gait cycle is the basic measurement of walking, running and sprinting actions (Novacheck, 1998). An understanding of the gait cycle is crucial as it allows for the breakdown of sprint running into smaller sub-phases using some of the kinematic methods mentioned previously. The cycle begins when one foot meets the ground and ends when the same foot contacts the ground again. Gait cycle alterations allow the identification of walking, running and sprinting actions. During walking actions, there are periods of double support (e.g. both feet on the ground), whereas periods of double float (e.g. both feet off the ground) allow the identification of running actions. When the initial foot strike pattern changes from a heel-strike to a forefoot contact, the action is categorised as a sprint (Novacheck, 1998). During walking, running or sprinting alike the gait cycle can be separated into different phases; the stance phase is the period of the cycle when the foot is in contact with the ground and the swing phase is the period when it is not (Richards, 2008). After the initial two steps the body's centre of gravity falls during the early part of contact (e.g. braking phase) and rises during the latter part of contact (e.g. propulsive phase). It is clear that an understanding of the gait cycle helps with the identification of different running actions as well as enabling a more detailed analysis, however, there are a several other variables that are often discussed and may need to be considered e.g. step length and step frequency.

2.2.3. Step length and step frequency

Sprint velocity is the product of step length and step frequency (Hunter, et al., 2004). Therefore, it is unsurprising that these kinematic measures are commonly reported in the literature (Cronin, et al., 2008; Murphy, et al., 2003). Step length is influenced by stance distance (e.g. touchdown distance, foot movement distance and take-off distance) and flight distance (e.g. height at take-off, take-off angle, take-off speed and air resistance during flight) (Figure 2.1) (Hunter, et al., 2004). Step frequency is primarily determined by stance time (e.g. horizontal velocity during stance and stance distance) and flight time (e.g. height at take-off, vertical velocity at take-off and air resistance during flight) (Figure 2.2) (Hunter, et al., 2004). To improve sprint velocity at least one of these factors must increase, if the other factor does not undergo an equal or larger decrease (Hunter, et al., 2004). Any practitioners looking to enhance either step length or frequency should consider the possibility of a negative interaction (e.g. the effect that step length may have on frequency and vice versa). The interaction between stride length and step frequency is complex and at present remains inconclusive, however there is a wide variation in step combinations. Hunter et al., (2004) supports this, they reported a wide range of step length and frequency combinations, such variation was evident between athletes with similar sporting backgrounds and sprint velocities. However, in studies where the same participants ran at different speeds both step rate and step length increased with greater speeds. Linear increases were reported for speeds up to 7 $m.s^{-1}$ (Mero, et al., 1992). Ultimately, step frequency is limited by the ability to contract and relax skeletal musculature as well as the time taken to accelerate and decelerate body segments through space. An argument can be made for focusing on improving the ability to rapidly generate and transfer forces to the ground through the kinetic chain, as such, an understanding of sprint kinetics is crucial.

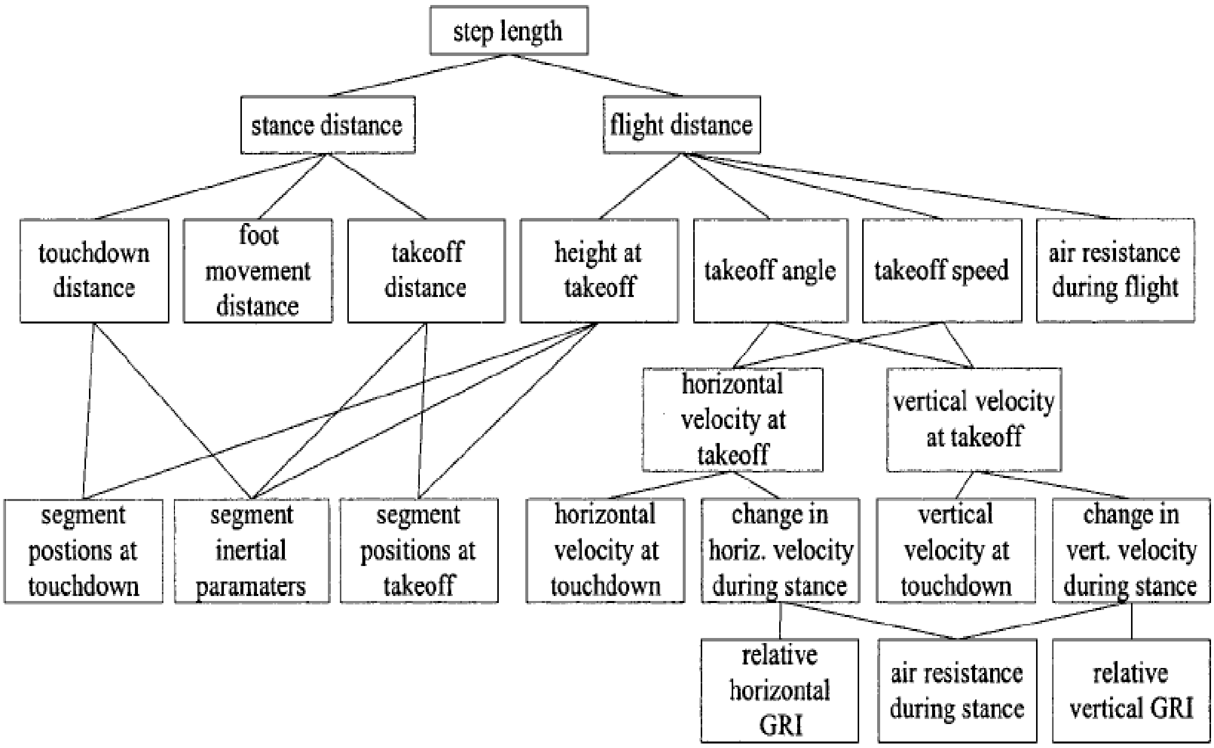

Figure 2.1: Determinants of step length (Adapted from Hay (1994)).

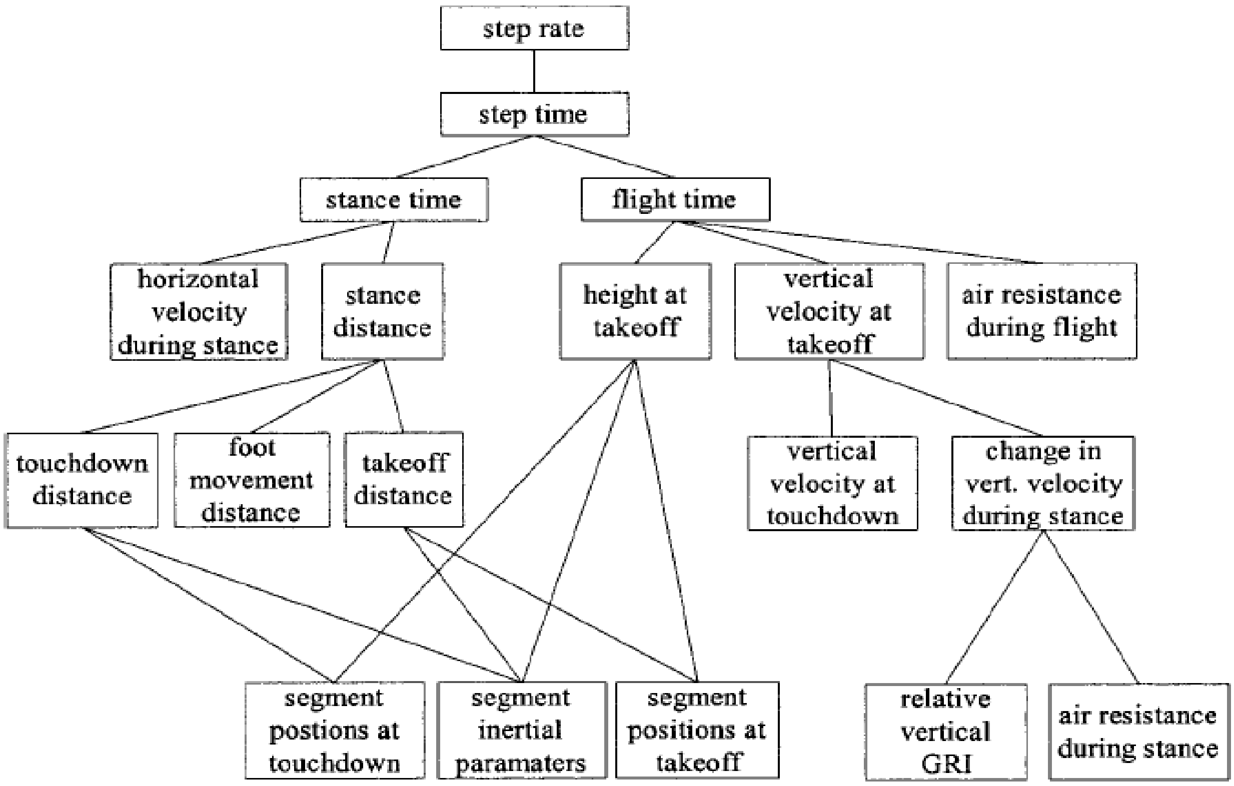

Figure 2.2: Determinants of step frequency (Adapted from Hay (1994)).

2.2.4. Kinetic measurements

Ground reaction forces (GRF) are often measured using force plates, which typically utilise strain gauges or piezoelectric transducers (Harris & Wertsch, 1994). Force platforms measure GRF and their point of application. A GRF consists of three components, vertical forces, anterior-posterior forces and medial-lateral forces. Piezoelectric force plates are more accurate than the strain gauge alternatives, they also sample at higher frequencies (e.g. 1000 Hz) in all three directions (Richards, 2008). Force platforms allow us to obtain various graphs and plots, such as vertical, anterior-posterior, medial-lateral force graphs. These graphs enable researchers to identify key points in the gait cycle or sporting actions, such as propulsive durations or peak forces and the corresponding temporal characteristics (Richards, 2008). The kinematic and kinetic measurement and analysis of running varies greatly depending on intensity. ST is typically performed at maximal intensities and is categorised as sprint running.

2.3. Sprint running

Sprinting activities are performed at high intensities over short periods of time (Novacheck, 1998); such actions are complex with a high neuromuscular demand requiring co-ordinated movement and appropriate sequencing of muscle activations (Young, 2005). During sprint running, athletes use a stretch-shortening mechanism, thus allowing them to take advantage of the elastic component of muscle action and enhance muscle force production around the hip, knee, and ankle joints (Debaere, et al., 2013). During the stance phase power is transferred in a proximal to distal temporal sequence starting at the hip joint and finishing at the ankle joint (Johnson & Buckley, 2011).

Sprint running is not only an athletic event in itself but is essential for success in many sports (Duthie, et al., 2006; Frost, et al., 2008; Murphy, et al., 2003). Sprinting is often divided into sub-phases (e.g. acceleration, mid-acceleration, transition and MV) and in terms of sprint mechanics, each phase is unique and may require a different approach in training (Barr, et al., 2013; Johnson & Buckley, 2011). Barr et al., (2013) conducted a review on sprinting in rugby players and suggested that approximately the first 6 m from a standing start could be considered initial acceleration, 6 to 18 m the mid-acceleration phase, and that the transition to MV was 18 m onwards leading up to the MV phase. This group of athletes attained MV between 33 and 38 m, which is much shorter than the distances reported for elite sprinters (Barr, et al., 2013). The different sprint phases are regularly tested and monitored as they are considered key determinants of overall sprint performance (Petrakos, et al., 2016). All phases are similar as they all consist of braking and propulsive phases; however, the ratios are different (Mero, et al., 1992).

2.3.1. The acceleration phase

Sprint acceleration is defined as the capacity to generate as high a velocity as possible in as short a distance or time as possible (Linthorne & Cooper, 2013), and is essential for success in the majority of sports (Duthie, et al., 2006; Murphy, et al., 2003). Maximal accelerations of this nature tend to occur around crucial match actions such as making a break or tackle (Murphy, et al., 2003). While MV is important in team-sports, the ability to sprint over short distances is often seen as being of greater significance (Kawarmori, et al., 2013; Murphy, et al., 2003).

An explosive start requires a rotation of the centre of mass followed by a powerful extension of all lower-extremity joints as well as a forceful arm drive (Maulder, et al., 2008; Nagahara, et al., 2014; Wild, et al., 2011). In comparison to the MV phase, kinematic parameters (e.g. step length, step frequency and stance phase duration) change dramatically during this period of the sprint (Yu, et al., 2015). Both step length and step frequency will increase while contact time reduces (Mero, et al., 1992; Murphy, et al., 2003; Yu, et al., 1999). Contact times in this phase of sprint running typically range between 0.20 and 0.12 seconds in the early and later stages, respectively (Wild, et al., 2011). Previous research has highlighted the significance of stance time during the acceleration phase, which will reduce up to the attainment of MV (Mero, et al., 1992). Murphy et al. (2003) investigated the kinematic differences between team-sport athletes with fast and slow acceleration. They suggested that rapid early acceleration was a result of short contact times, resulting in an improved step frequency. During the acceleration phase each of the joints of the lower-extremities (hip, knee and ankle) play an important role allowing athletes to rapidly increase sprint velocity. At foot-strike the ankle initially dorsiflexes and then plantarflexes until toe-off. Whereas, the knee and hip joints extended throughout the stance phase, although for some the knee may start to flex just prior to toe-off (Wild, et al., 2011).

The goal of this phase is to rapidly increase velocity, as such researchers have placed great emphasis on high net propulsive forces (Yu, et al., 2015). In agreement, research by Hunter et al., (2005) suggested that an increased forward body lean would enhance horizontal force application. An initial rotation of centre of mass and an increased forward body lean changes the athlete’s centre of mass, so it is positioned ahead of their base of support (Nagahara, et al., 2014; Wild, et al., 2011). In this instance the resultant force vector is directed more horizontally propelling the athlete forward, thus highlighting the important interplay between the kinetics and kinematics. It was also speculated that the vertical force application should be enough to allow lower limb repositioning, but all other force application should be horizontal (Hunter, et al., 2005). Therefore, during the early acceleration phase the force is applied over a much longer time and the average force in the propulsive phase is large (Figure 2.3) (Mero, et al., 1992). Mero (1988) investigated force production in the first contact after the starting blocks, they reported that values in the propulsive phase were much greater than those of the braking phase. The maximal and average vertical forces were 739 and 431N respectively. These, compared to maximal and average horizontal forces of 788 and 526N were lower and highlight the importance of force application (Mero, 1988). In contrast, maximal forces are greater during the braking phase when sprinting at MV with maximal vertical forces of 1707N and horizontal forces of 445N being reported (Mero, et al., 1992).

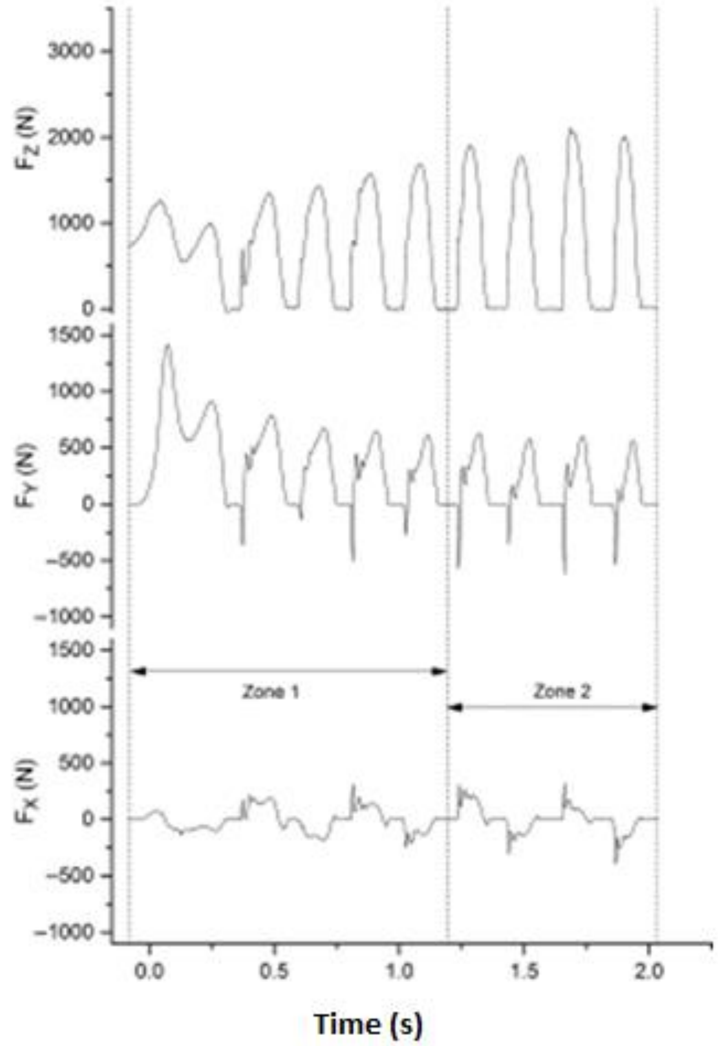

Figure 2.3: Typical signals of instantaneous vertical (F_Z), anterior-posterior (F_Y) and medial-lateral (F_X) component of the GRF obtained during 15 m sprint trials in world-class elite athletes (Adapted from Rabita et al., (2015)).

2.3.2. The mid-acceleration and transition phases

After the initial acceleration phase, acceleration continues until the attainment of MV. These periods of the sprint are generally known as the mid-acceleration and transition phases (Figure 2.4) (Johnson & Buckley, 2011). Unlike the initial acceleration phase and the MV phase the mid-acceleration and transition phases have not been investigated extensively. A study by Johnson & Buckley (2001) reported that during mid-acceleration minimal power generation occurred from foot-strike until mid-stance (by which time the centre of mass is ahead of the stance limb). This, in support of previous discussions would thrust the athlete forward. They suggested that large power outputs were generated through hip extension transferring to the ankle joint and ground. In support of research by Delecluse, (1997) they found that the main role of the knee extensors was to maintain the athletes centre of mass height. In accordance with the acceleration phase, kinematic and kinetic parameters will change significantly up to the attainment of MV (Yu, et al., 2015). Horizontal impulses decrease throughout the acceleration and transition phases until athletes reach MV. The opposite is true for measures of vertical force, which are greatest at MV (Wild, et al., 2011).

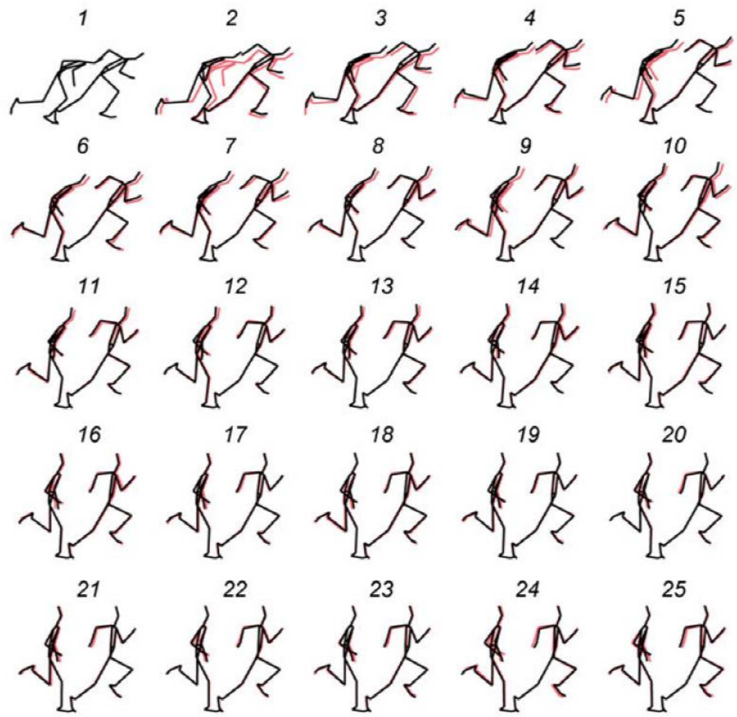

Figure 2.4: Changes in sprint motion during the acceleration phase. The stick figure represents the body position at foot-strike and toe-off. The numbers indicate the respective steps. Red figures highlight the body position of the previous step (Nagahara, et al., 2014).

2.3.3. The maximum velocity phase

Elite track athletes may not reach their MV until 50-60 m into the race (Brown & Vescovi, 2012). This may have led to the misconception that MV is not important for team-sport athletes. However, although team-sport athletes typically sprint shorter distances during training and competition (e.g. 10-30 m) they reach MV sooner (Barr, et al., 2013; Kawarmori, et al., 2013). Not only do team-sport athletes reach MV much earlier than track athletes, the majority of sprints occur from a flying start, and as such athletes reach high speed quickly (Brown & Vescovi, 2012; Duthie, et al., 2006; Vesconi & McGuigan, 2007). Thus, MV training has an important place in the strength and conditioning programmes of team-sport athletes.

Unlike the acceleration phase, kinematic and kinetic parameters remain consistent throughout this phase of the sprint (Yu, et al., 2015). To achieve high MV athletes should preserve optimal postural stability, minimise braking forces and increase the vertical propulsive forces (Young, 2005). Postural stability is a dynamic process whereby internal stability and appropriate postural alignment are maintained, thus allowing a stable origin for the movement of limbs. Ideally, a sprinter's head, neck and spine should be neutrally aligned with a slight posterior tilt of the pelvis. This posture enables freedom of movement and promotes frontside mechanics while limiting backside mechanics (Young, 2005). The lower-extremity joint kinematics (hip, knee and ankle) differ greatly when compared to the acceleration phase. At foot-strike the ankle and knee joints typically decrease (approximately 60% of the stance phase) before extending until toe-off, whereas the hip extends during the entire phase (Wild, et al., 2011).

Braking forces are those forces, which act in the opposite direction of intended movement. It is important to minimise such forces, as they will result in deceleration, often caused by an initial ground contact that is too far in front of the athlete's centre of mass. Ideally, the distance between the point of ground contact and the athlete's centre of mass should be minimised (Young, 2005). Finally, it is essential that the vertical force component is maximised, this offers several benefits. High vertical forces enable athletes to counteract the effects of gravity and produce larger flight phases with shorter ground contact times (typically ranging from 0.080 to 0.100 s) (Alcaraz, et al., 2008; Hunter, et al., 2005; Weyand, et al., 2000). This is important as contact times have been shown to decrease significantly as sprint velocity increases (Mero, et al., 1992). The ability to increase limb stiffness with a co-contraction of antagonistic muscles acting on the joint appears key in allowing faster sprinters more vertical displacement during flight and less downward displacement during the ground contact (Majumdar & Robergs, 2011). Overall, there are large vertical force components in both contact phases (e.g. braking and propulsive) while horizontal forces are low, especially during the braking phase (Mero, et al., 1992). While the mechanics of the different phases of sprint running are clearly defined, the optimal training methods and exercises to improve performance in each phase remain somewhat unclear.

2.4. Strength training methods

Generally, two different exercise types may be utilised when looking to improve sprint performance. Non-specific or general strength exercises and sprint-specific exercises can be programmed separately or incorporated into the same periodised plan at different phases.

2.4.1. Non-specific strength training

Non-specific strength training involves lifting moderate to heavy loads with moderate inter-set recovery using free weights or resistive machines (Kraemer & Ratamess, 2004). During such exercises e.g. squats or deadlifts, athletes produce high forces through a triple extension (hip, knee and ankle) (Wild, et al., 2011). Non-specific training exercises are typically incorporated into the early stages of a programme and are thought to be valuable because they allow for the development of a balanced neuromuscular system and serve as a base from which to train more specifically at later stages (Bompa & Haff, 2009). Findings suggest that the principle of specificity (dynamic correspondence) becomes more important as training age and sport performance increase, as such beginners may achieve good transfer from non-specific training whereas more experienced athletes may require a more specific training stimulus (Wild, et al., 2011; Young, 2006).

2.4.2. Sprint-specific strength training

Sprint-specific training modalities may have a better transfer to performance compared to non-specific strength training (Brughelli, et al., 2010; Loturco, et al., 2018). Therefore, exercises of this nature are often implemented in the later specific preparation phases of the programme (Bompa & Haff, 2009). Sprint-specific strength exercises have similar contact times, forces comparable to those of uninhibited sprint running and utilise a fast stretch shortening cycle (contact times of less than 0.25 s) (Wild, et al., 2011). These methods often involve adding an external load to the body (Paulson & Braun, 2011). RST methods such as ST, parachutes, weighted vests, bungees and uphill running offer practitioner's alternative approaches to uninhibited sprint training (UST). RST modalities are performed in a horizontal direction, and involve the relevant muscles, velocities and ranges of motion to those of uninhibited sprinting but are used with the intention of increasing force production and power output (Alcaraz, et al., 2014; Spinks, et al., 2007). Of all the RST modalities ST has received the most attention, however parachute and uphill sprinting are popular and have been investigated previously (Paulson & Braun, 2011; Paradisis & Cooke, 2006). Research speculates that such sprint-specific training methods place an emphasis on the development of rapid concentric strength and can lead to greater speed development, however it is often difficult to determine exactly which adaptations led to such enhancements (Brughelli, et al., 2010; Wild, et al., 2011). Such exercises are generally incorporated into training programmes with a lack of consideration (e.g. movement quality and programming variables). Therefore, a better understanding of the acute changes and long-term adaptations to RST using optimal strategies would prove beneficial.

2.4.3. Adaptations to training

The performance enhancement ensuing a training period may be attributed to a number of different physiological adaptations (Campos, et al., 2002; Carroll, et al., 2001; Kyröläinen, et al., 2005). Although the methods used to explore muscle adaptations are often invasive (e.g. muscle biopsy's) in nature several studies have investigated them after resistance or sprint training interventions (Campos, et al., 2002; Dawson, et al., 1998). Without such measures it is difficult to accurately determine which muscle architecture adaptations occurred. Similarly, the precise nature of the neuromuscular adaptations that occur are unknown, however various alterations such as motor unit force development and enhanced muscular co-ordination likely contribute (Carroll, et al., 2001; Kyröläinen, et al., 2005). Improvements during the early stages of a training programme are predominantly associated with these neuromuscular adaptations (Carroll, et al., 2001; Kyröläinen, et al., 2005; Makaruk, et al., 2013). In the later stages of a training programme, performance increases are commonly attributed to muscle fibre and contractile adaptations (Campos, et al., 2002; Costill, et al., 1979; Dawson, et al., 1998; Deschenes & Kraemer, 2002).

Whilst the physiological adaptations associated with traditional resistance training have been researched extensively (Campos, et al., 2002; Carroll, et al., 2001; Costill, et al., 1979; Kyröläinen, et al., 2005), the movement velocity and programming variables associated with power training are generally more in line with RST. Strength improvements following power training have been attributed to neuromuscular adaptations (James, et al., 2018; Kyröläinen, et al., 2005). Adaptations transpired during the first ten weeks, after which no further enhancements were seen (Carroll, et al., 2001; Kyröläinen, et al., 2005). In contrast to resistance training (Dawson, et al., 1998; Deschenes & Kraemer, 2002) there were no changes in muscle fibre or contractile properties following a power training intervention (Kyröläinen, et al., 2005). This finding is not surprising; research highlights that manipulation of the different training variables (sets, reps, recovery, intensity and loads) allows muscles to be stressed in very different ways. As such, the plyometric nature of the power-training programme will lead to different adaptations when compared to the resistance training programmes (Campos, et al., 2002; Kyröläinen, et al., 2005). The lack of hypertrophic development resulting from power training or RST is not generally an issue as these exercises often form part of a mixed methods approach, during which resistance training will be undertaken alongside. This mixed training approach has been found superior to power training alone (Lyttle, et al., 1996) and is generally the recommended programming method.

Understanding the physiological, mechanical and technical adaptations that occur during and after RST is vital to determine relevant sled loading strategies and programme variables. ST interventions have been shown to improve sprint performance (Harrison & Bourke, 2009; Lockie, et al., 2003; West, et al., 2013) as well as various jump and strength measures (Alcaraz, et al., 2014; Harrison & Bourke, 2009; Spinks, et al., 2007). Researchers have speculated as to which physiological adaptations have led to the performance enhancements. Unfortunately, the pre/mid/post performance testing employed in many of the intervention studies makes it difficult to ascertain exactly which adaptations led to the enhanced performance measures.

2.4.4. Resisted Sprint Training

Although identifying the exact adaptations of RST after an intervention can be challenging, in the first instance it is important to have a basic knowledge of the different RST methods. An appreciation of the key characteristics of each type as well as an understanding of the kinematic and kinetic alterations would prove insightful.

2.4.5. Parachute sprint training

Parachute sprint training is one of the more popular methods of RST. During parachute sprints, the external load (e.g. air resistance) is applied directly behind the body in the form of a parachute attached via a cord and waist or shoulder harness (Figure 2.5) (Paulson & Braun, 2011). However, in contrast to other forms of RST the resistance provided by the parachute is at its lowest during the early acceleration phase and increases in line with sprint velocity. Parachutes are often selected based on size, larger parachutes will provide greater resistance and researchers have suggested that they may be more beneficial for the acceleration phase of sprinting (Alcaraz, et al., 2008). Several studies have investigated the acute kinematic alterations that occur during parachute sprints (Alcaraz, et al., 2008; Paulson & Braun, 2011) and others after an intervention period (Martinopoulou, et al., 2011). Both acute investigations focused on kinematics around the 20 m point of the sprint, as such results may not be comparable to the research on other forms of RST. Paulson & Braun (2011) investigated the acute effects of parachute sprinting on lower body kinematics. They reported no significant differences in lower extremity kinematics or contact time variables and concluded that parachute training did not substantially overload the participants. In agreement Alcaraz et al., (2008) reported no significant kinematic alterations during parachute sprints. Whereas, Martinopoulou et al., (2011) highlighted improvements in acceleration (0 - 20 m) and the MV phase (40 – 50 m) of sprinting after a four-week parachute training programme. Differences in parachute size should be taken into considered when comparing the aforementioned studies, the acute studies utilised medium sized parachutes (Alcaraz, et al., 2008; Paulson & Braun, 2011) compared to a large sized parachute used through the intervention study (Martinopoulou, et al., 2011). Therefore, the optimum training strategies of parachute training remain unclear; as such, more research into the acute and long-term adaptations is required.

Figure 2.5: Parachute sprint running.

2.4.6. Uphill sprint training

Uphill sprint training is another commonly utilised RST method. The aim of uphill sprinting is to increase the loading on the hip extensors; athletes use this muscle group to overcome the positive slope and propel themselves forward (Behrens & Simonson, 2011). Inclines of around 3° are generally suggested (Paradisis & Cooke, 2006), although inclines as high as 8° have been recommended to target the early acceleration phase (Dintiman & Ward, 2003). Novel approaches, such as, sprint training on combined uphill and downhill slopes have also been implemented and compared to uphill only training. It was hypothesised that the combined approach would target the different phases of sprint running (Behrens & Simonson, 2011; Paradisis & Cooke, 2006). The results of a six-week training intervention indicated that a combined approach was more effective than uphill sprint training alone for longer distances (e.g. 35 m). The combined approach led to significantly greater MV and step rates compared to baseline, whereas all changes for the uphill only group were negligible (Paradisis & Cooke, 2006). Therefore, in line with the parachute training research the ideal implementation of uphill sprinting remains equivocal; as such, more research into the acute and long-term adaptations is required.

2.5. Sled towing

ST is the most popular form of RST; this method is used across sport at all levels of performance. This training uses an external load in the form of a sled towed via a shoulder or waist harness and cord, behind the athlete. The mass of the sled and the friction coefficient between the sled and the ground surface affect the external load and the subsequent impact on performance (Figure 2.6) (Linthorne & Cooper, 2013).

Figure 2.6: Sled towing.

2.5.1. Sled loading strategies

Sled loadings can be determined using various strategies, such as using an absolute load (e.g. 5kg). Many of the earlier studies employed this methodology (Zafeiridis, et al., 2005). In more recent investigations sleds were generally loaded based on a percentage of body mass (BM) or percentage of velocity decrement (V_{Dec}) (Kawamori, et al., 2014; Spinks, et al., 2007).

However, loadings based on a percentage BM do not account for individual variations in strength, power or technical ability (Kawamori, et al., 2014). As such, loading sleds based on V_{Dec} over a given distance is the preferred approach (Petrakos, et al., 2016). The importance of this loading strategy is emphasised in research by Alcaraz et al., (2008) who found that a loading of 16% BM resulted in a 10% V_{Dec} on their cohort of semi-elite track athletes. In comparison, Makaruk et al., (2013) reported that a load of 7.5% BM was sufficient to cause a 10% V_{Dec} in their testing population of active females. Had sled loadings been determined based on a percentage of BM the different populations in these studies participants would likely be under or overloaded. As discussed previously, 3-D kinematic analysis provides researcher/practitioners with a valuable movement description of ST.

2.5.2. Acute kinematic alterations

Acute ST studies are important as they allow researchers to investigate how different loading strategies can alter kinetics and kinematics. These acute changes may determine long-term adaptations. Sled loading strategies have varied greatly between studies, some researchers have investigated loads as light as 5% BM (Murray, et al., 2005) and others as heavy as 80% BM (Morin, et al., 2017). Unsurprisingly, findings indicate that as sled loadings increase, sprint kinematics (velocity, contact time, stride length and stride frequency etc.) were changed to a greater extent (Lockie, et al., 2003; Monte, et al., 2017; Murray, et al., 2005). As such, some investigations have recommended sled loadings of approximately 10% BM or 10% V_{Dec} to minimise the alterations to sprint kinematics (Maulder, et al., 2008). However, recent investigations have reported that moderate to heavy sled loadings may be required to provide an optimal overload for sprint acceleration (Monte, et al., 2017). These loadings may increase horizontal GRF, which have been shown to be a key determinant of sprint acceleration (Morin, et al., 2011). Kinetics and lower body kinematics have been explored over a range of different ST loads, despite numerous investigations (Kawamori, et al., 2014; Maulder, et al., 2008; Murray, et al., 2005) there is little agreement on the optimum sled loading to develop the acceleration phase.

Stride frequency and stride length are two kinematic variables that have been consistently measured in all acute studies focussing on the acceleration phase. Without exception, stride length was found to significantly decrease as sled loading increased (Cronin, et al., 2008; Lockie, et al., 2003; Maulder, et al., 2006; Maulder, et al., 2008; Murray, et al., 2005). This is due to the added frictional resistance provided by the sled. During the stance phase participants will need to exert more force to overcome the extra resistance. However, unlike uninhibited sprinting during ST frictional forces will still be acting on the athlete throughout the flight phase, leading to a decrease in stride length. Stride frequency was significantly reduced in three investigations (Cronin, et al., 2008; Lockie, et al., 2003; Maulder, et al., 2008) whereas reductions were found to be negligible in others (Murray, et al., 2005). The increase in ground contact time is resultant of the increased time taken to produce the larger forces required to tow the sled. Over time, the extra muscular effort required to drive the hips is thought to lead to increased hip extensor strength (Alcaraz, et al., 2014; Cronin, et al., 2008; Lockie, et al., 2013; Maulder, et al., 2008). In contrast, some researchers have suggested that athletes may compensate for the decrease in stride length by increasing stride frequency with short choppy steps (Lockie, et al., 2013). Although an increased stride frequency can prove beneficial the athlete needs sufficient ground contact time to exert the appropriate horizontal force. This may provide a negative training stimulus and it will be observable by a significant reduction in stride length.

Early acceleration requires a powerful arm drive, it has been suggested that this vigorous action can increase forward propulsion (Bhowmick & Bhattacharyya, 1988). Bhowmick and Bhattacharyya (1988) investigated the arm drive, suggesting that the horizontal action of the swing may help to increase stride length and regulate the leg movement, while the vertical action may enable a greater leg drive during the stance phase. In support of these findings, other studies have suggested that elite sprinters are able to adjust their centre of mass by positioning their arms further forward (front and rear) when compared to well-trained sprinters (Slawinski, et al., 2010). Few studies have investigated the upper body kinematics of athletes during ST. Previous research by Lockie et al., (2003) examined the arm drive and results indicated that there are few upper body kinematic changes during ST. However, the researchers did highlight a trend for greater movement around the shoulder joint as sled loading was heavier (32.2% BM). This leading to the suggestion that when practitioners want to enhance arm drive they should utilise heavier sled loadings (Lockie, et al., 2003).

An increased trunk lean may be beneficial in that it overloads the body in a specific manner to the acceleration phase (Spinks, et al., 2007; West, et al., 2013). This theory is supported by Kugler et al., (2010) who proposed that if the resultant GRF vector points further forward (e.g. trunk lean) then the ratio of vertical to propulsive force will be biased towards forwards propulsion. In this instance greater GRF can be applied without the negative effects associated with high vertical force application. Cronin et al., (2008) also suggested that braking forces at foot-strike may be reduced as a result of greater trunk lean. Two of the investigations measured trunk angle changes during the acceleration phase of loaded sled trials (Cronin, et al., 2008; Lockie, et al., 2003). Both studies reported that ST significantly increased trunk lean when compared to uninhibited sprinting (Figure 2.7).

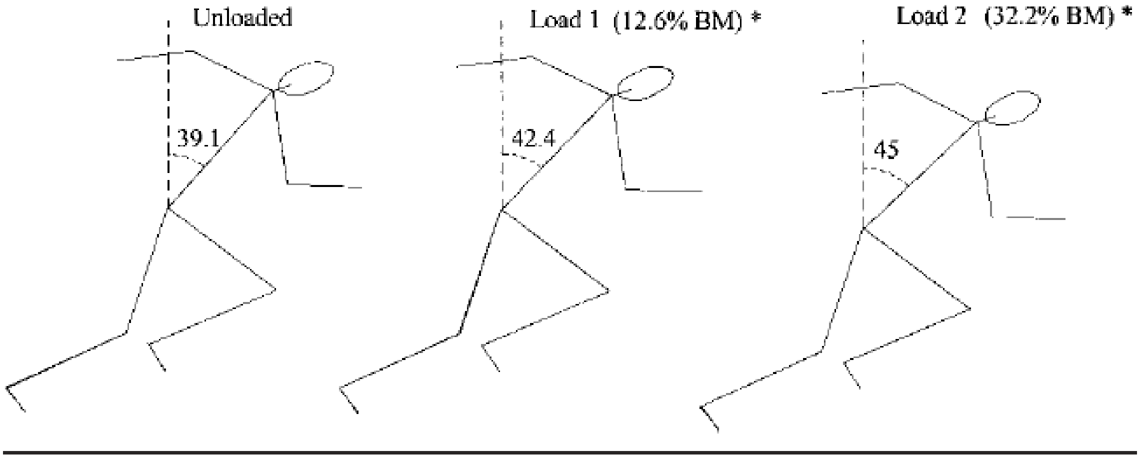

Figure 2.7: Trunk angle changes compared to uninhibited sprinting (Lockie, et al., 2003).

However, there are suggestions that when an athlete's trunk angle increases too much it may reduce their hip flexion capacity and limit stride length (Lockie, et al., 2013). Sleds are generally attached via a cord and shoulder harness or waist belt. Researchers suggest that a shoulder harness will increase forward trunk lean to a greater extent because the applied load is higher compared to the pivot point (the hips) and the athlete will compensate by leaning further forward. When attached via a waist harness the load passes through the pivot point and as such produces no additional torque (Alcaraz, et al., 2008). More detailed kinematic analysis is required to fully understand which harness attachment site is best suited for ST. It appears that due to the different kinematic and kinetic requirements of the acceleration and MV phases, they may benefit from different harness attachment sites.

Rapid sprint acceleration requires a powerful extension of the lower limbs (Lockie, et al., 2003), thus understanding the lower body kinematic changes resulting from ST is important. Lockie et al., (2003) investigated the hip and knee kinematics of team-sport athletes during ST and compared them to uninhibited sprinting. Sleds were loaded at 12.6% and 32.2% BM which resulted in approximately 10 and 20% reduction in maximum speed over 15 m. Hip extension was not significantly affected over the first two steps during ST, in contrast hip flexion was significantly impacted (Lockie, et al., 2003). Although hip flexion increased during ST trials the heavier loaded condition did not appear to result in greater flexion. Lockie et al., (2003) speculated that the increase in hip flexion signifies an increase in activity which may lead to positive strength and power adaptations. A study by Cronin et al., (2008) found that knee flexion at foot-strike increased during ST trials in the acceleration phase, they suggested that as a result propulsive force could be applied through a greater range of movement (ROM). In contrast an earlier investigation reported that ST had no significant impact on knee flexion, although knee extension increased in the heavier ST trials at the second step (Lockie, et al., 2003). More recent research by Cronin et al., (2008) also reported significantly greater thigh extension at toe-off, they analysed joint kinematics at various distances (5, 15, 25 m) with sleds loaded at 10 and 20% BM. Greater knee extension may allow the athletes to increase propulsive forces to overcome the additional resistance, long-term this acute alteration could improve acceleration (Lockie, et al., 2003; Cronin, et al., 2008). Although the kinematics of ST provide a crucial insight into the movement characteristics of ST the kinetic changes are equally important.

2.5.3. Acute kinetic alterations

Since the overall aim of a ST programme is to enhance an athlete's force application during sprinting it seems unusual that little research has focused on this aspect of performance (Kawamori, et al., 2014). Factors such as the direction of force application, rate of force development, net force and impulses will ultimately determine the kinematics of performance and therefore allow us to further understand the training stimulus that will be provided.

A study by Kawamori et al., (2014) investigated the acute kinetic effects of ST during the acceleration phase of the sprint. Specifically, GRF data were collected for the stance phase of each participant's second step and compared across three conditions (uninhibited, 10% BM and 30% BM loading). They reported that the GRF measures for the 10% BM group were not significantly different from the uninhibited group. As such, the researchers suggested that this loading strategy may not provide enough resistance to produce the overload needed for adaptations to occur. Therefore, it appears possible that sled loading strategies that don't impact on kinematics might not provide enough resistance to stimulate physiological adaptation. To identify exactly which muscle groups are being overloaded during ST more kinetic and joint-specific angular kinematic analysis may be required (Clark, et al., 2010). Net horizontal and propulsive impulses were much greater in the 30% BM trials than those recorded for the uninhibited sprint group were. However, the significantly different GRF values were explained simply by longer contact times during which more horizontal and propulsive force could be applied. The findings of this investigation need to be interpreted with caution for several reasons. Participants inside the laboratory were attached to the sled outside the laboratory using a 23.1 m lead. Not only did the two surfaces have different coefficients of friction, the extended attachment cord meant the resistance of the sled was acting on the participants from an angle uncommon to that of ST practice. Although significantly longer ground contacts may not be an ideal training stimulus, the adaptations following an intervention period are unknown. Before examining the long-term training adaptations of ST there are a number of important considerations, the athletes training age and how this affects their response to training should be discussed.

2.5.4. Training age

Training age is a major consideration when designing and implementing the training programme. As mentioned previously, athletes with a low-level training age will respond very differently (both acutely and over the longer-term) to those with a moderate to high training age (James, et al., 2018; Young, 2006). Stronger athletes with a higher training age have been found to improve performance in high-velocity movements through neural and force-velocity adaptations. In contrast, performance enhancements in weaker athletes with a lower training age resulted from more general adaptations (e.g. shifts of both force and velocity alongside moderate changes in the magnitude and rate of muscle activation) (James, et al., 2018). Research also suggests that semi-elite and competitive-elite athletes may have the ability to tolerate higher sled loading without influencing sprint kinematics as dramatically (Maulder, et al., 2008). These studies have used different testing populations with varied training ages.

The acute impact of ST on sprint kinematics has been well researched, Maulder et al., (2008) used a semi-elite testing population of track sprinters of international and national standard. They found that the 10% BM sled loading strategy had a negligible impact on sprint kinematics. The 20% BM sled loading significantly affected a few of the sprint kinematic measures. Murray et al., (2005) investigated several sled loading strategies on team-sport athletes, they simply stated that the testing population had used ST regularly during training. Although the significance is not reported, they highlight kinematic differences, in stride length during the 10% BM loading trials. Although not directly comparable, Lockie et al., (2003) examined the kinematic impact of 12.6% sled loading on an active male population. They reported significant changes in a number of kinematic measures; stride length, stride frequency and ground contact time. Athletes with a higher training age may be able to tolerate heavier sled loadings due to greater strength/power and better sprint techniques (Kawamori, et al., 2014).

Research suggests that over the long-term ST interventions may be implemented on athletes with any training status. A number of the long-term studies used semi-elite and competitive-elite training populations (Alcaraz, et al., 2014; Harrison & Bourke, 2009; West, et al., 2013), all of which found significant improvements in sprint performance post ST intervention testing. Similarly, ST interventions have been shown to have a significant impact on untrained or recreational testing populations (Makaruk, et al., 2013; Zafeiridis, et al., 2005). There appears to be a lack of consistency in the way in which different researchers determine the participant's training status. As such, the interpretation of training status may differ between studies and a clear definition or outline of the training status terminology would prove useful when comparing research. In addition to the athletes training age the programming variables (e.g. sets, reps, recovery periods and intervention duration) will have a significant impact on long-term adaptations.

2.5.5. Sets, reps and recovery periods

Practitioners can design or adapt a periodised programme by manipulating the number of sets, repetitions, the exercises performed, the amount or type of resistance utilised, the amount of rest between sets or exercises, the type of contractions used or the frequency of training (Rhea, et al., 2002). Generally, participants in the longitudinal ST studies were required to attend 2 - 3 training sessions per week. Many of the successful intervention studies followed a two sessions per week programme, which appears to be adequate (Figure 2.8) (Alcaraz, et al., 2014; Harrison & Bourke, 2009; Spinks, et al., 2007; West, et al., 2013). Akin to any training that has a high neuromuscular demand; ST should be undertaken when athletes are minimally fatigued (Green, 1997). Programming a ST session, the day after a physically demanding training day or match would likely be counterproductive and increase the interference effect (Fyfe & Loenneke, 2018). Research suggests that a period of 24 - 48 hours should be left between ST sessions (Cissik, 2004).

Training sessions generally included a standardised warm-up protocol followed by several ST sprints (typically between 6 - 12 sprints in total) interspersed by a recovery period (Clark, et al., 2010; Harrison & Bourke, 2009; West, et al., 2013). Passive recovery periods between repetitions varied from 2 - 4 minutes (Alcaraz, et al., 2014; Clark, et al., 2010; West, et al., 2013; Zafeiridis, et al., 2005). Rest periods between sets also differed, these were generally between 4 - 8 minutes (Alcaraz, et al., 2014; West, et al., 2013) in length but as much as 10 minutes (Zafeiridis, et al., 2005). In summary, research indicates that sets, reps and recovery periods of 3, 3, and 2 minutes respectively can be employed successfully when training for the acceleration phase. Longer rest periods of 4 minutes are sufficient between sets.

Table 2. The experimental sprint training protocol.

	Training session 1	Training session 2
Week	Reps × distance (rest between reps)	Reps × distance (rest between reps)
1	3 × 18.3 m (3.0 min)	2 × 54.9 m (4.0 min)
	2 × 36.6 m (3.5 min)	2 × 36.6 m (3.5 min)
	2 × 54.9 m (4.0 min)	3 × 18.3 m (3.0 min)
	Total volume = 237.7 m	Total volume = 237.7 m
2	3 × 18.3 m (3.0 min)	2 × 54.9 m (4.0 min)
	3 × 36.6 m (3.5 min)	3 × 36.6 m (3.5 min)
	2 × 54.9 m (4.0 min)	3 × 18.3 m (3.0 min)
	Total volume = 274.3 m	Total volume = 274.3 m
3	3 × 18.3 m (3.0 min)	3 × 54.9 m (4.0 min)
	3 × 36.6 m (3.5 min)	3 × 36.6 m (3.5 min)
	3 × 54.9 m (4.0 min)	3 × 18.3 m (3.0 min)
	Total volume = 329.2 m	Total volume = 329.2 m
4	2 × 18.3 m (3.0 min)	3 × 54.9 m (4.0 min)
	4 × 36.6 m (3.5 min)	4 × 36.6 m (3.5 min)
	3 × 54.9 m (4.0 min)	2 × 18.3 m (3.0 min)
	Total volume = 347.5 m	Total volume = 347.5 m
5	2 × 18.3 m (3.0 min)	4 × 54.9 m (4.0 min)
	4 × 36.6 m (3.5 min)	4 × 36.6 m (3.5 min)
	4 × 54.9 m (4.0 min)	2 × 18.3 m (3.0 min)
	Total volume = 402.3 m	Total volume = 402.3 m
6	2 × 18.3 m (3.0 min)	No training session due to school holiday
	2 × 36.6 m (3.5 min)	
	2 × 54.9 m (4.0 min)	
	Total volume = 219.5 m	
7	3 × 18.3 m (3.0 min)	3 × 54.9 m (4.0 min)
	3 × 36.6 m (3.5 min)	3 × 36.6 m (3.5 min)
	3 × 54.9 m (4.0 min)	3 × 18.3 m (3.0 min)
	Total volume = 329.2 m	Total volume = 329.2 m

Figure 2.8: An example of a ST training programme (Clark, et al., 2010).

2.5.6. Long-term adaptations

The long-term adaptations to ST will be partly determined by the duration of the training intervention, as mentioned previously. Firstly, it is important to note that participants in the majority of the ST intervention studies had to undertake a pre-intervention generalised training programme, done so in order to standardise protocols (Alcaraz, et al., 2014; Zafeiridis, et al., 2005). ST studies have implemented interventions of different durations, a number of studies employed a four-week intervention period (Alcaraz, et al., 2014; Makaruk, et al., 2013) in comparison other studies completed an eight-week ST intervention (Spinks, et al., 2007;

Zafeiridis, et al., 2005). Results indicate that both intervention periods can have a significant impact on sprint performance. Alcaraz et al., (2014) suggested that improvements in sprint velocity were a result of an increased rate of force development; this adaptation is likely neural in nature and as a result occurred during a four-week ST intervention. In agreement with the short-term intervention studies, Spinks et al., (2007) also suggested that improvements in sprint velocity were a result of an increased rate of force development. However, in contrast to the shorter intervention studies, Alcaraz et al., (2014) suggested the reported improvements in reactive strength were resultant of adaptations in musculotendinous stiffness, measured in-directly with a 50 cm drop jump test. Physiological adaptations of this nature will likely only occur during longer intervention studies.

Whilst acute studies indicate that ST may alter sprint mechanics in a way beneficial to the acceleration phase longitudinal investigations are important to monitor these adaptations. A number of longitudinal studies have looked at the participant's trunk lean following a ST intervention (Alcaraz, et al., 2014; Makaruk, et al., 2013; Zafeiridis, et al., 2005). Results indicate that the ST interventions did lead to significantly greater forward trunk lean during the acceleration phase. As discussed previously, the increased trunk lean should aid acceleration as it enhances horizontal force application (Kugler & Janshen, 2010; Majumdar & Robergs, 2011). In contrast this increased trunk lean may reduce MV performance as vertical forces are imperative to minimise contact times (Weyand, et al., 2000). The findings of Zafeiridis et al. (2005) who measured sprint kinematics following a prolonged ST programme support this adaptation. They found an increased trunk lean and subsequent improvement in acceleration whereas no significant differences were found in the MV phase.

Additional research is required to establish whether this kinematic adaptation is a result of changes in GRF application or a transferable change in skill execution.

Many studies have investigated the effects of ST over various training periods, however the majority have used active or recreational populations (Lockie, et al., 2012; Makaruk, et al., 2013; Spinks, et al., 2007; Zafeiridis, et al., 2005). A previous study by Harrison & Bourke (2009) investigated ST in semi-elite and competitive-elite rugby players over a six-week period. Players were assigned to a ST or control group and continued with a concurrent in-season training programme, the intervention group undertook two additional ST sessions per week. They reported significant improvements in the ST group over 5 m and improvements in various jumps. A more recent study by West, et al., (2013) also investigated ST over a six-week period; their participants were professional rugby players. This study focussed on the pre-season phase and compared UST combined with ST and UST only. They reported significant improvements in 10 and 30 m sprint times for both intervention groups. Although the ST group promoted greater improvements, these were not significant. It appears ST can enhance early acceleration; however, these studies used light sled loading strategies. More recent investigations have suggested moderate to heavy or very heavy sled loadings may be more appropriate (Monte, et al., 2017; Morin, et al., 2017; Petrakos, et al., 2016).

To date few investigations on semi-elite, competitive-elite or successful-elite athletes have extended the intervention period over six-weeks, as a result it is not known whether all the adaptations will have occurred during a six-week programme. Thus, the optimal duration of a ST programme remains unanswered, the various adaptations may occur at different points in the programme. Therefore, a long-term ST intervention study on semi-elite or competitive-elite athletes with regular testing sessions may be necessary to determine the point at which adaptations are optimal for sprint performance. Much of the ST research focuses on the acceleration phase, while it appears that the kinematic and kinetic alterations are ideally suited to this phase it is still necessary to examine ST and the MV phase.

2.5.7. Sled towing for the maximum velocity phase

The characteristics of the MV phase are unique as the athlete attempts to maintain postural stability and maximise vertical force application (Young, 2005). As such, either phase specific (acceleration and MV) sled loading strategies may be important or ST should not be utilised when training for the MV performance. Generally, there is a lack of research into ST for the MV phase with only one study investigating the acute responses (Alcaraz, et al., 2014). Alcaraz et al., (2014) compared ST (loaded based on a 10% V_{Dec}) with a parachute (medium sized) and weighted belt (9% BM). Unsurprisingly, the ST condition resulted in the largest reductions in MV due to the additional frictional forces between the sled and surface. None of the three conditions affected stride frequency and stride length was only significantly reduced in the ST trials. Trunk lean was also significantly increased in the ST trials. However, as discussed previously, an increased trunk lean is not beneficial for the MV phase as vertical force application is important in reducing contact time and braking forces (Kugler & Janshen, 2010; Zafeiridis, et al., 2005). When implemented for the MV phase a waist belt attachment would seem more suitable than a shoulder harness as the athlete's trunk lean may be minimised (Alcaraz, et al., 2014).

Sprint performance at MV has been measured pre and post ST interventions. Unfortunately, many of the studies used the same loading strategies for both the acceleration and MV phases (Alcaraz, et al., 2014; Clark, et al., 2010; Zafeiridis, et al., 2005). Two of the aforementioned investigations reported significant improvements in the acceleration phase (Alcaraz, et al., 2014; Zafeiridis, et al., 2005) and none found any increases in MV. Therefore, the ST loading strategies or programming variables being implemented at present are not suited to this phase. In line with the acute investigations, an increased trunk lean was the only adaptation that occurred in both of the studies that undertook a kinematic analysis for the MV phase (Alcaraz, et al., 2014; Zafeiridis, et al., 2005).

The weight of the sled is clearly a limitation when training for the MV phase. Sleds generally weigh between 4.0 - 7.5kg and as a result, it is not possible to train with lighter loads. In this instance, other forms of RST such as parachutes might be more suitable (Alcaraz, et al., 2009). Neural adaptations (e.g. improved co-ordination and timing) are crucial to the MV phase due to the limited stance phase (Carroll, et al., 2001; Kyröläinen, et al., 2005), as such it is not surprising that studies have suggested that UST is more beneficial than ST for this phase (West, et al., 2013; Zafeiridis, et al., 2005). Therefore, it is recommended that ST programmes are best designed with the acceleration phase in mind.

2.6. Summary of Literature

This literature review has provided a valuable insight into the important aspects surrounding the topic area, such as sprint running, RST, ST, and the ideal periodisation strategies when working with team-sport athletes. Over recent years there has been a lot interest surrounding these sports-specific training modalities which is reflected in the considerable research base.

All sprinting activities are performed at high intensities over short periods of time (Novacheck, 1998). However, the acceleration and MV phases of sprint running have very distinct characteristics (Murphy, et al., 2003; Young, 2005). Early acceleration requires a powerful extension of all lower-extremity joints as well as a forceful arm drive (Maulder, et al., 2008; Nagahara, et al., 2014). During this phase the athlete's centre of mass is positioned ahead of their base of support, thus maximising horizontal force application (Nagahara, et al., 2014). Both step length and step frequency will increase dramatically as the athletes approach the MV phase (Murphy, et al., 2003). In contrast, to achieve high MV athletes should preserve optimal postural stability, minimise braking forces, minimise contact times and increase the vertical propulsive forces (Young, 2005).

Regardless of loading ST has been shown to reduce velocity, increase contact times, reduce step length and increase trunk lean (Lockie, et al., 2003; Monte, et al., 2017; Murray, et al., 2005). These changes are more in line with the characteristics of the acceleration phase. Therefore, it is not surprising that MV performance did not improve after a ST intervention period (Alcaraz, et al., 2014; Zafeiridis, et al., 2005). In contrast, research indicates that ST can be used to improve acceleration performance (Harrison & Bourke, 2009; West, et al., 2013). However, many of the ST intervention studies have employed light sled loading strategies based on % BM, whereas % V_{DEC} loading strategies and moderate to heavy sleds have been recommended more recently (Petrakos, et al., 2016). Therefore, acceleration performance might be further enhanced if sled setup and loading strategies are adjusted accordingly. Studies suggest these sprint-specific training methods may have a better transfer to performance compared to non-specific strength training (Brughelli, et al., 2010; Young, 2006).

Exercises of this nature may be an ideal transition between the high-force low-velocity strength exercises which are common and the more sport-specific low-force high-velocity plyometric exercises of a programme. This is of importance for the more advanced athlete who will have already benefitted from the general strength adaptations of non-specific training (James, et al., 2018).

Many sports such as rugby league require the need for strength, power, endurance and muscular size (Gabbett, 2005). As such, a range of training modalities are utilised to prepare these athletes for competition. ST is suited to the specific preparation and competition phases, benefitting from the strength, co-ordination and postural stability qualities developed in the earlier general preparation phases (Issurin, 2010). Research indicates that sets, reps and recovery periods of 3, 3, and 2 minutes respectively can be employed successfully when training for the acceleration phase (Clark, et al., 2010; Harrison & Bourke, 2009; West, et al., 2013). Typically, ST intervention periods have ranged between four and eight-weeks. Interventions of different lengths have been successful with neural adaptations being indicated as the key to performance enhancement (Alcaraz, et al., 2014; Makaruk, et al., 2013; Spinks, et al., 2007). Such adaptations likely occur during the early stages of training (James, et al., 2018), as such, shorter intervention periods may be more effective as well as being easier to incorporate into the training programme.

2.6.1. Thesis rationale

Generally, sleds are attached via a cord (3 m) and harness system, with the most common being either a shoulder or waist attachment point. At present no studies have explored how the different harness attachment points of ST affect sprint performance. Lawrence et al., (2013) investigated the effects of different harness attachment points (shoulder and waist) on walking ST. They reported differences in joint moments, concluding that the shoulder harness would challenge the knee extensors and the waist harness the hip extensors. Over time, they speculated that the different harness attachments could lead to positive strength adaptations related to the aforementioned joints, thereby allowing practitioners to tailor the ST to the areas of their athlete's weakness (Lawrence, et al., 2013). Although no studies have compared harness attachment points during sprint ST, research has highlighted the importance of the hip extensors during the acceleration phase of sprinting (Delecluse, 1997). As such, it appears a waist harness may challenge athletes in a sprint-specific manner and therefore be the preferred attachment point, however further research is necessary to confirm this theory.

Several studies have examined the acute kinematic responses of ST with light to moderate sled loading strategies. Many of these investigations have explored the kinematic changes that occur during ST in comparison to uninhibited sprinting (Lockie, et al., 2003; Maulder, et al., 2008; Murray, et al., 2005). Whereas, other investigations have focused purely on the kinetic variables (Kawamori, et al., 2014). As sprint kinematics are determined by force application, it would seem important to measure both elements when investigating sled loading strategies. In addition, more recent studies have suggested that heavier sled loading strategies may prove beneficial to the acceleration phase; as such, moderate to heavy sled loadings should be examined (Kawamori, et al., 2014; Lockie, et al., 2003; Petrakos, et al., 2016).

The early ST investigations frequently used an absolute sled loading strategy (Zafeiridis, et al., 2005). However, a blanket approach of this nature does not differentiate between different athletes, such as different body composition. The most common sled loading method used in research and practice at present is to scale loadings based on a percentage of BM (West, et al., 2013). This method does not account for individual differences in strength, power or technical ability, therefore velocity-based loading is the preferred approach (Kawamori, et al., 2014; Petrakos, et al., 2016). When implementing this strategy sleds are loaded based on a V_{Dec} over a given distance; few studies have investigated this loading strategy.

Many investigations have highlighted the acute kinematic adaptations to ST over a range of different sled loads (Lockie, et al., 2003; Maulder, et al., 2008; Murray, et al., 2005). The long-term performance adaptations to lighter sled loading strategies have also been studied previously (Harrison & Bourke, 2009; West, et al., 2013). However, at present the optimal sled setup and loading strategies remain unclear. Therefore, research on the different harness attachment points, moderate to heavy sled loading strategies and V_{Dec} loading strategies on acute sprint performance or longer-term intervention studies would allow practitioners to better prescribe ST interventions.

2.6.2. Key thesis objectives

The lack of recommendations regarding the optimal sled setup and a consensus over loading strategies make it difficult for practitioners to integrate ST in the strength and conditioning training programme. This thesis will review the existing literature and implement various movement analysis techniques to identify the important kinematic and kinetic alterations associated with ST. These lab-based experiments will inform a final ST intervention study.

The key objectives of this thesis were:

- To investigate the 3-D kinematics and kinetics of ST with different harness attachment points, to determine whether a waist or shoulder harness attachment point should be utilised during ST.

- To examine the 3-D kinematics and kinetics of different sled loadings to suggest the optimum strategy for the acceleration phase of sprinting. Sleds will be loaded to reduce velocity by 10, 15 and 20% over a 6 m sprint and compared to uninhibited sprint acceleration.

- To investigate the benefits of an eight-week in-season ST intervention. Sled loadings will be based on the outcomes of previous studies and performance measures will be taken pre, mid and post to (a) determine whether a ST or an uninhibited sprint intervention would be more effective at improving sprint acceleration, and (b) investigate whether the interventions benefit other performance measures.

2.6.2. Hypothesises

The following hypothesises were investigated during the main studies of this thesis:

Study 1: Impact of harness attachment point on kinetics and kinematics during sled towing.

- The differences between the kinetic parameters will be negligible between all conditions.
- Both ST conditions will be significantly different from the uninhibited sprint trials in terms of their 3-D lower limb and trunk kinematics.
- The waist and shoulder harness attachment points will impact 3-D trunk, hip, knee and ankle joint kinematics differently.

Study 2: The effect of velocity-based loading on acceleration kinetics and kinematics during sled towing.

- The disruption to 3-D lower limb and trunk kinematics will be greater as sled loadings increase.
- Measures of propulsive peak force will be greatest during the 20% V_{Dec} sled trials.
- Measures of propulsive impulse will be largest during the 20% V_{Dec} sled condition.

Study 3: The effect of in-season velocity-based sled towing on acceleration in semi-elite rugby league players.

- Both intervention groups (ST and UST) will significantly improve sprint performance.
- The ST intervention will lead to significantly greater improvements over the initial 5 m distance compared to the UST group.
- The ST intervention will significantly improve performance in the CMJ test compared to the UST group.

3. Justification of Methods

This section will provide an overview and justification of the general methods utilised throughout this thesis. More specific developmental methods will be provided during the subsequent chapters as needed.

3.1. Introduction

All of the laboratory-based experiments carried out during this thesis utilised the same motion analysis system and techniques. These studies were undertaken using an infra-red stereophotogrammetric camera system synchronised with a force platform. The final intervention study was implemented off-site in field-based conditions; as such, portable testing equipment was necessary.

3.2. 3-D motion analysis system

3.2.1. Qualisys Oqus 310

The Qualisys motion analysis system (Qualisys Gothenburg, Sweden) captured data throughout at 250 Hz and uses passive infrared technology to track retro reflective markers. Eight cameras were utilised during all laboratory-based testing (Figure 3.1).

Figure 3.1: Qualisys Oqus 310 motion analysis camera.

3.2.2. Camera setup

The motion analysis cameras were setup in an umbrella configuration (Figure 3.2). This type of configuration enables researchers to use complex marker sets and ensures that at least three cameras are tracking the data for each marker (Richards, 2008).

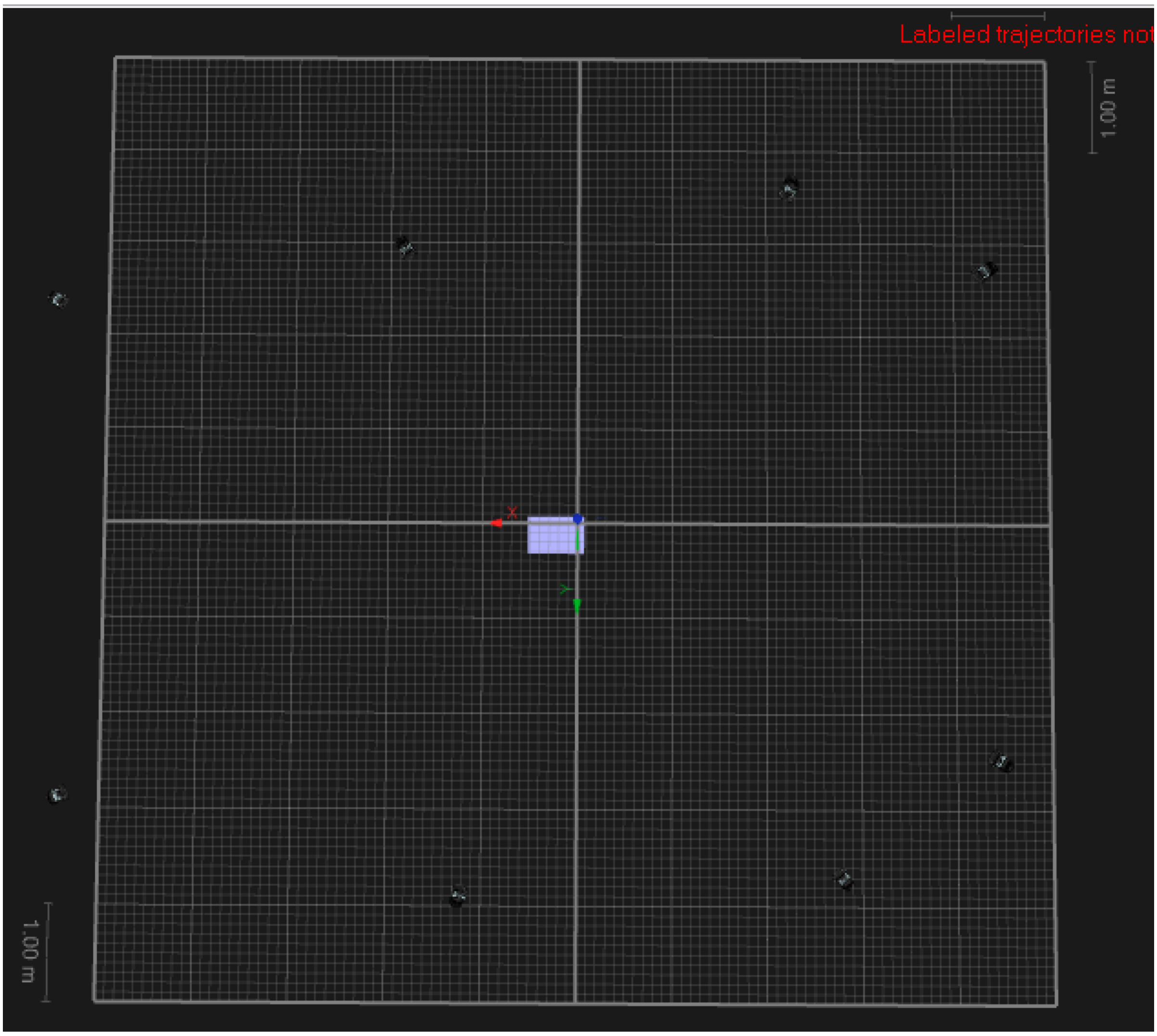

Figure 3.2: The eight-camera umbrella configuration.

3.2.3. Calibration techniques

The image space (the area in which the movement is to be recorded in) must be calibrated to allow for the calculation of the positional information with respect to a known frame of reference. In this instance, a reference L-frame (dimensions; length 750 mm and width 500 mm) is placed into the capture zone and is recorded as a static calibration (Figure 3.3). The static calibration L-frame should be visible to all cameras and once recorded the frame should be removed so that data can be collected. In addition to the static reference L-frame, a wand is moved (dimensions; 750 mm) dynamically through the capture zone (Figure 3.3). A procedure known as a bundle adjustment is undertaken, thus allowing the position and orientation of the cameras as well as the 3-D coordinates of the wand to be generated (Richards, 2008).

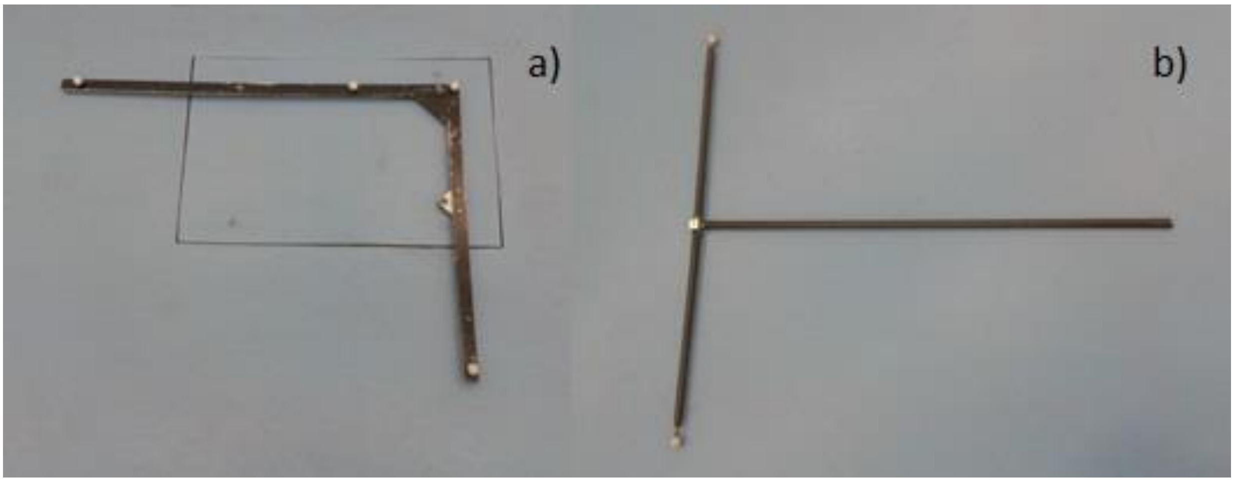

Figure 3.3: a. the Qualisys Oqus system calibration L-frame and b. the wand.

The Qualisys motion analysis system was calibrated prior to all data collection sessions. The reference L-frame was used for the static calibration in conjunction with the dynamic wand calibration. The calibration was implemented in the expected capture zone allowing measures of error to be calculated. Two measures of error were investigated, the norms of residuals that are associated with the camera system and the standard deviation of known wand length indicates the potential errors in the calculation of marker positions (Richards, 2008). Lower average residuals and standard deviation of wand length are associated with fewer errors, thus improving the subsequent data collection (Richards, 2008).

3.2.4. Anatomical model and marker set

The calibrated anatomical system technique (CAST) was developed to enable researchers to standardise movement description and is considered the gold standard (Sinclair, et al., 2012). This technique relies on the identification of anatomical landmarks and tracking markers to identify an anatomical frame for each body segment. This method relies on external palpation and allows researchers to model each segment in six degrees of freedom (Cappozzo, et al., 1995). Retro-reflective markers (Figure 3.4) were placed on the anatomical landmarks and utilised during a static (anatomical) calibration only, whereas retro-reflective markers as well as dynamic tracking marker sets (Figure 3.4) were placed on each body segment and remained in place during the static calibration and data collection (Richards, 2008).

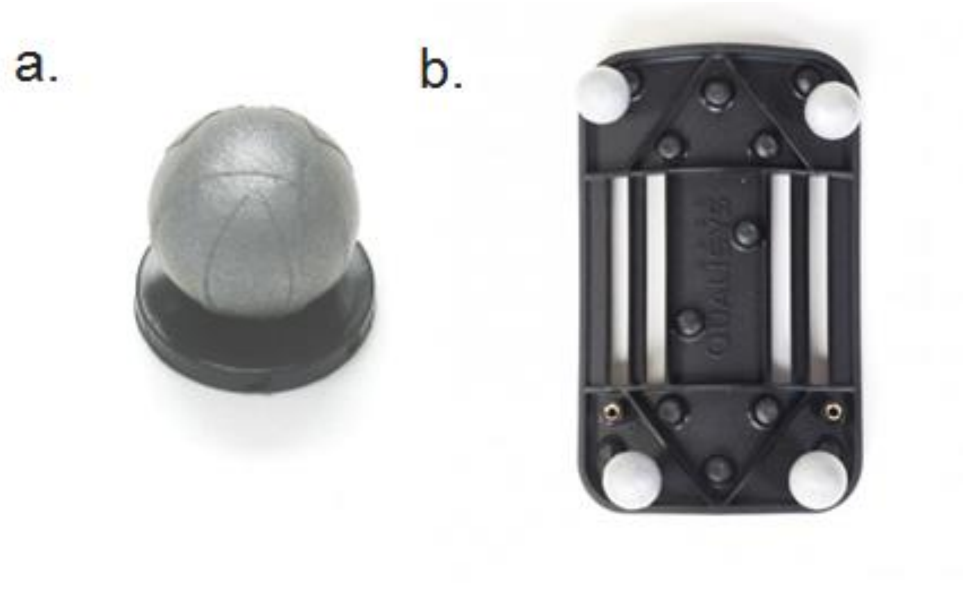

Figure 3.4: Examples of a. retro-reflective marker and b. dynamic marker set.

The static calibration markers were placed on the lateral and medial aspects of joints on anatomical landmarks at the proximal and distal ends of the segment. In order to determine trunk, stance leg kinematics of the right thigh (femoral), right shank (tibial), and right foot segments, markers were placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, acromion process (both), T12 and C7, in agreement with Cappozzo et al., (1995). As discussed previously, all static non-tracking markers were removed prior to the dynamic data collection trials (Figure 3.5).

Additional rigid dynamic marker sets (clusters) were placed down the long axis of each segment to allow tracking during the data collection trials. A minimum of at least three non-linear markers were required to track each segment during data collection trials (Richards, 2008). The trunk was tracked using markers at both acromion processes, as well as the T12 marker. The anterior (ASIS) and posterior (PSIS) superior iliac spine markers and greater trochanters were used as tracking markers for the pelvis. Rigid cluster tracking markers were also positioned on the right thigh and shank segments. During the data collection trials, the foot segment was tracked using the calcaneus, 1st and 5th metatarsal heads (Figure 3.5).

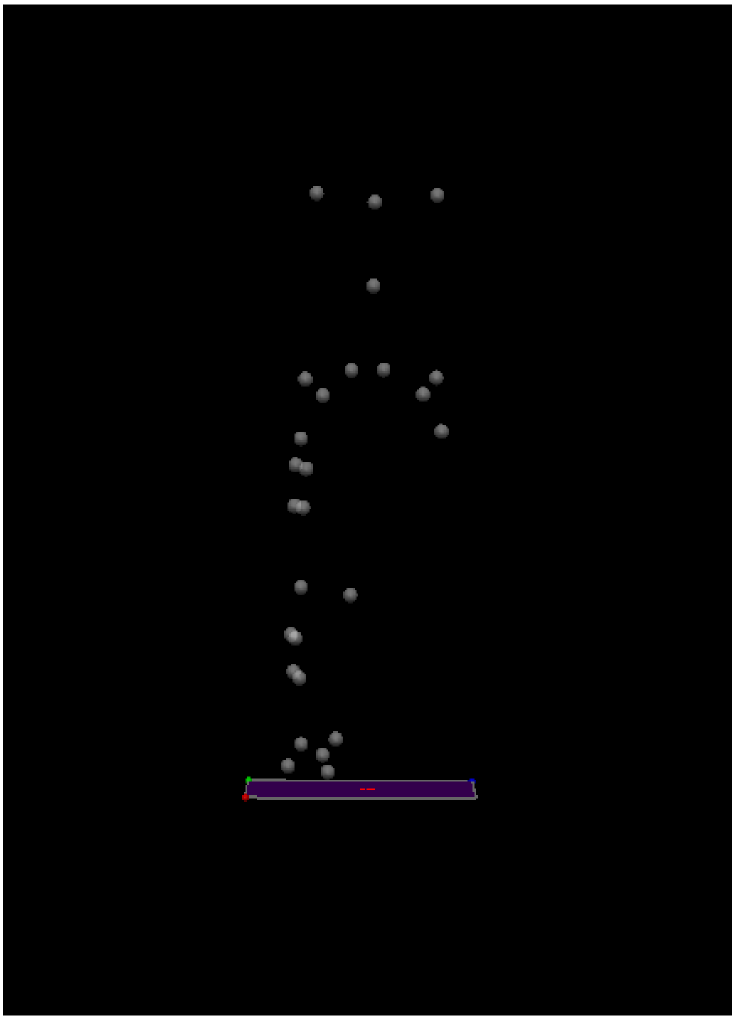

Figure 3.5: The complete marker set used during calibration.

3.2.5. Kinematic data processing

Motion files were collected through the Qualisys track manager software and exported as C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA). The Visual 3-D software allows the analysis of many different kinematic and kinetic variables. Once calculated all Visual 3-D data were exported to Microsoft Excel (Microsoft Corp., Redmond, WA, USA) before being formatted in a manner suitable for further statistical analysis.

All sprint motion files were filtered with a cut-off frequency of 12 Hz using a Butterworth 4th order filter. The Butterworth 4th order filter is a low-pass digital filter commonly utilised when smoothing movement data (Gordon, et al., 2003). The purpose of any filtering method is to reduce the errors associated with noise while leaving the true signal intact (Winter, et al., 1974). During the Butterworth filtering method, a weighted average of data points across the kinematic waveform is produced (Sinclair, et al., 2013). Although it is generally accepted that a Butterworth 4th order low-pass filter is an effective smoothing strategy, determining the appropriate cut-off frequency is also important (Yu, et al., 1999). The ideal cut-off frequency is dependent on the quality of the input data and should ideally be as high as possible without making the data uninterpretable due to excessive noise (Bezodis & Salo, 2013). This frequency was selected in order to filter and adequately suppress motion artefacts without inducing excessive smoothing of the traces, 12 Hz has also been used in similar studies on early acceleration (Debaere, et al., 2013; Slawinski, et al., 2013).

The method of quantifying the angular position of a rigid dynamic frame with respect to a reference frame is via the utilisation of independent angles known commonly as Cardan angles (Schache, et al., 2001). Different Cardan sequences can influence the angular calculations of any movement. The International Society of Biomechanics and previous research recommend that lower extremity angular kinematics be calculated using an XYZ cardan sequence when the dominant movement is flexion-extension in the sagittal plane (Sinclair, et al., 2012). Other studies have supported this suggestion, highlighting the importance when the sporting action being analysed utilises large ROM in the sagittal plane (Cole, et al., 1993). Therefore, 3-D kinematics of the lower extremities and trunk in this thesis were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane; Y represents the coronal plane and Z the transverse plane).

3.2.6. Identifying joint centre location

Anatomical landmarks without any palpable bony prominences are referred to as 'internal'. In terms of the lower extremities, the geometric centres of the hip and knee joints are commonly used (Della Croce, et al., 2005). These joints are assumed to have spherical shapes and common centres, as such regression equations may be utilised to predict the 3-D location of joint centre. Both the accuracy and precision with which the hip joint centre location is estimated are crucial for consistency and the subsequent kinematic and kinetic measurements of the hip and knee joints (Della Croce, et al., 2005). The main sources of error associated with these measurements are; location of anatomical landmarks, soft tissue artefact and the definitions of joint centres and axes (Kainz, et al., 2015). Predictive methods use regression equations based on data from medical imaging, other methods such as medical imaging-based and functional movement approaches can be used but they are expensive, impractical or require the collection of additional calibration trials during gait analysis (Kainz, et al., 2015).

Therefore, throughout this thesis, hip joint centre was determined based on the popular Bell, et al., (1989) equation. Defined as 0.36* distance between the ASIS markers medial to the ASIS marker distance, 0.19* distance between ASIS markers posterior to the ASIS marker and 0.3* distance between ASIS inferior to the ASIS marker. Knee and ankle joints and axes of rotation were determined using the locations of anatomical landmarks (Cappozzo, et al., 1995), both using a two marker method. Knee joint centre was delineated as the mid-point between the femoral epicondyle markers. Identification of joint centre using this method has been highlighted as being accurate and reliable when compared to the alternative functional strategies (Sinclair, et al., 2015). Test-retest reliability measures were particularly high for sagittal plane movement and Sinclair et al., (2015) stressed that the selection of knee joint centre technique is not a concern. The ankle joint centre was identified as the mid-point between the malleoli markers. This two marker method has been proposed by previous research comparing a range of techniques due to fewer errors (Graydon, et al., 2015).

3.2.7. The anatomical frame and segment definitions

The anatomical frame for each body segment was defined and modelled using a segment co-ordinate systems method (Figure 3.6). This method uses the proximal and distal endpoints of the segment to determine an orientation of the X, Y, Z axes of the joint (Figure 3.7) (Richards, 2008). The foot was modelled and tracked as a single segment system with the distal end being defined by the 1st and 5th metatarsal head while the medial and lateral malleoli defined the proximal end. The distal end of the shank was modelled using the medial and lateral malleoli's whereas the proximal end of the shank was defined using the medial and lateral epicondyles. The distal end of the thigh was defined using the medial and lateral epicondyles whereas the hip joint centre was used when defining the proximal end. The pelvis was modelled using the CODA option on visual 3-D via the positions of the left and right ASIS and PSIS. Finally, the trunk was modelled and tracked as a single rigid segment. The right and left iliac crests were utilised to define the distal end, while the right and left PSIS were used to define the proximal end. The segment co-ordinate systems axis for the foot, shank, thigh and trunk were positioned at the proximal ends of the segment, while the midpoint between the ASIS markers was used for the pelvis. The relevant segments (trunk, thigh, shank and foot) and reference segments (pelvis, thigh and shank) were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively.

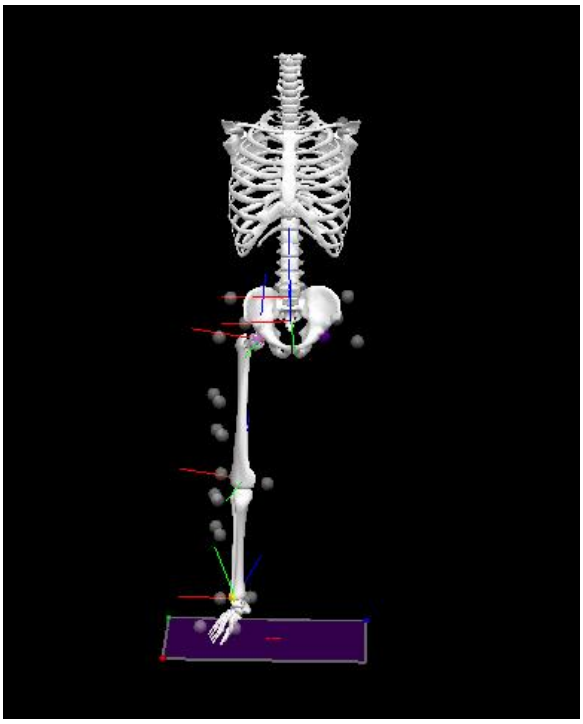

Figure 3.6: The visual 3-D model (trunk, pelvis, thigh, shank and foot).

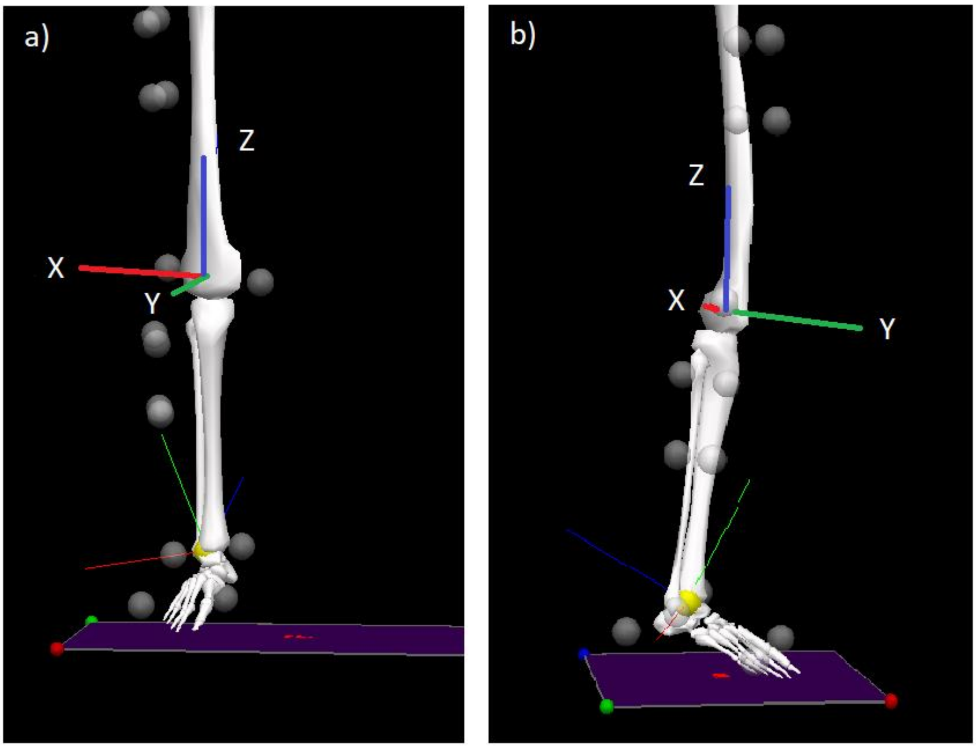

Figure 3.7: The orientation of the X, Y, Z axes of knee joint in a) the coronal plane, and b) the sagittal plane.

3.2.8. Identifying kinematic events

The important kinematic events (foot-strike and toe-off) were established using the threshold recognition function in Visual 3-D. The stance phase was determined as time over which 20 N or greater of vertical force was applied to the force platform. Foot-strike was defined as the first instance vertical GRF was above 20 N and toe-off was the first instance vertical GRF fell below 20 N (Sinclair, et al., 2011). However, for some of the experimental studies this method was not appropriate as the force platform was not utilised, in this instance events were identified using further kinematic analysis (See Chapter 4). Once foot-strike and toe-off had been identified, various other kinematic measures from the trunk, hip, knee and ankle joints could be investigated. Angles were generated for all the joints discussed at foot-strike, at toe-off, peak, ROM (the angular displacement from foot-strike to toe-off), and the relative ROM (the angular displacement from foot-strike to peak angle). Additionally, resultant velocity at toe-off was calculated using the velocity of horizontal and vertical centre of mass:

$$Resultant\ velocity = \sqrt{(horizontal\ vel^2)} + (vertical\ vel^2)$$

All kinematic variables were extracted from each of the five trials for each joint; data were then averaged within participants for a comparative statistical analysis.

3.3. Force plate

An embedded piezoelectric force platform, sampling at 1000 Hz, was utilised throughout the laboratory-based testing of this thesis (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd). The force plate was positioned in the middle of the umbrella camera configuration and all data were processed through the Qualisys track manager software, therefore allowing 3-D kinematic and GRF data to be obtained synchronously. The force plate was installed by the manufacturer and set up to their recommendations.

3.3.1. Kinetic data processing

Force plate data were collected through the Qualisys track manager software and exported to Visual 3-D (C-Motion Inc., Germantown, USA) for processing. The durations of the braking and propulsive phases were based on anterior and posterior horizontal GRF. Peak GRF was determined for the following components: vertical, braking, propulsive. Vertical impulse was calculated as the area under the vertical force-time curve (using a trapezoidal function) minus body weight impulse over the time of ground contact. The braking and propulsive impulses were determined by integrating all the negative and positive values of horizontal GRF, respectively, over the time of ground contact (Kawamori, et al., 2014). Net horizontal impulse was calculated as propulsive impulse minus the absolute value of braking impulse. Similarly, mean values of vertical and net horizontal GRF were obtained by dividing respective impulse values by the contact time. Mean braking and propulsive GRF were calculated by dividing the respective impulse values by the time duration of the braking and propulsive phases, respectively (Kawamori, et al., 2014).

3.4. Normalization of data

The normalization of data enables researchers to increase the validity of the results (Mullineaux, et al., 2006). Various normalization techniques were utilised throughout this thesis. In terms of the kinematic data, numerous events were established (in Visual 3-D) and normalised to 100% of the stance phase (time over which 20 N or greater of vertical force was applied to the force platform). GRF and impulse measures are generally normalised using BM (Mullineaux, et al., 2006). All GRF data were divided by the participant's BM in Newtons, as such GRF was reported in BM ($N.kg^{-1}$). All impulse measures were normalised to BM, so they represent changes in velocity of centre of mass during ground contact ($m.s^{-1}$) (Mullineaux, et al., 2006).

3.5. SmartSpeed Pro timing gate system

The SmartSpeed timing gate system (Fusion Sport, Queensland, Australia) uses electronic photocell technology to send a single light beam between an emitter and reflector (Figure 3.8), the instant the beam is broken the time is recorded (Earp & Newton, 2012). Accurate and reliable timing is essential when monitoring sprint performance. Automatic timing gate systems are considered the gold standard when monitoring sprint performance as they eliminate the human error and bias associated with manual timing (Earp & Newton, 2012). Although automatic timing gate systems are more accurate compared to manual timing strategies these systems are associated with false signal errors (Haugen, et al., 2014). In this instance, the beam is broken by an outstretched arm or leg instead of the torso. To reduce false signal errors manufacturers have developed dual-photocell timing systems. These systems have two photocells aligned vertically positioned 30 cm apart, when using these systems, the time is recorded the instant both beams are broken (Earp & Newton, 2012). Generally, dual-photocell timing gate systems are thought to reduce the incidence of false signal errors (Haugen, et al., 2014). However, some single-photocell systems have been developed with software (signal post-processing) that examines the signal from a gate in its entirety, allowing the determination of frequency and how long the beam has been disrupted for. Times are recorded at the start of the longest duration of disruption. Research shows that false signal errors can be eliminated with this technology; as such, the SmartSpeed Pro timing gate system is an appropriate system when measuring sprint performance (Earp & Newton, 2012).

Figure 3.8: Examples of the SmartSpeed timing gate system (reflectors and emitters).

Prior to the testing sessions participants completed a familiarisation session, during this session all testing protocols were explained and practiced. During testing (pre, mid and post intervention) on completion of the warm up participants completed 3 x 20 m sprints from a standing staggered stance with their non-dominant foot forward through the electronic timing gate system (Fusion Sports, SmartSpeed, Australia). Participants started 0.3 m behind the starting point, timing gates were positioned on 0, 5, 10 and 20 m (Figure 3.9). Participants were instructed to start when they were ready and to sprint through 5 m past the final gate. The fastest time recorded over 20 m (out of the three attempts) was used in subsequent data analysis.

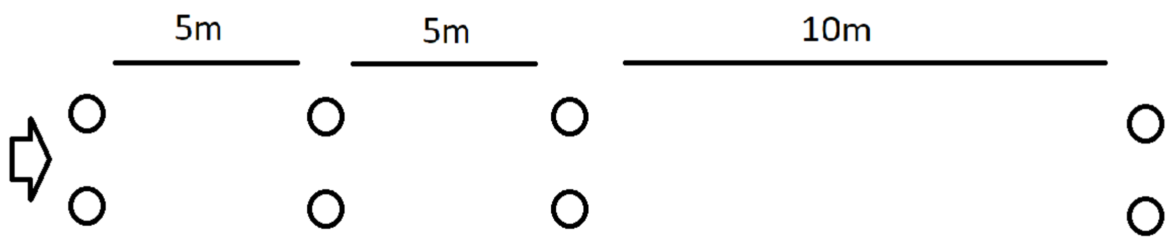

Figure 3.9: Timing gate system set up during the 20 m sprint testing.

3.6. SmartSpeed SmartJump system

The SmartSpeed jump mat system (Figure 3.10) (Fusion Sports, Queensland, Australia) calculates jump height and many other measures (e.g. contact time, flight time and peak power output) using time in the air based on a linear motion equation (Reeve & Tyler, 2013). Although there are other methods available (e.g. measuring take-off velocity) these often require expensive equipment such as a force plate that may not be available in the field. The countermovement jump (CMJ) is commonly utilised in research and the applied setting to assess vertical jump height (Reeve & Tyler, 2013). A study by Reeve & Tyler (2013) investigated the validity of the SmartJump contact mat using different protocols. They found discrepancies when compared to the force plate method, thus it was suggested that during field-based testing practitioners should be consistent with apparatus and protocols in order to get a more accurate and reliable measurements.

Figure 3.10: The SmartJump contact mat.

Prior to the testing session's participants completed a familiarisation session, during this session all testing protocols were explained and practiced. During testing (pre, mid and post intervention) on completion of the warm up the CMJ test began with participants standing tall with hands on their hips. They were instructed to perform a countermovement by simultaneously flexing the hips and knees to a self-selected height then to explosively jump as high as possible. Participants were instructed to land in the same position on the mat with a toe first contact. As suggested in previous research participants hands had to remain on their hips throughout the CMJ (Figure 3.11) (Reeve & Tyler, 2013). All participants performed three jumps with adequate rest between (2 minutes). The participant's largest CMJ was recorded and used in future data analysis.

Figure 3.11: The CMJ protocol.

3.7. The sled, cord and harness

The same sleds (Innova Brands Ltd, United Kingdom) were used throughout this thesis (Figure 3.12). The sled had a mass of 7.5 kg and was 83 cm in length and 58 cm width. The sled travelled on two parallel metal tubes about 4 cm in diameter. The sliding tubes on the base of the sled were bare steel. The sled was attached to the participants using a 3 m non-elasticated attachment cord, and either a double shoulder strap or single waist belt (depending on the study).

Figure 3.12: An image of the sled, cord and waist harness attachment.

3.7.1. Sled loading strategy

Sled loadings were determined using a given V_{Dec} over a set distance. As discussed previously this is the preferred approach and was therefore utilised throughout the different investigations of this thesis (Petrakos, et al., 2016). Sled loadings were determined in specific familiarisation sessions during which participants completed a 6 or 10 m baseline sprint having completed a standardised warm-up protocol. A 6 m baseline was used during the laboratory-based studies due to space restrictions whereas 10 m baseline sprints were employed during the field-based intervention study. Sleds were then loaded at the equivalent % BM and participants sprinted back through the timing gates. Sled loadings were adjusted accordingly, and participants completed further sprints until sprint times were reduced by the selected V_{Dec} (accurate within 2%). Short distances were utilised as the different kinetics and kinematics of the transition and MV phases (10 m and over) may not represent the acceleration phase of sprint running, which as highlighted previously is particularly important during rugby league match-play.

3.8. Statistical analyses

Throughout this thesis, all statistical analyses were undertaken using SPSS (Versions 20 and 22, IBM SPSS Inc., Chicago, USA). Descriptive statistics were presented (means and standard deviations) to describe the outcome measures and characteristics of the participants (e.g. age, stature and BM).

Prior to any inferential statistical analysis, several statistical assumptions were examined to determine whether the data was parametric or non-parametric. Firstly, the normality of distribution was examined using a Shapiro-Wilks test. This is thought to be an effective test of normality for smaller sample sizes. The assumption of homogeneity was examined using the Levene's test. Results indicated that the data was normally distributed, and the equality of variance was accepted, as such various parametric tests were utilised throughout the thesis.

The main laboratory-based outcomes were examined using one-way repeated measures analysis of variance (ANOVA). Data was averaged across multiple sprint trials which represented the participant's generalised and typical movement (James, et al., 2007). Thus, allowing the comparison of the means of the different conditions (e.g. harness attachment point or sled loading) with the different outcome measures (e.g. velocity, contact time, kinetics and kinematics). Although, recent research suggests alternative methods may be more effective at reducing the influence of poorly executed trials, protocols were put in place during testing to ensure quality (Dos'Santos, et al., 2018). In addition, one-way repeated measures ANOVAs were used to investigate the effect of fatigue on sprint performance over the duration of the testing sessions (Studies 1 and 2). Whereas, a 2 x 3 mixed ANOVA was utilised to compare the means of the different conditions throughout the intervention (group X time) for each of the performance measures (e.g. CMJ height, sprint and agility times). Post hoc pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment. Bonferroni corrections are commonly utilised in sport science research, they are simple and valid but often thought to be overly conservative (Sinclair, et al., 2013). Such corrections reduce the likelihood of type I errors, however, the probability of making type II errors may increase and therefore important findings may be deemed non-significant (Sinclair, et al., 2013). All results were interpreted with caution and other statistical analyses such as the Holm-Bonferroni method and Šidák correction were considered. Mauchly's test was used to confirm sphericity for each analysis. If the assumption of sphericity was violated, a Greenhouse-Geisser adjustment was used. Significance levels were set at $p \leq 0.05$. Effect sizes were calculated using partial eta^2 ($p\eta^2$), in accordance with Cohen (1988) $p\eta^2 = 0.2$ considered small, $p\eta^2 = 0.5$ medium and $p\eta^2 = 0.8$ large.

3.9. Participant information

All participants provided written informed consent before undertaking any of the studies as part of this thesis. Procedures were explained verbally and in writing and participants were asked to complete a health screening (PAR-Q) form. Participants were familiarised with all equipment and procedures prior to testing and they were asked not to participate in any strenuous physical activity 24 hours before the sessions. All participants that participated in the developmental studies in this thesis were either students at the University of Central Lancashire or academy players from Wigan Warriors rugby league team. The laboratory-based sled loading and final ST intervention studies were undertaken by the academy players from Wigan Warriors rugby league team only, as such participants were resistance trained (≥ 3 years) with ST experience. These athletes have been classified as semi-elite according to the guidelines set by Swann et al., (2015). Semi-elite athletes are categorised as those whose highest level of participation is below the top standard possible in their sport (Swann, et al., 2015). All had between 2-5 years' experience in a talent development programme. In accordance with the principles of the Declaration of Helsinki the Institutional Ethics Committee at the University of Central Lancashire approved the all testing procedures implemented in this thesis (Reference number – BuSH 202). No external funding was provided for any of the studies.

3.10. Sample size rationale

Previous ST investigations have reported significant alterations in kinematic and kinetic measures with as few as ten participants (Kawamori, et al., 2014; Maulder, et al., 2006). To determine a suitable number of participants for each study and avoid type II errors a statistical priori power analysis was performed (Hopkins, 2002). Sprint velocity was utilised in this analysis as trials were monitored using this variable, however it is possible that some of the kinematic and kinetic measures may have been more appropriate. The analysis revealed that a minimum of twelve participants would be sufficient for the laboratory-based experiments in this investigation. Training intervention studies on semi-elite athletes can be challenging, as such a number previous studies have used less than twenty participants for a between-groups designs and found significant improvements in sprint performance (Harrison & Bourke, 2009; West, et al., 2013). Participation in this study was limited by the size of the playing squad; as such, twenty-eight participants started the final training intervention study and twenty-six completed it.

4. Developmental methods

This section will provide an overview of the pilot studies that were carried out to develop the subsequent testing protocols and assess accuracy/validity of methods.

Published Abstracts

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) The impact of force plate striking on lower body kinematics during sprinting. Journal of Sports Sciences, 33, S21-24.

Conference Presentations

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) The impact of force plate striking on lower body kinematics during sprinting. BASES Annual Conference, St George's Park, UK.

4.1. General Overview of developmental methods

Prior to the pilot studies several more generic calibration, accuracy and validation studies were undertaken (See Appendices). These studies proved important and subsequently helped to inform the main pilot studies as well as the main investigations. Firstly, all the lab-based experiments in this thesis were completed using a 3-D motion analysis system. As such, an initial study was used to assess the accuracy of the different calibration techniques (See Appendix A). Based on the results of this study all subsequent laboratory-based experiments which utilised the motion analysis camera system were calibrated using a combination of straight and rotational wand movements. An assessment of the test re-test reliability of the primary researcher's marker placement skills was also conducted (See Appendix B). Again, this study was critical as many participants were tested during each of the main studies. A lack of marker placement consistency would have had a significant impact on the data quality. The results of this study indicated that that the primary researcher's marker placement skills were reliable and could be repeated accurately. Therefore, all participants were markered up by the primary researcher in this thesis.

Although the sled loadings were based around V_{DEC} it was important to examine the friction coefficient of the different surfaces utilised (See Appendix C). This study was crucial allowing a comparison with other sled towing studies which may have used alternative sled loading strategies. Results indicated that there were distinct differences between the dynamic coefficient of friction for the different surfaces used during the lab-based and field-based testing of this thesis. Although, all sled loadings were prescribed using the V_{Dec} strategy the dynamic coefficient of friction was still reported for all surface types, thus allowing comparison with previous research that employed % BM sled loading. Participants have been known to alter their natural running gait to ensure contact with devices (e.g. force plates), such deliberate striking is known as targeting. During the main studies of this thesis participants were required to sprint across a force platform, therefore it was important to assess the effect of targeting on lower-body 3-D kinematics. This study (See Appendix D) utilised individuals involved in recreational sport and required them to perform numerous sprints across and next to the force platform to allow a comparison. The results indicated that force plate targeting could have a significant impact on participant's subjective comfort and the kinematic measures of the lower extremities, particularly at the hip and knee joints. However, the results of this experiment may not be transferable to a semi-elite testing population. Force plate targeting is expected to have less impact on these athletes because they regularly perform high intensity sprints during training and competition.

Pilot study one was used to investigate the impact of force plate targeting on a semi-elite rugby league population respectively. All force plate trials were compared to uninhibited sprint acceleration to the side of the force plate. Pilot study two was used to examine the reliability of the different measurement variables (velocity, kinematic and kinetic) collected during uninhibited sprint acceleration across the force platform. This study provided an insight into the variability of measures across several trials and enabled meaningful comparisons during the main ST investigations. Finally, pilot study three was an investigation into the weekly variation in sprint performance of semi-elite rugby league players during the competitive phase of the season. This study was critical as it allowed for meaningful conclusions to be drawn from the results of the ST intervention.

4.2. Pilot Study 1: Force platform targeting in a semi-elite rugby league population

4.2.1. Introduction

An initial study (See Appendix D) highlighted the impact of sprinting across a force plate on the kinematics of the lower extremities in recreationally active participants. Targeting had a significant impact on participant's subjective comfort and the kinematic measures of the lower extremities, particularly those at the hip and knee joints. However, athletes with a higher training age and skill level may be more consistent, as such; force plate targeting may not have a significant impact on performance. Therefore, the aim of the current investigation was to examine force plate striking on 3-D kinematics during the acceleration phase of sprint running in semi-elite rugby league players.

4.2.2. Methods

Participants

Twelve semi-elite male rugby league players volunteered to take part in this investigation (age: 18.9 ± 0.54 years; BM: 88.2 ± 9.15 kg; stature: 179.8 ± 8.22 cm). All participants were injury free at the time of data collection.

Procedures

All participants attended a familiarisation session approximately one week prior to testing. During this session participants practiced sprinting across the embedded force plate and by the side of it without concern for striking it. Feedback was provided throughout and starting positions were adjusted so the participants felt equally comfortable in both conditions (through completion of subjective comfort on a Likert scale).

Participants were asked not to participate in any physical activity 24 hours before the testing session. No food could be consumed during testing, though water was allowed throughout. The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several sprints building up to maximum intensity (4 x submaximal and 2 x maximal).

Participants sprinted 6 m in two conditions, 1) over an embedded force plate, and 2) uninhibited sprinting to the side of the force plate without concern for striking it. Participants had two minutes recovery between each of the sprint trials. Five trials were collected for each condition in a randomised order. The embedded force plate (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd.) which sampled at 1000 Hz was positioned approximately 3 m from the starting position. In order for the trials to be deemed successful, the whole foot had to contact the force platform. Starting positions were adjusted so that the dominant (right) foot contacted the force plate (during striking trials) on their third step following the starting stance. All participants chose to start with their left foot leading in the 3-point starting position. Regardless of the starting point, participants sprinted a total distance of 6 m before decelerating.

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. The system was calibrated before every testing session. In order to determine stance leg kinematics (foot, shank and thigh segments) retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1^{st} metatarsal head, 5^{th} metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle (Cappozzo, et al., 1995). The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell et al., (1989) equations via the positions of the PSIS and ASIS markers. During dynamic trials the foot segment was tracked using the calcaneus, 1^{st} and 5^{th} metatarsal heads. Rigid cluster tracking markers were also positioned on the right shank and thigh segments (Cappozzo, et al., 1997). The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. A static calibration was completed and used as reference for anatomical marker placement in relation to the tracking markers. After which all non-tracking markers were removed.

As force data were not available in both conditions, foot-strike and toe-off were determined using kinematic based methods, identical to those used by Nagahara & Zushi, (2013). This method relied on a kinematic detection method using the marker placed on the 1^{st} metatarsal head. Peak vertical acceleration was used to determine the initial foot-strike, and toe-off was identified when the marker reached its lowest point (towards the end of the stance phase) (Nagahara, et al., 2014). After the testing session participants were asked to rate their subjective comfort in striking the force plate in relation to uninhibited sprinting next to the force plate using a 10-point Likert scale, 10 representing totally comfortable and 0 being totally uncomfortable.

Data processing

Trials were digitized using Qualysis track manager, exported to Visual 3-D (C-motion, Germantown, USA) and filtered at 12 Hz using a Butterworth 4^{th} order filter. Lower extremity kinematics were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). All kinematic waveforms were normalised to 100% of the stance phase and then processed trials were averaged. Various stance phase 3-D kinematic parameters (hip, knee and ankle) were extracted for statistical analysis; angle at foot-strike, angle at toe-off, peak angle during stance, range of motion (the angular displacement from foot-strike to toe-off during stance) and the relative range of motion (Rel ROM) (the angular displacement from foot-strike to peak angle).

Statistical analysis

Descriptive statistics were calculated for each of the sprint conditions (mean ± standard deviation (SD)). Differences between kinematic, velocity and subjective parameters were examined using multiple paired samples t-tests ($p \leq 0.05$). No alpha level adjustments were made, in line with the analysis methods suggested previously (Sinclair, et al., 2013). All statistical procedures were conducted using SPSS 20.0 (SPSS Inc, Chicago, USA).

4.2.3. Results

Table 4.1 presents the velocity data from the uninhibited and targeting conditions. Tables 4.2 – 4.5 show the 3-D kinematic data at the different joints under both conditions. Table 4.5 presents the subjective ratings of comfort for the uninhibited and targeting conditions.

Table 4.1: Velocity (means and standard deviations) observed during uninhibited and force plate sprint trials.

	Uninhibited	**Force Plate**	**Mean Difference ($m.s^{-1}$)**
Velocity ($m.s^{-1}$)	6.29 ± .32	6.26 ± .33	.03

* Significantly different from uninhibited sprinting p ≤ 0.05

The results show that there was no significant difference in velocity between conditions ($t_{(11)} = -0.700$, $p = 0.500$).

The overall patterns of the resultant 3-D kinematic waveforms were qualitatively similar (Figure 4.1), although statistical differences were observed at the hip and ankle joints (Tables 4.2 & 4.4).

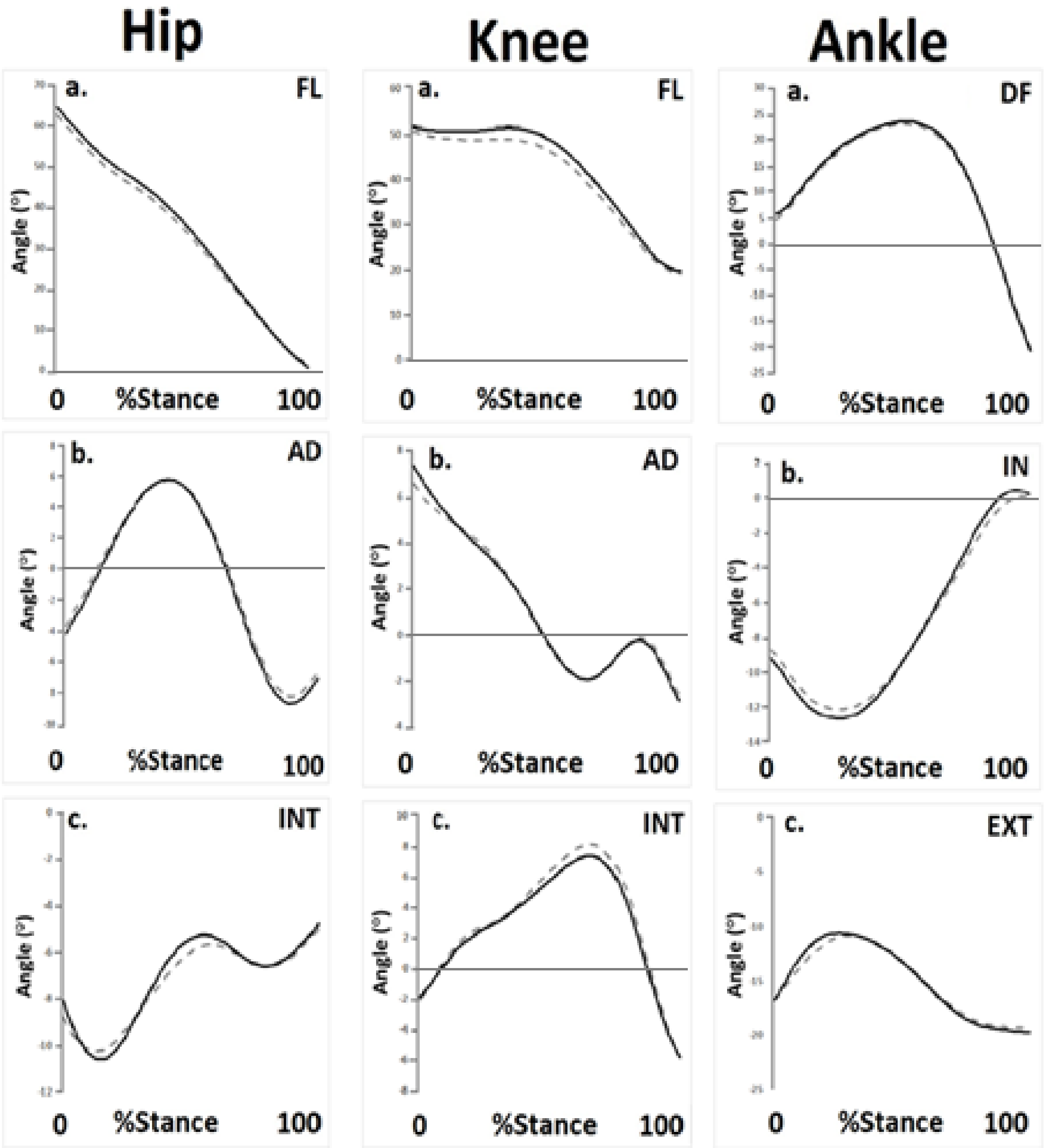

Figure 4.1: Mean hip, knee and ankle joint kinematics in the a) sagittal, b) coronal and c) transverse planes during force plate striking (dashed line) and uninhibited (black line) sprint trials.

Table 4.2: Hip joint kinematics (means and standard deviations) observed during uninhibited and force plate sprint trials.

	Uninhibited	**Force Plate**	**Mean Difference (°)**
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	64.91 ± 11.83	63.13 ± 11.17	1.78
Angle at toe-off (°)	.38 ± 8.74	1.16 ± 8.25	.78
Peak flexion (°)	64.91 ± 11.83	63.13 ± 11.17	1.78
ROM (°)	64.52 ± 7.20	61.98 ± 7.01*	2.54
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	-4.01 ± 4.71	-3.25 ± 4.55	.76
Angle at toe-off (°)	-6.93 ± 4.85	-6.51 ± 4.40	.42
Peak adduction (°)	6.34 ± 5.10	6.24 ± 4.53	.10
ROM (°)	4.44 ± 3.04	4.70 ± 3.52	.26
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-7.98 ± 5.15	-8.52 ± 5.48	.54
Angle at toe-off (°)	-4.34 ± 7.08	-4.64 ± 6.67	.30
Peak external rotation (°)	-12.25 ± 6.08	-11.66 ± 5.72	.59
ROM (°)	6.59 ± 2.68	6.12 ± 3.16	.47

* Significantly different from uninhibited sprinting $p \leq 0.05$

Hip joint kinematics (Table 4.2) were significantly affected by the different sprinting conditions. In the sagittal plane, ROM ($t_{(11)} = 3.276$, $p = 0.008$) was significantly greater in the uninhibited sprinting condition when compared to the force plate striking condition.

Table 4.3: Knee joint kinematics (means and standard deviations) observed during force plate and uninhibited sprint trials.

	Uninhibited	**Force Plate**	**Mean Difference (°)**
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	51.36 ± 6.06	50.63 ± 5.53	.73
Angle at toe-off (°)	19.70 ± 5.49	19.36 ± 4.69	.34
Peak flexion (°)	53.19 ± 5.97	52.02 ± 4.94	1.17
ROM (°)	31.66 ± 2.78	31.27 ± 2.77	.39
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	7.40 ± 3.11	6.68 ± 3.12	.72
Angle at toe-off (°)	-2.86 ± 1.99	-2.62 ± 2.26	.24
Peak abduction (°)	-3.36 ± 2.14	-3.25 ± 2.36	.11
ROM (°)	10.26 ± 3.72	9.30 ± 3.69	.96
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-2.16 ± 5.03	-2.27 ± 4.99	.11
Angle at toe-off (°)	-6.20 ± 6.99	-6.28 ± 6.72	.08
Peak internal rotation (°)	7.69 ± 5.23	8.27 ± 5.11	.58
ROM (°)	5.53 ± 3.32	5.57 ± 3.16	.04

* Significantly different from uninhibited sprinting $p \leq 0.05$

None of the measurement variables were (Table 4.3) significantly influenced by force plate targeting ($p > 0.05$).

Table 4.4: Ankle joint kinematics (means and standard deviations) observed during force plate and uninhibited sprint trials.

	Uninhibited	Force Plate	Mean Difference (°)
X (+=dorsiflexion/-=plantarflexion)			
Angle at foot-strike (°)	5.85 ± 5.29	5.04 ± 5.64	.81
Angle at toe-off (°)	-21.04 ± 6.46	19.96 ± 7.30	1.08
Peak dorsi-flexion (°)	23.99 ± 6.07	23.46 ± 5.73	.53
ROM (°)	26.89 ± 5.63	25.00 ± 7.00*	1.89
Y (+=inversion/-=eversion)			
Angle at foot-strike (°)	-8.90 ± 5.79	-8.73 ± 5.85	.17
Angle at toe-off (°)	.14 ± 3.06	.14 ± 2.36	00
Peak eversion (°)	-13.33 ± 5.70	-12.75 ± 5.45	.58
ROM (°)	9.04 ± 5.98	8.87 ± 5.20	.17
Z (+=external/-=internal)			
Angle at foot-strike (°)	-16.78 ± 3.64	-16.69 ± 3.82	.09
Angle at toe-off (°)	-19.53 ± 7.11	-19.24 ± 6.69	.29
Minimum external rotation (°)	-9.85 ± 5.52	-10.18 ± 4.99	.33
ROM (°)	2.34 ± 4.18	3.95 ± 3.28	1.61

* Significantly different from uninhibited sprinting $p \leq 0.05$

Ankle joint kinematics (Table 4.4) were significantly affected by force plate targeting. It was shown that ROM was greater during the uninhibited sprint condition compared to the force plate striking condition in the sagittal plane ($t_{(11)} = 3.872$, $p = 0.003$).

Table 4.5: Subjective ratings of comfort (means ± standard deviations) for uninhibited and force plate trials.

	Uninhibited	**Force Plate**	**Mean Difference**
Subjective rating of comfort	9.92 ± .28	9.77 ± .44	.15

* Significantly different from uninhibited sprinting $p \leq 0.05$

Results indicate that there was no significant difference in subjective ratings of comfort between conditions ($t_{(11)} = 1.477$, $p = 0.165$).

4.2.4. Discussion

The aim of the current investigation was to examine the influence of force plate targeting on the kinematics of the lower extremities and subjective perceptions in a semi-elite population during sprint acceleration.

The results showed that force plate targeting caused very few lower extremity kinematic alterations in this semi-elite population, this in contrast to the results of previous studies (See Appendix D) and previous research (Challis, 2001). Negligible differences were found at the knee joint and majority of measures at the other joints (hip and ankle joints). Only sagittal plane ROM at the hip and ankle joints were significantly different during the embedded force plate trials. The ROM values were determined as the difference between angle at foot-strike and angle at toe-off (non-significant differences observed in both), negligible changes in these variables resulted in significant reductions in ROM.

The ratings of perceived comfort were not significantly different between conditions. Although subjective, these findings highlight the influence training age and performance level can have on performance and execution of explosive actions. All participants in this study were involved in semi-elite rugby league at the time of data collection. As such, the results may not be generalisable to other populations.

Conclusion

This study provides an insight into force plate targeting during the acceleration phase of sprinting in a semi-elite rugby league population. The results indicated that force plate targeting had a negligible impact on subjective comfort and the majority of kinematic measures of the lower extremities; as such, the procedures utilised during this study were employed in all laboratory-based experiments.

4.3. Pilot Study 2: Reliability of uninhibited sprint variables when accelerating across a force plate (velocity, kinematic and kinetic)

4.3.1. Introduction

Prior to any testing and/or data analysis it is important to establish the reliability of measures. Reliability is defined as the extent to which measurements can be replicated. Thus, representing not only the degree of correlation but also agreement between measurements (Koo, 2016). There are a few different types of reliability to consider, for example interrater and intrarater reliability would be used to investigate variation between two or more testers and variation for one tester across several trials (Koo, 2016). Test-retest reliability refers to the variation of measures taken on the same piece of equipment for the same participant over several trials.

The total error associated with any given variable is a result of both the system bias and random error. Systematic bias refers to a general trend for measurements to be different in a particular direction. This may be positive or negative between repeated trials or tests (Atkinson & Nevill, 1998). For example, retest measures might be higher than baseline measures due to a prior test due to a learning effect being present. Random error refers to the amount of random differences which could arise due to inherent biological or mechanical variation, or inconsistencies in the measurement protocol etc. The variation due to random error is generally greater than that of system bias (Atkinson & Nevill, 1998).

Reliability measures are important as they allow researchers to determine whether a measurement is of value or meaningful, thus allowing practitioners to interpret data with confidence (Atkinson & Nevill, 1998; Koo, 2016). Therefore, the aim of this study was to investigate the test-retest reliability of all dependant variables during early acceleration across an embedded force plate.

4.3.2. Methods

Participants

Twelve semi-elite rugby league athletes (age: 18.9 ± 0.6 years; total BM: 90.2 ± 10.0 kg; stature: 1.80 ± 0.06 m) participated in this study. All participants were resistance trained (≥ 3 years) with ST experience and provided informed consent before attending the testing sessions.

Procedures

Participants were asked not to participate in any physical activity 24 hours before the testing session. The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several short sprints building up to maximum intensity (4 x submaximal and 2 x maximal).

Measures were taken to ensure that no force plate targeting occurred. Firstly, participants were given time for familiarisation to determine an individual starting position. Starting positions were adjusted so that each participant's right foot (dominant) contacted the force plate on their third step. Starting positions of the ST trials were also adjusted accordingly and practiced until participants could consistently land on the force plate. To standardise starting positions, trials began in a 3-point position. All participants chose to start with their left foot leading in the 3-point starting position. Regardless of the starting point, participants sprinted a total distance of 6 m.

Procedures were identical to those described previously in the familiarisation section. Participants sprinted across an embedded force platform, recording five sprints and having 3 minutes recovery between trials. The force platform was positioned at approximately 3 m from the start (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd). In order for the trials to be deemed successful, the whole foot had to contact the force platform. Trials were discarded in cases where any part of the foot did not land the force platform. Sprint times were generated for every trial, and any trials in which sprint velocity deviated more than ± 5% of the initial trial in that condition were not used in the final analysis. In this instance, an extended recovery period of 4 minutes was implemented, and trials were repeated.

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. In order to determine stance leg kinematics of the trunk, thigh, shank, and foot segments, retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, acromion process (both), T12 and C7 (Cappozzo, et al., 1995). The trunk was tracked using markers at both acromion processes, as well as the T12 marker. The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell et al. (1989) equations via the positions of the PSIS and ASIS markers. The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. Rigid cluster tracking markers were also positioned on the right thigh and shank segments (Richards, 2008). Knee joint centre was delineated as the mid-point between the femoral epicondyle markers. The ankle joint centre was identified as the mid-point between the malleoli markers. During dynamic trials the foot segment was tracked using the calcaneus, 1st and 5th metatarsal heads. A static calibration was completed and used as reference for anatomical marker placement in relation to the tracking markers, after which all non-tracking markers were removed.

Data processing

Motion files collected through the Qualisys track manager software and exported as C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and filtered with a cut-off frequency of 12 Hz using a Butterworth 4th order filter to adequately suppress motion artefacts without inducing excessive smoothing of the traces (Debaere, et al., 2013) (Slawinski, et al., 2013). 3-D kinematics of the lower extremities and trunk were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). The relevant segments (thorax, thigh, shank and virtual foot) and reference segments (pelvis, thigh and shank) were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively. The stance phase was determined as time over which 20 N or greater of vertical force was applied to the force platform (Murphy, et al., 2003). Kinematic waveforms were time-normalised to 100% of the stance phase and then all processed trials were averaged. Various kinematic measures from the trunk, hip, knee and ankle joints were investigated: angle at foot-strike, angle at toe-off, peak angle, ROM (the angular displacement from foot-strike to toe-off), and the Rel ROM (the angular displacement from foot-strike to peak angle). Resultant velocity at toe-off was calculated using the vertical and horizontal centre of mass. These variables were extracted from each of the five trials for each joint, data were then averaged within participants for a comparative statistical analysis.

Force plate data were collected through the Qualisys track manager software and exported to Visual 3-D (C-Motion Inc., Germantown, USA) for processing. The durations of the braking and propulsive phases were based on anterior and posterior horizontal GRF. Peak GRF was determined for the following components: vertical, braking, propulsive. Vertical impulse was calculated as the area under the vertical force-time curve (using a trapezoidal function) minus body weight impulse over the time of ground contact. The braking and propulsive impulses were determined by integrating all the negative and positive values of horizontal GRF, respectively, over the time of ground contact (Kawamori, et al., 2014; Kawamori, et al., 2013). Net horizontal impulse was calculated as propulsive impulse minus the absolute value of braking impulse. All impulse measures were normalised to BM so they represent changes in velocity of centre of mass during ground contact (Mullineaux, et al., 2006). Similarly, mean values of vertical and net horizontal GRF were obtained by dividing respective impulse values by the contact time. Mean braking and propulsive GRF were calculated by dividing the respective impulse values by the time duration of the braking and propulsive phases, respectively (Kawamori, et al., 2014). GRF measures were also normalised relative to BM (Kawamori, et al., 2014).

Statistical analysis

Descriptive statistics were calculated and presented as mean ± SD. Dependant variables were examined using the uninhibited sprint trials. Test-retest reliability and within-subject variation was evaluated using intraclass correlation coefficient (ICC) and coefficients of variance (CV%). ICC is widely used to evaluate interrater, test-retest and intrarater reliability, without these measures it's difficult to draw conclusions from the results (Koo, 2016). Two-way mixed effects ICC (3, k) models were used as this is the preferred method for test re-test protocols (Koo, 2016). Magnitudes of ICC were classified according to the following thresholds: > 0.9 nearly perfect; 0.7–0.9 very large; 0.5–0.7 large; 0.3–0.5 moderate; and 0.1–0.3 small (Hopkins, 2002). Acceptable thresholds were determined using a coefficient of variance of ≤ 10%, which has been suggested previously (Cormack, et al., 2008). ICC and CV% were calculated using an online spreadsheet (Hopkins, 2015).

4.3.3. Results

Table 4.6: presents the reliability measures of the velocity, contact and GRF variables whereas Tables 4.7 – 4.9 show the reliability measures of the kinematic measures of trunk and lower extremities.

Table 4.6: Reliability assessment of velocity, contact and GRF measures (means and standard deviations) observed during sprint trials.

Dependant Variable	Mean ± SD	ICC	CV%
Velocity and Contact Measures			
Velocity (m.s-1)	5.49 ± .25	.98	.7
Contact time (s)	.17 ± .01	.92	1.7
Brake time (s)	.02 ± .01	.82	12.0
Propulsive time (s)	.15 ± .01	.89	2.1
Ground Reaction Forces			
Vertical peak force ($N.kg^{-1}$)	9.53 ± 1.69	.59	13.1
Vertical mean force ($N.kg^{-1}$)	2.94 ± .94	.65	19.0
Vertical impulse ($m.s^{-1}$)	.51 ± .16	.67	18.7
Net horizontal mean force ($N.kg^{-1}$)	3.39 ± .27	.78	3.8
Net horizontal impulse ($m.s^{-1}$)	.58 ± .03	.59	3.1
Braking peak force ($N.kg^{-1}$)	3.09 ± 1.72	.91	21.9
Braking mean force ($N.kg^{-1}$)	1.43 ± 1.04	.87	26.0
Braking impulse ($m.s^{-1}$)	.02 ± .02	.88	22.5
Propulsive peak force ($N.kg^{-1}$)	6.73 ± .42	.77	3.0
Propulsive mean force ($N.kg^{-1}$)	3.93 ± .29	.78	3.6
Propulsive impulse ($m.s^{-1}$)	.61 ± .03	.79	2.8

ICC = intraclass correlation coefficient, CV = coefficient of variation

Results (Table 4.6) indicate that the velocity and contact variables test-retest reliability was good with at least a very large ICC value (ICC = 0.82 – 0.98). Variability was very low for sprint velocity (CV% = 0.7%) and within the acceptable range for all other measures except brake time which had a CV% of 12.0. There was a greater range of ICC value for the GRF measures (ICC = 0.59 – 0.91) and a much greater variation across trials (CV% = 26.0 – 2.8).

Table 4.7: Reliability assessment of sagittal plane trunk and lower body kinematics (means and standard deviations) observed during sprint trials.

Dependant Variable	Mean ± SD	ICC	CV%
Trunk			
Angle at foot-strike (°)	6.49 ± 7.28	.99	5.4
Angle at toe-off (°)	-6.60 ± 7.57	.98	6.4
Peak flexion (°)	7.24 ± 6.91	.98	6.2
ROM (°)	13.09 ± 6.59	.98	6.9
Rel ROM (°)	.74 ± 1.41	.91	3.2
Hip			
Angle at foot-strike (°)	64.85 ± 8.42	.97	2.2
Angle at toe-off (°)	3.44 ± 9.01	.99	12.7
Peak flexion (°)	64.85 ± 8.42	.97	2.2
ROM (°)	61.41 ± 9.22	.98	2.4
Knee			
Angle at foot-strike (°)	50.74 ± 5.39	.94	2.6
Angle at toe-off (°)	20.97 ± 5.04	.96	5.2
Peak flexion (°)	51.99 ± 5.36	.95	2.3
ROM (°)	29.77 ± 6.70	.93	8.5
Rel ROM (°)	1.25 ± 1.91	.89	5.0
Ankle			
Angle at foot-strike (°)	4.25 ± 3.71	.92	8.9
Angle at toe-off (°)	-24.10 ± 6.20	.99	3.2
Peak dorsiflexion (°)	23.62 ± 3.96	.93	4.3
ROM (°)	28.36 ± 5.26	.96	3.6
Rel ROM (°)	19.37 ± 2.75	.95	3.4

ICC = intraclass correlation coefficient, CV = coefficient of variation

Results (Table 4.7) for the sagittal plane kinematics measures at the trunk, hip, knee and ankle joints highlight generally high test-retest reliability. Magnitudes of ICC values ranged from 0.89 to 0.99, indicating at least very large reliability and all CV% except hip angle at toe-off (CV% = 12.7) was within the acceptable threshold (CV% = 8.9 – 2.2).

Table 4.8: Reliability assessment of coronal plane trunk and lower body kinematics (means and standard deviations) observed during sprint trials.

Dependant Variable	Mean ± SD	ICC	CV%
Trunk			
Angle at foot-strike (°)	6.43 ± 4.15	.95	5.4
Angle at toe-off (°)	-10.51 ± 4.88	.97	5.0
Peak flexion (°)	-10.62 ± 4.96	.97	4.9
ROM (°)	16.93 ± 3.38	.96	4.7
Rel ROM (°)	17.05 ± 3.48	.96	4.4
Hip			
Angle at foot-strike (°)	-4.03 ± 3.53	.95	5.5
Angle at toe-off (°)	-8.14 ± 3.90	.94	9.6
Peak flexion (°)	3.79 ± 3.84	.98	4.7
ROM (°)	4.3 ± 3.69	.93	8.1
Rel ROM (°)	7.82 ± 3.4	.94	11.5
Knee			
Angle at foot-strike (°)	1.33 ± 6.51	.95	15
Angle at toe-off (°)	-3.85 ± 2.22	.96	7.6
Peak flexion (°)	-5.96 ± 2.52	.95	4.0
ROM (°)	5.83 ± 5.31	.88	40.7
Rel ROM (°)	7.28 ± 5.64	.97	16.4
Ankle			
Angle at foot-strike (°)	-.59 ± 4.53	.94	6.9
Angle at toe-off (°)	5.98 ± 2.95	.95	4.5
Peak dorsiflexion (°)	-7.84 ± 3.57	.90	12.6
ROM (°)	6.83 ± 4.04	.92	27.5
Rel ROM (°)	7.25 ± 4.01	.91	19.8

ICC = intraclass correlation coefficient, CV = coefficient of variation

Results (Table 4.8) for the coronal plane kinematics measures at the trunk, hip, knee and ankle joints highlight generally high test-retest reliability. Magnitudes of ICC values ranged from 0.88 to 0.98, indicating at least very large reliability. There was more CV% difference between measures, all kinematic variables at the trunk were within the acceptable range (ICC ≤ 10%). The ROM, Rel ROM values at the knee (CV% = 40.7 and 16.4 respectively) and ankle joints (CV% = 27.5 and 19.8 respectively) showed high variation as well as Rel ROM at the hip (CV% = 11.5).

Table 4.9: Reliability assessment of transverse plane trunk and lower body kinematics (means and standard deviations) observed during sprint trials.

Dependant Variable	Mean ± SD	ICC	CV%
Trunk			
Angle at foot-strike (°)	-4.93 ± 2.71	.92	9.3
Angle at toe-off (°)	8.01 ± 3.93	.94	6.8
Peak flexion (°)	11.4 ± 3.93	.89	15.7
ROM (°)	12.94 ± 5.17	.93	19.1
Rel ROM (°)	16.33 ± 5.3	.94	9.8
Hip			
Angle at foot-strike (°)	-12.82 ± 7.51	.99	6.5
Angle at toe-off (°)	-11.21 ± 7.56	.92	17.0
Peak flexion (°)	-17.68 ± 6.23	.98	9.7
ROM (°)	6.36 ± 4.27	.98	7.0
Rel ROM (°)	4.86 ± 3.46	.93	5.9
Knee			
Angle at foot-strike (°)	2.45 ± 7.07	.99	4.7
Angle at toe-off (°)	-.03 ± 5.66	.98	10.2
Peak flexion (°)	13.58 ± 4.66	.98	6.5
ROM (°)	5.08 ± 3.43	.87	32.5
Rel ROM (°)	11.13 ± 5.14	.95	14.7
Ankle			
Angle at foot-strike (°)	-4.75 ± 2.78	.94	5.2
Angle at toe-off (°)	2.61 ± 4.31	.96	8.1
Peak dorsiflexion (°)	4.1 ± 4.0	.95	7.1
ROM (°)	7.36 ± 3.63	.95	17.3
Rel ROM (°)	8.85 ± 3.26	.93	11.9

ICC = intraclass correlation coefficient, CV = coefficient of variation

Results (Table 4.9) for the transverse plane kinematics measures at the trunk, hip, knee and ankle joints indicate generally high test-retest reliability. Magnitudes of ICC values ranged from 0.87 to 0.99, highlighting at least very large reliability. There was more CV% difference between measures, at the trunk peak flexion and ROM were above the acceptable ranges (CV% = 15.7 and 19.1 respectively). Angle at toe-off at the hip and knee joints were also above the acceptable threshold (CV% = 17.0 and 10.2 respectively). Similarly, the ROM, Rel ROM values at the knee (CV% = 32.5 and 14.7 respectively) and ankle joints (CV% = 17.3 and 11.9 respectively) showed high variation as well.

4.3.4. Discussion

The aim of this study was to assess the reliability of the velocity, contact, kinematic and kinetic variables that were analysed during sprint trials. This represents an important study, as interpretation of such data determined the subsequent practical recommendations.

The results of this investigation show that reliability was generally high across the different variables and within the accepted ranges (ICC > 0.7 and CV% < 10) (Cormack, et al., 2008; Hopkins, 2002). However, there are several measures which fell outside the acceptable ranges and therefore changes in these measures may need to be interpreted with caution. The variability of all vertical and brake GRF measures appear to be greater than the recommendations (CV% > 10), as such changes in these variables may need to be considerable greater for them to be deemed important. In terms of the kinematic variables the ROM and Rel ROM measures may need to be interpreted with caution (CV% > 10). ROM was defined as angular displacement from foot-strike to toe-off and Rel ROM was defined as the angular displacement from foot-strike to peak angle. It is not surprising that these variables show a slightly lower reliability and more variability than other measures, possibly due to the multiple measures required to calculate them.

Throughout this thesis, steps were taken to reduce variability and increase reliability. All participants undertook familiarisation trials prior to data collection, all trials were repeated five times and when different conditions were required (e.g. ST trials) they were completed in a random order unless there were methodological reasons for not doing (e.g. the impact that ST trials could have on uninhibited sprints).

Conclusion

The results of this study highlight the generally high reliability of the test-retest sprint variables. All testing protocols were designed to minimise total error, thus allowing data to be interpreted with greater confidence.

4.4. Pilot Study 3: Variation of in-season sprint performance

4.4.1. Introduction

The physiological characteristics of rugby league players are well documented, requiring high levels of aerobic fitness, speed, power and agility; with these qualities increasing with playing level (Baker, 2002; Gabbett, 2005). Investigations of this nature typically undertake the battery of testing on one to four occasions throughout the season (e.g. the start and finish of pre-season as well as the start and finish of the competitive phase of the season). Intermittent measures of this nature may provide practitioners with a valuable insight into the fitness qualities required to play rugby league at different ages or competition levels (Gabbett, 2005; Till, et al., 2014). However, to investigate the weekly variation of fitness components more consistent measures would be necessary. Weekly variation in the different fitness qualities may be impacted by; the competition schedule resulting in less time to train, residual fatigue from the previous games, a high number of collisions or injury (Gabbett, 2005).

Therefore, the purpose of this study was to investigate the weekly variation in sprint performance (10 and 20 m) of semi-elite rugby league players during the competitive phase of the season. It was hypothesised that the variation from week to week would be relatively low and within the acceptable ranges. Findings from this investigation will enable a more meaningful interpretation of sprint times observed following the final intervention study of this thesis.

4.4.2. Methods

Participants

Twenty semi-elite rugby league athletes (age: 18.9 ± 0.5 years; BM: 88.7 ± 10.8 kg; stature: 1.79 ± 0.09 m) participated in this study. All participants were resistance trained (≥ 3 years) and provided informed consent before undertaking the testing. Any participants that missed more than one of the scheduled testing sessions were removed from the study. Dropout largely resulted from injuries that occurred during match-play.

The training programme

Weekly sprint performance was measured over an eight-week period during the competitive phase of the season. All testing sessions were incorporated into the normal training programme. Participants were exposed to the same standardised training programme in the four weeks prior to testing. Normal training resumed during the testing period, typically involving three gym and three field-based sessions per week. Four competitive rugby league games were also played during the data collection period. The gym-based sessions formed a weekly undulating strength training programme, with Monday, Tuesday and Thursday sessions focussing of hypertrophy, strength and power respectively. These sessions lasted approximately 45 minutes, whereas the field-based sessions would typically last approximately 70 minutes.

Testing procedures

All data collection sessions were scheduled on Thursday mornings at 8 am and identical testing protocols were followed throughout. This standalone session was scheduled on

Thursday mornings following the Wednesday recovery day. All participants had a testing familiarisation session one week prior to the initial testing session. BM and stature were recorded during this session. Participants were asked not to participate in any physical activity 24 hours before the testing session.

The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several short sprints building up to maximum intensity (4 x submaximal and 2 x maximal). On completion of the warm up participants completed 3 x 20 m sprints from a standing staggered stance with their non-dominant foot forward through the electronic timing gate system (Fusion Sports, SmartSpeed, Australia). Participants started 0.3 m behind the starting point, timing gates were positioned on 0, 10 and 20 m. Participants were instructed to start when they were ready and to sprint through the 5 m past the final gate. The fastest time out of the three attempts was used in the data analysis.

Statistical analysis

Descriptive statistics were calculated and presented as mean ± SD. As discussed previously, test-retest reliability and within-subject variation was evaluated using ICC (3, k) and CV%. Acceptable thresholds were determined using a CV of ≤ 10% (Cormack, et al., 2008). Magnitudes of ICC were classified according to the following thresholds: > 0.9 nearly perfect; 0.7–0.9 very large; 0.5–0.7 large; 0.3–0.5 moderate; and 0.1–0.3 small (Hopkins, 2002).

4.4.3. Results

Table 4.10: presents the results of an eight-week in-season sprint testing period.

Table 4.10: Variation in weekly sprint performance (means and standard deviations).

Dependant Variable	Mean ± SD	ICC	CV%
10m sprint (s)	1.71 ± 0.05	.95	0.6
20m sprint (s)	2.95 ± 0.12	.54	1.6

ICC = intraclass correlation coefficient, CV = coefficient of variation

Results (Table 4.10) indicate that the 10 m sprint time test-retest reliability was good with a nearly perfect ICC value of 0.95. Variability between weekly sprint times was also found to be very low, with a CV% of 0.6%. The magnitude of ICC for the 20 m sprints were lower, highlighting a large reliability measure (ICC = 0.54). Variability between weekly sprint times was again found to be very low, with a CV% of 1.6%.

4.4.4. Discussion

The purpose of this study was to investigate the weekly variation in sprint performance of semi-elite rugby league players during the competitive phase of the season. This investigation enabled a meaningful interpretation of the data collected before, during and after the final ST intervention study of this thesis.

The results highlighted that the variation of weekly sprint performance was low for 10 m and 20 m distances over an eight-week period in-season (CV% = 0.6 and 1.6 respectively). Similarly, reliability measures were higher for the 10 m sprint compared to the 20 m distance (ICC = 0.95 and 0.54 respectively). Although, previous studies on team-sports have investigated seasonal changes in sprint performance, reporting significant improvements from pre-season through to post-season (Ostojic, 2003; Till, et al., 2014) the sprint testing was undertaken sporadically. These investigations also included the pre-season phase which is a period of training specifically designed around competition preparation, as such it is not surprising they reported significant performance improvements. In comparison the in-season schedule and training is often disrupted due to the competition schedule, residual fatigue and a high number of collisions or injury (Gabbett, 2005). Therefore, training adaptations and performance gains are often compromised during this phase (Gabbett, 2005).

Conclusion

The results of this study highlighted the low variability of weekly sprint performance. As such, any sprint performance improvements following an intervention period should be easily distinguishable.

4.5. Summary of the developmental studies

The pilot studies of this thesis were used to inform the methodologies and protocols of the main investigations. Pilot study one provided an insight into force plate targeting during the acceleration phase of sprinting in a semi-elite rugby league population. Results highlighted that targeting had little impact on this highly-trained population. There was no significant impact on the participant's subjective comfort and majority of the kinematic measures of the lower extremities. Thus, during the main investigations participants were given familiarisation trials, feedback and additional adjustments were made to starting positions as required. Pilot studies two and three examined the variation of the measurement variables, these studies proved essential when interpreting the results of the main investigations. Pilot study two provided a valuable insight into the test-retest reliability of all dependant variables during early acceleration across an embedded force plate. The results of this study highlighted the generally high reliability of the test-retest measurement variables (e.g. velocity, contact, kinematic and kinetic). Pilot study three was used to investigate the weekly variation in sprint performance (10 and 20 m) of semi-elite rugby league players during the competitive phase of the season. Results highlighted the low variability of weekly sprint performance during the competitive phase of the season. As such, all sprint acceleration improvements following the intervention period should be distinguishable.

5. <u>Study 1: Impact of harness attachment point on kinetics and kinematics during sled towing</u>

Journal Articles

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2016) Impact of harness attachment point on kinetics and kinematics during sled towing. Journal of Strength and Conditioning Research, 30 (3) 768-776.

Conference Presentations

Bentley, I., Atkins, S., Edmundson, C., Metcalfe, J. and Sinclair, J. (2015) Influence of different harness attachment points on kinetics and kinematics during sled towing. Poster Presentation at the UKSCA Annual Conference, Chesford Grange, UK.

5.1. Introduction

In intermittent team-sports where the need to reach the ball first or be in position for a play to develop is decisive, speed is a crucial factor (Lockie, et al., 2013; Silvestre, et al., 2006). It is generally accepted that while MV is important in team-sports, the ability to accelerate is seen as being of greater significance (Dawson, et al., 2004; Murphy, et al., 2003). The kinematic and kinetic characteristics of the acceleration and maximal velocity phases of sprinting are quite different. The acceleration phase requires a greater forward trunk lean (Hunter, et al., 2005). Kugler et al., (2010) proposed that if the force vector points further forward (trunk lean) then the ratio of vertical to propulsive force will be biased towards forwards propulsion. In this instance, greater GRF can be applied without the negative effects associated with high vertical force application.

The different RST modalities, such as sled towing, parachute, and bungees, provide practitioners with alternative or additional sport specific training strategies. During ST, the external resistance is provided by the mass of the sled and the coefficient of friction between the sled and the surface (Cronin & Hansen, 2006). Sled loading strategies, as well as the sets and repetitions used to implement ST, remain equivocal (Alcaraz, et al., 2008; Cronin, et al., 2008; Lockie, et al., 2003; Maulder, et al., 2008; Murray, et al., 2005). There are several different methods by which sleds can be loaded; sled loading based on an absolute load or relative load relating to BM have been commonly employed, however these methods do not take the athlete's strength capabilities into consideration (Harrison & Bourke, 2009; West, et al., 2013). As such, loading sleds based on a reduction of sprint velocity is the preferred method (Alcaraz, et al., 2014; Clark, et al., 2010; Makaruk, et al., 2013; West, et al., 2013). Many studies have reported lighter sled loads to be the most effective as they have been shown to have less impact on contact time variables and joint angles (Kawamori, et al., 2014; Maulder, et al., 2008; Murray, et al., 2005). Several researchers have used sled loadings based on a 10% V_{Dec} to improve performance (Clark, et al., 2010; Makaruk, et al., 2013; Spinks, et al., 2007). Whilst information on loading strategies is undergoing a process of confirmation, there is a dearth of literature relating to the practicalities of ST, notably with regard to attachments for harness systems.

Lawrence et al., (2013) investigated the effects of different harness attachment points (shoulder and waist) on walking sled pulls. They reported differences in joint moments between the different attachments, concluding that the shoulder harness would challenge the knee extensors, and the waist harness the hip extensors. Over time, it is expected that the different harness attachments would lead to positive strength adaptations related to the aforementioned joints, thereby allowing practitioners to tailor the sled pulls specifically to areas of weakness.

Generally, sleds are attached to the athletes via a lead (3 m) and harness system, the most common being a shoulder or waist attachment point. At present, it is not known how the different harness attachment points impact on ST kinematics and kinetics. Therefore, the purpose of this study was to investigate the 3-D kinematics and kinetics of ST during the acceleration phase when sleds were loaded to cause a 10% V_{Dec} in sprint velocity. Participants completed sprint trials under different conditions (uninhibited sprinting, shoulder attachment and waist attachment). It was hypothesised that 1) the differences between the kinetic parameters would be negligible between all conditions, 2) both ST conditions would be significantly different from the uninhibited sprint trials in terms of the 3-D lower limb and trunk kinematics, and 3) the waist and shoulder attachment points would impact 3-D trunk, hip, knee and ankle joint kinematics differently. These findings will allow practitioners to alter their use of ST to better suit the acceleration phase.

5.2. Methods

5.2.1. Research design

This study used a cross-over design to compare the effects of different harness attachments during ST. Fourteen resistance trained males performed a series of 6 m sprints in three different conditions (uninhibited, with shoulder and waist attachments). The key dependant variables were the sagittal, coronal and transverse plane kinematic measures of the lower extremities and trunk, as well as the kinetic data obtained from the force platform and various contact time measures.

5.2.2. Participants

Fourteen resistance trained males (age: 26.7 ± 3.5 years; BM: 84.2 ± 12.3kg; stature: 174.4 ± 6.4 cm) participated in this study. All participants were resistance trained (≥ 2 years) with ST experience.

5.2.3. Procedures

One week prior to testing, all participants completed a familiarisation session. During this session participants were able to practice ST using the different harness attachment points.

The same sled was used during all the loaded trials. The sled was attached to the participants using a 3 m non-elasticated attachment cord, and either a double shoulder strap or single waist belt (Figure). Using a 6 m sprint as a baseline, sleds were loaded so that sprint velocity was reduced by 10% (waist condition), as recommended by Kawamori et al. (2014). Sprint velocity was monitored using the SmartSpeed infrared timing lights (Fusion Sport, Queensland, Australia).

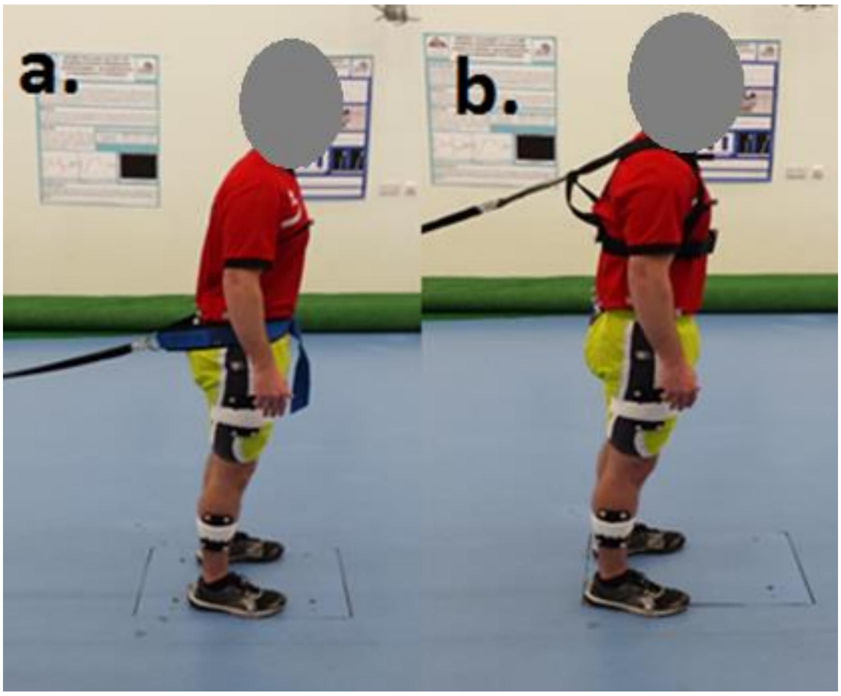

Figure 5.1: Examples of the harness attachments; a. waist harness and b. shoulder harness.

Measures were taken to ensure that no force plate targeting took place. Firstly, the familiarisation session was used to determine an individual starting position for each subject. Starting positions were adjusted so that each participant's right foot contacted the force plate on their third step. Starting positions of the ST trials were also adjusted accordingly and practiced until participants consistently landed on the force plate. To standardise starting positions, trials began in a 3-point position. Each participant chose to start with his left foot leading in the 3-point starting position. Regardless of the starting point, participants sprinted a total distance of 6 m.

Participants were asked not to participate in any physical activity 24 hours before the testing session. No food could be consumed during testing, though water was allowed. The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several short sprints building up to maximum intensity (4 x submaximal and 2 x maximal).

Previous research has shown that ST trials can impact on the kinematics of any subsequent uninhibited sprint trials (Kawamori, et al., 2014). Thus, the uninhibited sprint trials were completed before either of the sled conditions (shoulder or waist). Once the uninhibited sprint trials had been recorded, the ST trials were randomised using specialist software (Research Randomizer, www.randomizer.org/). Testing procedures were identical to those described previously in the familiarisation section. All participants had 2 minutes recovery between each of the sprint trials. Five trials were collected for each of the conditions. Again, participants sprinted a distance of 6 m in a 22 m lab. An embedded force platform, sampling at 1000 Hz, was positioned at approximately 3m from the start (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd). For the trials to be deemed successful, the whole foot had to contact the force platform. Trials were discarded in cases where any part of the foot did not land the force platform. Sprint times were generated for every trial, and any trials in which sprint velocity deviated more than ± 5% of the initial trial in that condition were not used in the final analysis. In this instance, an extended recovery period of 4 minutes was implemented, and trails were repeated.

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. The system was calibrated before every testing session. In order to determine stance leg kinematics (foot, shank, thigh and trunk segments) retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, acromion process (both), T12 and C7 (Cappozzo, et al., 1995). The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell et al., (1989) equations via the positions of the PSIS and ASIS markers. During dynamic trials the foot segment was tracked using the calcaneus, 1st and 5th metatarsal heads. Rigid cluster tracking markers were also positioned on the right shank and thigh segments (Cappozzo, et al., 1997). The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. The trunk was tracked using markers at both acromion processes, as well as the T12 marker. A static calibration was completed and used as reference for anatomical marker placement in relation to the tracking markers, after which all non-tracking markers were removed.

5.2.4. Data processing

Motion files were exported as C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and filtered at 12 Hz using a Butterworth 4th order filter. 3-D kinematics of the lower extremities and trunk were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). The relevant segments (thorax, thigh, shank and virtual foot) and reference segments (pelvis, thigh and shank) were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively. All kinematic waveforms were normalised to 100% of the stance phase and then processed trials were averaged. Various kinematic measures from the trunk, hip, knee and ankle joints were investigated: angle at foot-strike, angle at toe-off, peak angle, ROM from foot-strike to toe-off, and the Rel ROM (the angular displacement from foot-strike to peak angle). Resultant velocity at toe-off was calculated using the vertical and horizontal centre of mass. These variables were extracted from each of the five trials for each joint, data were then averaged within participants for a comparative statistical analysis.

Contact time was determined as time over which 20 N or greater of vertical force was applied to the force platform (Sinclair, et al., 2011). The durations of the braking and propulsive phases were based on anterior and posterior horizontal GRF. Peak GRF was determined for the following components: vertical, braking, propulsive. Vertical impulse was calculated as the area under the vertical force-time curve minus body weight impulse over the time of ground contact. The braking and propulsive impulses were determined by integrating all the negative and positive values of horizontal GRF, respectively, over the time of ground contact (Kawamori, et al., 2014). Net horizontal impulse was calculated as propulsive impulse minus the absolute value of braking impulse. Similarly, mean values of vertical and net horizontal GRF were obtained by dividing respective impulse values by the contact time, whereas mean braking and propulsive GRF were calculated by the time duration of braking and propulsive phases, respectively (Kawamori, et al., 2014). All GRF measures were expressed relative to total BM.

5.2.5. Statistical analysis

Descriptive statistics were calculated and presented as mean ± SD. One-way repeated measures ANOVA was used to compare the means of the different conditions (uninhibited, waist and shoulder) with the different outcome measures (velocity, contact time, kinematics, kinetics). The significance level was set at $p \leq 0.05$. Post hoc pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment to control for type I error. Effect sizes were calculated using partial Eta^2 (pη^2), in accordance with Cohen (1988) pη^2 = 0.2 considered small, pη^2 = 0.5 medium and pη^2 = 0.8 large.

5.3. Results

5.3.1. Reliability of measurement variables

In addition to examining the reliability of the test-retest measurement variables (Pilot Study 2) the effect of fatigue on sprint performance over the repeated trials was also investigated (uninhibited, shoulder and waist conditions). There were no significant differences in sprint velocity over the repeated trials ($p > 0.05$), thus indicating that fatigue had no impact on performance during the testing sessions.

Table 5.1 presents the stance phase velocity and contact time data. The kinetic measures are presented in Table 5.2. Tables 5.3 – 5.6 present the 3-D kinematic parameters from the trunk, hip, knee and ankle joints.

The mean sagittal, coronal and transverse plane angular kinematic waveforms were qualitatively similar (Figure 5.2), although statistical differences were observed at the trunk, hip, knee and ankle joints (Tables 5.3 – 5.6).

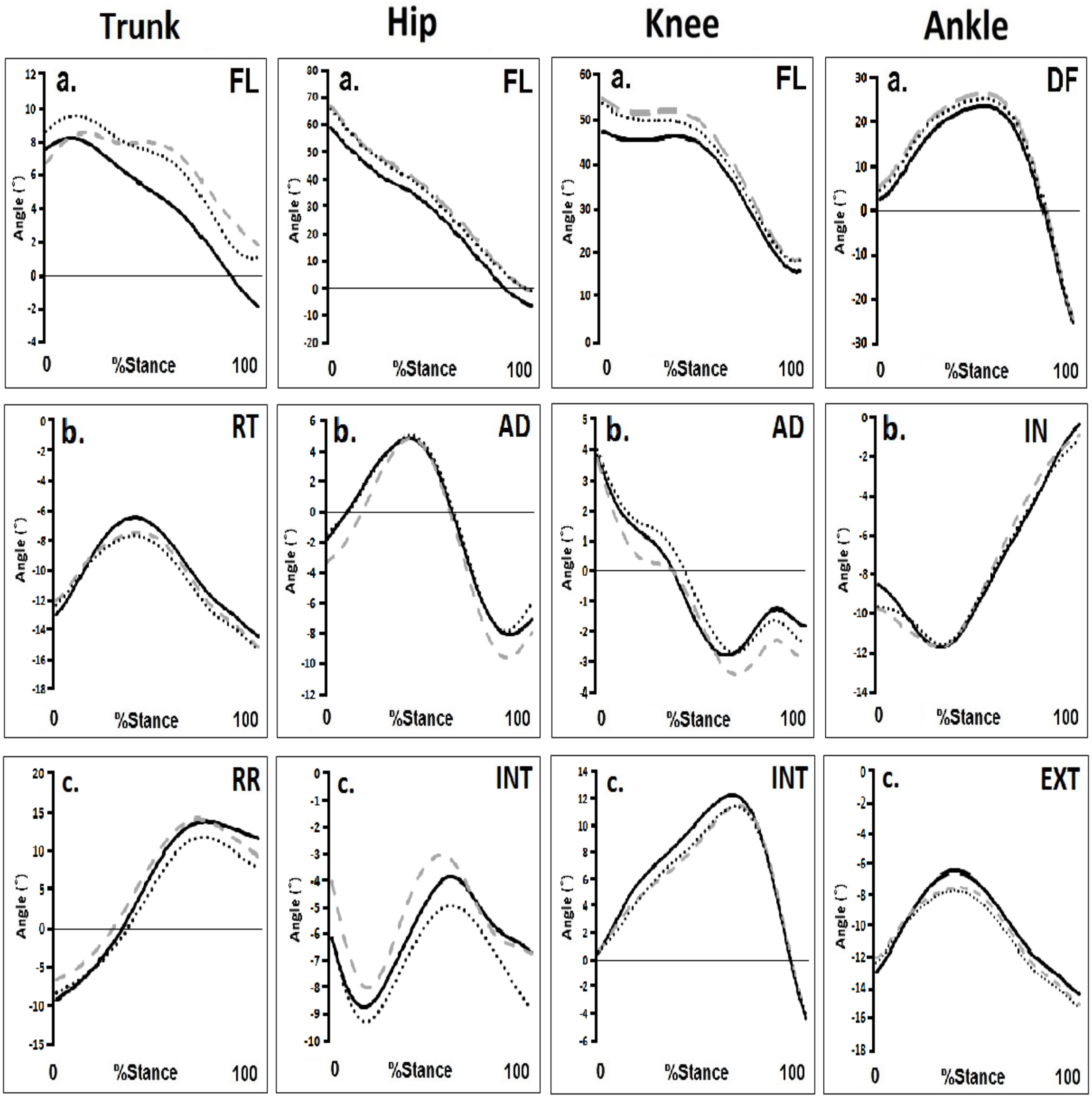

Figure 5.2: Mean trunk, hip, knee and ankle joint kinematics in the a) sagittal, b) coronal and c) transverse planes for the uninhibited (bold black line), shoulder (dashed grey line) and waist (dotted black line) conditions.

5.3.2. Velocity and contact variables

Table 5.1: Velocity and contact variables (means and standard deviations) under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	**Shoulder**	**Waist**
Velocity ($m.s^{-1}$)	5.61 ± 0.34	5.08 ± 0.3*	5.13 ± 0.31*
Contact time (s)	0.17 ± 0.02	0.19 ± 0.03*	0.19 ± 0.22*
Braking phase duration (s)	0.02 ± 0.02	0.02 ± 0.01	0.01 ± 0.00
Propulsive phase duration (s)	0.15 ± 0.02	0.18 ± 0.02*	0.17 ± 0.02*

* Significantly different from uninhibited sprinting $p \leq 0.05$

The results indicate that a significant main effect was observed for sprint velocity ($p < 0.001$, $p\eta^2 = 0.868$). Post hoc analysis revealed that sprint velocity was significantly reduced during the waist ($p < 0.001$) and shoulder ($p < 0.001$) trials compared to the uninhibited trials. There were no significant differences between the ST conditions ($p = 0.616$).

Similarly, a significant main effect was observed for the contact time of the stance leg ($p < 0.001$, $p\eta^2 = 0.66$). Post hoc analysis revealed that contact times of the stance leg were significantly shorter in the uninhibited condition compared to the waist ($p < 0.001$) and shoulder ($p < 0.001$) attachments. There was no significant difference between ST conditions ($p = 0.073$). Results highlighted a significant main effect for the duration of the propulsive phase of the stance ($p < 0.001$, $p\eta^2 = 0.480$). Post hoc tests indicated that the propulsive phase was significantly longer during the waist ($p = 0.024$) and shoulder ($p = 0.002$) attachment trials compared to the uninhibited sprint trials. There was no significant difference between ST conditions ($p = 0.841$).

5.3.3. Kinetic variables

Table 5.2: Kinetic variables (means and standard deviations) from the third step under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	Shoulder	Waist
Vertical peak force ($N \cdot kg^{-1}$)	10.28 ± 2.11	9.56 ± 2.07	9.77 ± 1.73
Vertical mean force ($N \cdot kg^{-1}$)	3.58 ± 1.20	3.14 ± 1.00	3.18 ± 0.98
Vertical impulse ($m \cdot s^{-1}$)	0.61 ± 0.16	0.60 ± 0.18	0.59 ± 0.18
Net horizontal mean force ($N \cdot kg^{-1}$)	3.23 ± 0.58	3.53 ± 0.52*	3.81 ± 0.48*
Net horizontal impulse ($m \cdot s^{-1}$)	0.55 ± 0.08	0.67 ± 0.08*†	0.71 ± 0.10*
Braking peak force ($N \cdot kg^{-1}$)	3.21 ± 1.58	3.18 ± 1.58	2.86 ± 1.64
Braking mean force ($N \cdot kg^{-1}$)	1.43 ± 0.90	1.48 ± 0.94	1.28 ± 0.91
Braking impulse ($m \cdot s^{-1}$)	0.03 ± 0.01	0.03 ± 0.01	0.02 ± 0.01
Propulsive peak force ($N \cdot kg^{-1}$)	6.90 ± 0.76	6.99 ± 0.81	7.16 ± 0.70
Propulsive mean force ($N \cdot kg^{-1}$)	3.81 ± 0.60	4.00 ± 0.54	4.26 ± 0.53*
Propulsive impulse ($m \cdot s^{-1}$)	0.58 ± 0.08	0.70 ± 0.07*	0.73 ± 0.09*

* Significantly different from uninhibited sprinting $p \leq 0.05$

† Significantly different from waist attachment condition $p \leq 0.05$

The results (Table 5.2) showed that there was a significant main effect for net horizontal mean force ($p < 0.001$, $p\eta^2 = 0.547$). Post hoc tests revealed that the uninhibited condition resulted in significantly lower net horizontal mean force than the shoulder attachment ($p = 0.020$) and the waist condition ($p = 0.001$). There was no significant difference between the ST conditions ($p = 0.056$). Similarly, there was a significant main effect for the net horizontal impulse between conditions ($p < 0.001$, $p\eta^2 = 0.742$). Post hoc tests indicated that both ST conditions were significantly greater than the uninhibited sprint trials ($p < 0.001$). The net horizontal impulses produced during the waist attachment condition were significantly larger than the shoulder condition ($p = 0.045$). There was a significant main effect for the propulsive mean force ($p = 0.006$, $p\eta^2 = 0.329$). Post hoc tests revealed that the waist condition led to significantly greater mean propulsive GRF than the uninhibited condition ($p = 0.004$). There was no significant difference between the ST conditions ($p = 0.056$). Finally, a significant main effect was observed for propulsive impulse measures ($p < 0.001$, $p\eta^2 = 0.746$). Post hoc tests revealed that the uninhibited condition resulted in significantly lower propulsive impulse measures than the shoulder attachment ($p < 0.001$) and the waist condition ($p < 0.001$). There was no significant difference between the ST conditions ($p = 0.063$).

5.3.4. Kinematic variables

Table 5.3: Trunk kinematics (means and standard deviations) under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	Shoulder	Waist
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	7.62 ± 9.42	6.75 ± 10.19	8.63 ± 10.10
Angle at toe-off (°)	-1.83 ± 8.70	1.89 ± 10.56	1.21 ± 10.71
Peak flexion (°)	9.42 ± 10.03	11.27 ± 10.45	11.96 ± 11.67
ROM (°)	9.46 ± 3.71	4.86 ± 3.90**	8.73 ± 3.86
Rel ROM(°)	1.81 ± 1.89	4.51 ± 3.52*	3.33 ± 3.56
	Y (+=right tilt/-=left tilt)		
Angle at foot-strike (°)	9.06 ± 4.42	10.37 ± 5.18	9.64 ± 5.27
Angle at toe-off (°)	-8.04 ± 3.96**	-11.31 ± 4.92	-9.92 ± 4.00
Peak tilt (°)	10.08 ± 4.99	10.99 ± 5.60	10.47 ± 5.71
ROM (°)	17.10 ± 5.15	21.68 ± 6.42**	19.56 ± 5.77
Rel ROM (°)	1.02 ± 1.80	.62 ± 1.50	.83 ± 1.53
	Z (+=right rotation/-=left rotation)		
Angle at foot-strike (°)	-9.09 ± 3.24**	-6.49 ± 4.06	-8.20 ± 3.37
Angle at toe-off (°)	11.78 ± 3.04**	9.39 ± 4.52	7.86 ± 4.20
Peak rotation (°)	14.77 ± 2.44	14.73 ± 3.88	12.39 ± 43**
ROM (°)	20.87 ± 4.76**	15.95 ± 5.69	16.06 ± 5.45
Rel ROM (°)	23.86 ± 3.83**	21.22 ± 4.43	20.59 ± 4.25

* Significantly different from uninhibited sprinting $p \leq 0.05$

**Significantly different from all other conditions $p \leq 0.05$

The results (Table 5.3) show that in the sagittal plane there was a significant main effect for the magnitude of ROM for the trunk ($p < 0.001$, $p\eta^2 = 0.783$). Post hoc tests revealed that trunk ROM was significantly lower during the shoulder condition compared to the uninhibited

($p < 0.001$) and waist ($p < 0.001$) conditions. A significant main effect was observed for the relative ROM of the trunk ($p = 0.001$, $p\eta^2 = 0.410$). Post hoc tests indicated that relative trunk ROM was significantly greater in the shoulder condition compared to the uninhibited sprinting condition ($p = 0.001$). In the coronal plane there was a significant main effect for trunk angle at toe-off ($p < 0.001$, $p\eta^2 = 0.536$). Further analysis revealed that the left tilt of the trunk was lower at toe-off during the uninhibited condition in comparison to the shoulder ($p < 0.001$) and waist ($p = 0.036$) trials. The results showed that there was a significant main effect for the magnitude of ROM for the trunk in the coronal plane ($p < 0.001$, $p\eta^2 = 0.523$). ROM was significantly greater in the shoulder harness condition compared to the waist ($p = 0.001$) and uninhibited trials (0.032). In the transverse plane there was a significant main effect for trunk angle at foot-strike ($p = 0.009$, $p\eta^2 = 0.407$). Post hoc analysis indicated that left rotation of the trunk was greater during the uninhibited sprint trials when compared to the shoulder ($p = 0.012$) and waist ($p = 0.001$) conditions. There was a significant main effect for trunk angle at toe-off ($p < 0.0019$, $p\eta^2 = 0.537$). Results showed that at toe-off right rotation of the trunk was greater during the uninhibited sprint trials when compared to the shoulder ($p = 0.031$) and waist ($p < 0.001$) conditions. There was a significant main effect for peak rotation of the trunk in the transverse plane ($p = 0.006$, $p\eta^2 = 0.328$). Post hoc tests revealed that peak rotation of the trunk was lower in the waist condition when compared to the shoulder ($p = 0.015$) and uninhibited trials (0.012). The results show that there was also a significant main effect for the magnitude of ROM for the trunk in the transverse plane ($p < 0.001$, $p\eta^2 = 0.5676$). ROM was significantly greater in the uninhibited sprint trials compared to the shoulder ($p < 0.001$) and waist conditions (0.000). Finally, a significant main effect was observed for the relative ROM of the trunk ($p < 0.001$, $p\eta^2 = 0.520$). Further analysis indicated that relative trunk ROM was significantly greater in the uninhibited trials compared to the shoulder (p = 0.001) and waist conditions (p = 0.001).

Table 5.4: Hip joint kinematics (means and standard deviations) from the stance limb under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	**Shoulder**	**Waist**
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	58.81 ± 8.29	67.08 ± 8.18*	65.80 ± 9.93*
Angle at toe-off (°)	-6.43 ± 6.40	-0.47 ± 9.22*	0.36 ± 8.33*
Peak flexion (°)	58.81 ± 8.29	67.08 ± 8.18*	65.80 ± 9.93*
ROM (°)	65.24 ± 6.74	67.55 ± 8.84	65.44 ± 9.74
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	-1.73 ± 5.41	-3.27 ± 6.72†	-1.37 ± 6.00
Angle at toe-off (°)	-7.08 ± 4.38	-7.91 ± 4.70†	-5.96 ± 5.16
Peak adduction (°)	5.36 ± 5.19	5.23 ± 5.51	5.34 ± 5.77
ROM (°)	5.98 ± 4.61	6.12 ± 5.82	6.02 ± 5.04
Rel ROM (°)	7.09 ± 3.70	8.50 ± 3.31†	6.72 ± 2.70
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-6.11 ± 7.44	-4.02 ± 7.82*	-6.16 ± 8.54
Angle at toe-off (°)	-6.66 ± 7.68	-6.71 ± 8.53	-8.76 ± 9.45
Peak external rotation (°)	-11.33 ±7.35	-11.72 ± 8.51	-13.02 ± 8.89
ROM (°)	5.22 ± 2.73	6.78 ± 3.19	6.86 ± 3.89
Rel ROM (°)	5.22 ± 2.88	7.70 ± 3.82*	6.86 ± 4.63

* Significantly different from uninhibited sprinting p ≤ 0.05

† Significantly different from waist attachment condition p ≤ 0.05

The results (Table 5.4) show that in the sagittal plane there was a significant main effect for hip joint angle at foot-strike ($p < 0.001$, $p\eta^2 = 0.473$). Flexion at the hip joint was significantly greater at foot-strike during the waist ($p = 0.015$) and shoulder ($p = 0.004$) attachment trials compared to the uninhibited trials. There was no significant difference between the ST trials ($p = 1.000$). Similarly, the results indicate that there was a main effect for hip joint angle at toe-off ($p = 0.002$, $p\eta^2 = 0.378$). Extension was greater in the uninhibited trials compared to the waist ($p = 0.015$) and shoulder ($p = 0.035$) attachment trials. There was no significant difference between ST trials ($p = 1.000$). A significant main effect was found for peak hip flexion ($p < 0.001$, $p\eta^2 = 0.473$). Peak hip joint flexion was significantly lower in the uninhibited sprint trials compared to the waist ($p = 0.015$) and shoulder ($p = 0.004$) attachment conditions. There was no significant difference between the ST sled trials ($p = 1.000$). In the coronal plane there was a significant main effect for hip joint angle at foot-strike ($p = 0.010$, $p\eta^2 = 0.300$). Post hoc analysis revealed that hip abduction was significantly greater during the shoulder condition compared to the waist condition ($p = 0.030$). There was no significant difference between uninhibited sprinting and the waist harness trials ($p = 0.080$). There was also a significant main effect for hip angle at toe-off ($p = 0.017$, $p\eta^2 = 0.332$). Further analysis showed that hip abduction was significant greater in the shoulder harness trials compared to the waist condition ($p = 0.001$). Differences between uninhibited sprinting and the waist harness trials were negligible ($p = 0.469$). There was a significant main effect for hip angle ROM in the coronal plane ($p = 0.006$, $p\eta^2 = 0.324$). Further analysis showed that hip joint ROM was significant greater in the shoulder condition compared to the waist condition ($p = 0.004$). Differences between uninhibited sprinting and the waist harness trials were negligible ($p = 0.092$). There was a significant main effect for hip joint angle at foot-strike in the transverse plane ($p = 0.010$, $p\eta^2 = 0.299$). The shoulder condition resulted in significantly more external rotation at foot-strike compared to the uninhibited trials ($p = 0.009$). There was no significant difference between the uninhibited and waist conditions ($p = 1.000$). Finally, there was a significant main effect for hip angle ROM in the transverse plane ($p = 0.006$, $p\eta^2 = 0.327$). Post hoc tests indicated that hip joint ROM was significant greater in the shoulder condition compared to uninhibited sprinting ($p = 0.002$). Differences between uninhibited sprinting and the waist harness trials were negligible ($p = 0.103$).

Table 5.5: Knee joint kinematics (means and standard deviations) from the stance limb under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	**Shoulder**	**Waist**
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	47.41 ± 5.48**	54.28 ± 6.60	53.27 ± 6.16
Angle at toe-off (°)	15.76 ± 5.79**	18.42 ± 5.60	18.95 ± 5.87
Peak flexion (°)	50.01 ± 5.38**	56.62 ± 5.49†	54.81 ± 5.68
ROM (°)	31.65 ± 6.57	35.86 ± 8.37*	34.33 ± 8.12
Rel ROM (°)	2.60 ± 4.80	2.34 ± 4.90	1.53 ± 3.31
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	.54 ± 7.50	.70 ± 8.18	.74 ± 7.96
Angle at toe-off (°)	-4.28 ± 4.11	-3.91 ± 5.62	-3.99 ± 6.26
Peak abduction (°)	-4.63 ± 3.62	-5.68 ± 3.59	-5.21 ± 3.77
ROM (°)	7.65 ± 4.58	7.57 ± 5.04	7.45 ± 4.96
Rel ROM (°)	8.98 ± 4.79	9.19 ± 5.74	8.89 ± 5.43
	Z (+=internal/-=external)		
Angle at foot-strike (°)	.54 ± 7.50	.70 ± 8.18	.74 ± 7.96
Angle at toe-off (°)	-4.28 ± 4.11	-3.91 ± 5.62	-3.99 ± 6.26
Peak internal rotation (°)	12.87 ± 5.95	12.08 ± 6.57	12.06 ± 7.50
ROM (°)	7.65 ± 4.58	7.57 ± 5.04	7.45 ± 4.96
Rel ROM (°)	12.33 ± 3.80	11.38 ± 4.94	11.32 ± 4.18

** Significantly different from all other conditions $p \leq 0.05$

† Significantly different from waist attachment condition $p \leq 0.05$

The results (Table 5) show that in the sagittal plane there was a significant main effect for knee joint angle at foot-strike ($p < 0.001$, $p\eta^2 = 0.732$). Post hoc tests revealed that knee joint flexion was significantly greater at foot-strike during the waist ($p < 0.001$) and shoulder ($p < 0.001$) attachment sled trials compared to the uninhibited sprint trials. There was no significant difference between ST conditions ($p = 0.441$). The results indicate that there was a significant main effect for knee joint angle at toe-off ($p = 0.003$, $p\eta^2 = 0.364$). Knee joint extension was greater in the uninhibited trials compared to the waist ($p = 0.018$) and shoulder ($p = 0.016$) attachment trials. There was no significant difference between ST trials ($p = 1.000$). A significant main effect was found for peak knee joint angle ($p < 0.001$, $p\eta^2 = 0.734$). Post hoc analysis revealed that all of the conditions were significantly different from one another. Knee flexion in the uninhibited trials was lower than the waist ($p = 0.001$) and shoulder ($p < 0.001$) attachment trials. Knee flexion was significantly greater in the shoulder attachment condition compared to the waist attachment trials ($p = 0.037$). Finally, there was a significant main effect for the magnitude of ROM at the knee joint ($p = 0.012$, $p\eta^2 = 0.29$). Post hoc tests indicated that knee joint ROM was significantly smaller in the uninhibited condition compared to the shoulder attachment condition ($p = 0.036$). There was no significant difference between the uninhibited and waist attachment trials ($p = 0.461$). The analysis revealed that harness attachment point had no significant impact on knee joint kinematics in the coronal or transverse planes when compared to uninhibited sprinting ($p > 0.05$).

Table 5.6: Ankle Joint kinematics (means and standard deviations) from the stance limb under the different conditions (uninhibited, shoulder and waist).

	Uninhibited	**Shoulder**	**Waist**
	X (+=dorsi-flexion/-=plantar-flexion)		
Angle at foot-strike (°)	2.72 ± 5.89**	5.85 ± 5.34	4.76 ± 6.69
Angle at toe-off (°)	-25.40 ± 4.01	-24.34 ± 3.44	-24.20 ± 3.05
Peak dorsi-flexion (°)	24.32 ± 4.82**	27.08 ± 6.00	26.00 ± 5.40
ROM (°)	28.11 ± 5.00	30.19 ± 3.95	28.96 ± 5.22
Rel ROM (°)	21.61 ± 6.23	21.22 ± 5.93	21.24 ± 5.82
	Y (+=inversion/-=eversion)		
Angle at foot-strike (°)	-8.50 ± 6.33	-9.72 ± 6.76	-9.63 ± 6.79
Angle at toe-off (°)	-.35 ± 5.76	-.83 ± 5.72	-1.11 ± 5.76
Peak eversion (°)	-12.56 ± 5.22	-12.95 ± 5.59	-12.86 ± 5.49
ROM (°)	8.19 ± 3.56	8.91 ± 3.61	8.74 ± 4.43
Rel ROM (°)	4.06 ± 2.86	3.24 ± 3.08	3.22 ± 3.53
	Z (+=external/-=internal)		
Angle at foot-strike (°)	-12.93 ± 5.41	-12.00 ± 6.11	-12.29 ± 7.01
Angle at toe-off (°)	-14.42 ± 5.69	-15.09 ± 5.47	-15.31 ± 6.57
Peak external rotation (°)	-5.44 ± 5.47	-6.00 ± 6.41	-6.07 ± 6.67
ROM (°)	3.06 ± 1.73	4.04 ± 2.83	4.06 ± 2.31
Rel ROM (°)	7.49 ± 4.47	6.00 ± 4.76	6.22 ± 4.88

** Significantly different from all other conditions $p \leq 0.05$

The results (Table 5.6) show that in the sagittal plane there was a significant main effect for ankle joint angle at foot-strike ($p = 0.001$, $p\eta^2 = 0.4$). Post hoc tests indicated that dorsi-flexion was significantly greater at foot-strike during the waist ($p = 0.041$) and shoulder ($p = 0.006$) attachment trials compared to the uninhibited sprint trials. There was no significant difference between the ST conditions ($p = 0.494$). Finally, a significant main effect was found for peak ankle dorsi-flexion ($p < 0.001$, $p\eta^2 = 0.459$). Peak ankle dorsi-flexion was significantly lower in the uninhibited trials compared to the waist ($p = 0.034$) and shoulder ($p = 0.002$) attachment conditions. There was no significant difference between the ST trials ($p = 0.248$). Results showed that harness attachment point had no significant impact on ankle joint kinematics in the coronal or transverse planes when compared to uninhibited sprinting ($p > 0.05$).

5.4. Discussion

The aim of this investigation was to examine the kinematics and kinetics of ST when different harness attachment points were used (shoulder and waist). Sleds were loaded to cause a 10% reduction in sprint velocity over a 6 m distance. To the authors knowledge this is the first study to examine the impact of different harness attachments on the lower body 3-D kinematics during ST. This study will have practical implications to strength and conditioning practitioners looking to improve acceleration performance.

Results show that there were significant kinetic differences between the ST conditions and the uninhibited sprint trials, supporting the rejection of the first hypothesis. These findings are contradictory to those of Kawamori et al. (2014) who measured various GRF variables with a similar 10% BM sled loading. Both ST conditions were significantly different from the uninhibited condition in numerous parameters: net horizontal mean force, net horizontal impulse, and propulsive impulse. Again, in contrast to Kawamori et al. (2014) the ST conditions in this study resulted in longer ground contact times and propulsive phase contact times compared to the uninhibited sprint trials. The increased propulsive contact times were not surprising as more propulsive force was required to overcome the extra resistance provided by the ST. However, the increased net horizontal force and propulsive impulse measures may also be explained by longer ground contact times thus allowing more time to push in a horizontal direction.

Previous studies have reported that a 10% sled loading (BM or velocity reduction) had no significant acute impact on sprint kinematics (Murphy, et al., 2003; Murray, et al., 2005). If this proved to be the case, then question would need to be asked about how loading with such a strategy would benefit performance. During sprints one of or both the kinetics and kinematics would need to be altered for adaptations to take place. In contrast, our hypothesis was that sprint kinematics during ST would be different from the uninhibited sprint condition. The results of the present study supported this. There were significant differences between uninhibited sprint trials and both ST conditions in the sagittal plane at the hip, knee and ankle joints. Peak hip flexion, flexion at foot-strike, and flexion at toe-off were greater during the ST trials. Similarly knee joint flexion was significantly greater for the ST conditions. Dorsi-flexion was significantly greater in the ST conditions at foot-strike as were the peak angles recorded. These findings contradict the theory that the 10% loading is the ideal because kinematics were not significantly altered (Maulder, et al., 2008; Murray, et al., 2005). It is beyond the scope of the present study to suggest what the longer-term implications of these alterations might be.

Finally, the third hypothesis was also accepted. Both harness attachment points altered kinematics differently. During ST, the harness attachment points affected the athletes differently to those reported previously in heavy walking sled pulls (Lawrence, et al., 2013). Sagittal trunk ROM was significantly lower during the shoulder attachment condition compared to the other conditions (Table 5.3). In contrast, sagittal plane trunk relative ROM was only significantly greater in the shoulder condition compared to the uninhibited trials. The shoulder attachment led to significantly greater peak knee flexion when compared to the waist harness. The knee joint ROM in the shoulder condition was significantly greater than the uninhibited condition, whereas differences between the waist condition and the other conditions were negligible (Table 5.5). It is speculated that such an adaptation may allow the participants to lower their centre of mass and increase horizontal force application.

Unexpectedly, the ST harness attachment points also impacted stance phase kinetics differently. The waist harness led to significantly greater net horizontal impulse compared to the shoulder attachment condition. Furthermore, the waist condition resulted in significantly greater propulsive mean GRF when compared to the uninhibited sprint condition. Importantly, none of the ST contact time measures were significantly different. Previous researchers (Kawamori, et al., 2013) have highlighted net horizontal impulses and propulsive force as being key to achieving high acceleration, as such it would appear that the waist harness is more suitable when training for the acceleration phase of sprinting. It seems apparent that the kinematic alterations caused by the waist harness changed the force vector, resulting in greater net horizontal impulse.

Results highlighted differences in trunk angle between ST conditions. Previous investigations have also discussed the importance of trunk lean during ST. Alcaraz et al. (2008) suggested that shoulder attachments would increase trunk lean to a greater extent than a waist harness attachment point. They reported, that due to the applied load being higher than the hips (pivot point), the athletes would have to compensate and increase trunk lean. It was proposed that the greater trunk lean would impact on the athlete's force vector so that more propulsive GRF was applied compared to vertical GRF. Conversely, when sleds were attached via waist belts the load passed through the hips, as such these attachments did not promote an increased trunk lean (Alcaraz, et al., 2008). As such, the authors suggested that shoulder harness attachments would be more beneficial when training for the acceleration phase, and waist attachments could be more suited to the MV phase (Alcaraz, et al., 2014). In contrast, results from this study indicated that negligible differences in peak flexion, angle at foot-strike and toe-off between exist between ST conditions at the trunk. The only differences were that trunk ROM was significantly lower during the shoulder attachment condition when compared to the other conditions. Interestingly, the trunk relative ROM was only significantly greater in the shoulder condition compared to the uninhibited trials. Importantly, kinematic differences between the waist and uninhibited sprint conditions were negligible. Therefore, our findings suggest that when the ST harness attachment is further away from the hips it alters trunk kinematics to a greater extent, thus reducing net horizontal impulse.

It appears that the 10% V_{Dec} loading strategy used in the study was not sufficient to cause kinematic alterations in the coronal and transverse plane kinematics at the hip or knee joints. Heavier sled loading may have a significant impact in all planes of motion of the lower extremities. Trunk kinematics were altered to a greater extent in all planes of motion when compared to the uninhibited trials. There were several coronal plane kinematic changes at the trunk, such as decreased trunk tilt during uninhibited trials compared to both ST conditions, this may be a compensation strategy. Thus, enabling the participants to further increase the body lean created by greater knee flexion and an attempt to lower centre of mass further. Alternatively, this may have been caused by the limited trunk rotation exhibited during the ST conditions compared to the uninhibited trials. Trunk and pelvis rotations are important during sprint running, at foot-strike thorax rotations are typically opposite to those of the pelvis. These rotations minimise the displacement of centre of mass (Preece, et al., 2016). Hip joint kinematics were affected in the coronal and transverse planes during the shoulder condition only. During shoulder trials hip abduction was greater at foot-strike, toe-off and the Rel ROM measures were higher when compared to the waist attachment trials. Similarly, in the transverse plane only the shoulder trials led to significantly different kinematic measures. Results indicate there was less external rotation at foot-strike and greater Rel ROM measures compared to uninhibited sprinting. Although, there were coronal and transverse plane kinematic changes in both ST conditions the shoulder trials appear to have a greater impact compared to all other conditions. The transverse plane pelvis and trunk kinematics appear key to stabilising centre of mass, as such significant changes may have a negative impact on sprint performance.

The all-male resistance trained testing population is a limitation. Previous investigations have demonstrated that females exhibit distinct lower body kinematics when compared with males (Sinclair, et al., 2012). As such, the results are limited to this population and may not be applicable to female athletes. Additionally, this study only looked at the harness attachment implications at a set sled loading (10% V_{DEC}). Numerous investigations have highlighted that the kinematic and kinetic alterations differ greatly dependant on sled loading (Cronin, et al., 2008; Kawamori, et al., 2014; Maulder, et al., 2008; Murray, et al., 2005). Thus, the findings from the present study may not be transferable to different sled loading strategies or the other phases of sprinting. Finally, feedback from the participants indicated that although the majority preferred the waist harness some favoured the shoulder harness attachment. In this instance although not optimal the coach may decide to use the shoulder attachment point.

5.4.1. Conclusion

The current investigation provides new information regarding the influence of different harness attachment configurations on the kinetics and kinematics of ST. The results indicated that ST, with the commonly prescribed loading to cause a 10% V_{Dec} in sprint velocity, will alter kinematics at the trunk, hip, knee, and ankle joints. Similarly, both ST conditions led to significant GRF alterations when compared to uninhibited sprinting. The kinematic and kinetic alterations observed in this study differ between the waist and shoulder attachment points. Results suggest that the waist attachment point appears to be the most suitable when training for the acceleration phase of sprinting. ST with this attachment led to fewer 3-D kinematic alterations and greater net horizontal impulses when compared to the shoulder attachment trials. Future research is necessary to explore how the observed harness attachment alterations impact on sprint performance/kinematics/kinetics after prolonged ST training interventions.

6. <u>Study 2: The effect of velocity-based loading on acceleration kinetics and kinematics during sled towing</u>

Journal Articles

Bentley, I., Sinclair, J., Atkins, S., Metcalfe, J., and Edmundson, C. (In Press) Effect of velocity-based loading on acceleration kinetics and kinematics during sled towing. Journal of Strength and Conditioning Research.

6.1. Introduction

The different sprint phases are regularly tested and monitored as they are considered key determinants of overall sprint performance (Petrakos, et al., 2016). Research shows that rapid acceleration requires a powerful drive of the arms, hips and legs resulting in short contact times and an increased stride frequency (Maulder, et al., 2008; Murphy, et al., 2003). Alternatively, other studies have placed a greater emphasis on a forward body lean (45 degrees), thereby increasing horizontal force application (Hunter, et al., 2005; Kugler & Janshen, 2010).

Sprint specific training modalities may have a better transfer to performance compared to non-specific strength training (Young, 2006). RST methods such as sled towing, parachutes, weighted vests, bungees and uphill running offer the practitioner an alternative approach to sprint training. RST methods are performed in a horizontal direction, and involve the relevant muscles, velocities and ranges of motion to those of uninhibited sprinting (Alcaraz, et al., 2014; Spinks, et al., 2007). ST provides an external load in the form of a sled towed via a shoulder or waist harness and cord, behind the athlete. The mass of the sled and the friction coefficient between the sled and the ground surface affect external load and the subsequent impact on performance (Linthorne & Cooper, 2013). Sleds are generally loaded based on a % BM or % V_{Dec} (Kawamori, et al., 2014; Spinks, et al., 2007). However, loadings based on a percentage BM do not account for individual variations in strength, power or technical ability. As such, loading sleds based on V_{Dec} over a given distance is the preferred approach (Petrakos, et al., 2016).

Acute ST studies are important as they allow researchers to investigate how different loading strategies can alter kinetics and kinematics. These acute changes may determine long-term adaptations. Sled loading strategies have varied greatly between studies, some researchers have investigated loads as light as 5% BM (Petrakos, et al., 2016) and others as heavy as 80% BM (Morin, et al., 2017). Unsurprisingly, findings suggest that as sled loadings increased, sprint kinematics (velocity, contact time, stride length and stride frequency etc.) were changed to a greater extent (Lockie, et al., 2003; Monte, et al., 2016; Murray, et al., 2005). As such, some investigations have recommended sled loadings of approximately 10% BM or 10% V_{Dec} in order to minimise the alterations to sprint kinematics (Maulder, et al., 2008). However, recent investigations have reported that moderate to heavy sled loadings may be required in order to provide an optimal overload for sprint acceleration (Monte, et al., 2016). These loadings may increase horizontal GRF, which have been shown to be a key determinant of sprint acceleration (Morin, et al., 2011). Kinetics and lower body kinematics have been explored over a range of different ST loads, despite numerous investigations (Kawamori, et al., 2014; Maulder, et al., 2008; Murray, et al., 2005) there is little agreement on the optimum sled loading to develop the acceleration phase.

The purpose of this study was to investigate the kinetics and 3-D kinematics of ST during the early acceleration phase of sprinting in a semi-elite rugby league population using a range of different loads. Participants completed trials with a range of different sled loads (10, 15 and 20% V_{Dec}) as well as uninhibited trials. It was hypothesised that (a) the disruption to 3-D lower limb and trunk kinematics would be greater as sled loadings increased, (b) measures of propulsive peak force would be greatest during the 20% V_{Dec} sled trials, and (c) measures of propulsive impulse would be largest during the 20% V_{Dec} sled condition. The findings will allow practitioners to understand the impact of different loading strategies and more accurately prescribe ST for the early acceleration phase.

6.2. Methods

6.2.1. Research design

This study used a cross-over design to compare the effects of different ST loadings and uninhibited sprinting. Twelve rugby league players performed a series of 6 m sprints in four different conditions (Uninhibited, 10, 15 and 20% V_{Dec}). The key dependant variables were the sagittal, coronal and transverse plane kinematic measures of the lower extremities and trunk, the kinetic data obtained from the force platform and various contact time measures.

6.2.2. Participants

Twelve semi-elite rugby league athletes (age: 18.9 ± .6 years; BM: 90.2 ± 10.0 kg; stature: 1.80 ± 0.06 m) participated in this study. All participants were resistance trained (≥ 3 years) with ST experience and provided informed consent before attending the testing sessions.

6.2.3. Procedures

One week prior to testing, all participants completed a familiarisation session. The same sled was used throughout testing. The sled was attached to the participants using a 3 m non-elasticated attachment cord and waist belt. Using a 6 m uninhibited sprint as a baseline, sleds loadings (10, 15 and 20%) were determined in a random order. Sprint times were recorded using infrared timing lights (SmartSpeed Ltd., Fusion Sports, Queensland, Australia) and sled loadings were adjusted to reduce 6 m average velocity by the appropriate percentages. Mean sled loadings (sled plus additional load) based on % V_{Dec} and the equivalent % BM values are shown in Table 6.1.

Table 6.1: Sled Loadings by percent of V_{Dec} (means and standard deviations).

Loading Strategy	10%	15%	20%
% V_{Dec} (kg)	11.6 ± 2.3	17 ± 4.4	22.9 ± 5.6
Equivalent % BM	12.8 ± 2.1	18.8 ± 3.9	25.4 ± 5.3
Velocity (m.s-1)	4.94 ± .26	4.69 ± .26	4.44 ± .29

Again, measures were taken to ensure that no force plate targeting occurred. Firstly, the familiarisation session was used to determine an individual starting position for each subject. Starting positions were adjusted so that each participant's right foot (dominant) contacted the force plate on their third step. Starting positions of the ST trials were also adjusted accordingly and practiced until participants could consistently land on the force plate. To standardise starting positions, trials began in a 3-point position. All participants chose to start with their left foot leading in the 3-point starting position. Regardless of the starting point, participants sprinted a total distance of 6 m. The semi-elite participants utilised in this study generally required fewer familiarisation sprints, this may be due to more consistent movement patterns and foot placement.

Participants were asked not to participate in any physical activity 24 hours before the testing session. The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several short sprints building up to maximum intensity (4 x submaximal and 2 x maximal).

Previous research has shown that ST trials can impact on the kinematics of any subsequent uninhibited sprint trials (Kawamori, et al., 2014). As such, the uninhibited sprint trials were completed before any of the sled trials (10%, 15% and 20% V_{Dec}). Once the uninhibited sprint trials had been recorded, the ST trials were randomised using specialist software (Research Randomizer, www.randomizer.org/). Testing procedures were identical to those described previously in the familiarisation section. All participants had 3 minutes recovery between each of the sprint trials. Five trials were collected for each condition. Again, participants sprinted 6 m in a 22 m lab. The surface friction coefficient (μ) of the lab (μ = 0.41) was determined using methods developed by Linthorne & Cooper (2013). An embedded force platform, sampling at 1000 Hz, was positioned at approximately 3 m from the start (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd). In order for the trials to be deemed successful, the whole foot had to contact the force platform. Trials were discarded in cases where any part of the foot did not land the force platform. Sprint times were generated for every trial, and any trials in which sprint velocity deviated more than ± 5% of the initial trial in that condition were not used in the final analysis. In this instance, an extended recovery period of 4 minutes was implemented, and trials were repeated.

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. In order to determine stance leg kinematics of the trunk, thigh, shank, and foot segments, retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, acromion process (both), T12 and C7 (Cappozzo, et al., 1995). The trunk was tracked using markers at both acromion processes, as well as the T12 marker. The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell et al. (1989) equations via the positions of the PSIS and ASIS markers. The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. Rigid cluster tracking markers were also positioned on the right thigh and shank segments (Cappozzo, et al., 1997). Knee joint centre was delineated as the mid-point between the femoral epicondyle markers. The ankle joint centre was identified as the mid-point between the malleoli markers. During dynamic trials the foot segment was tracked using the calcaneus, 1st and 5th metatarsal heads. A static calibration was completed and used as reference for anatomical marker placement in relation to the tracking markers, after which all non-tracking markers were removed.

6.2.4. Data Processing

Motion files collected through the Qualisys track manager software and exported as C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and filtered with a cut-off frequency of 12 Hz using a Butterworth 4th order filter to adequately suppress motion artefacts without inducing excessive smoothing of the traces (Debaere, et al., 2013) (Slawinski, et al., 2013). 3-D kinematics of the lower extremities and trunk were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). The relevant segments (thorax, thigh, shank and virtual foot) and reference segments (pelvis, thigh and shank) were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively. The stance phase was determined as time over which 20N or greater of vertical force was applied to the force platform (Sinclair, et al., 2011). Kinematic waveforms were time-normalised to 100% of the stance phase and then all processed trials were averaged. Various kinematic measures from the trunk, hip, knee and ankle joints were investigated: angle at foot-strike, angle at toe-off, peak angle, ROM, and the Rel ROM. Resultant velocity at toe-off was calculated using the vertical and horizontal centre of mass. These variables were extracted from each of the five trials for each joint, data were then averaged within participants for a comparative statistical analysis.

Force plate data was collected through the Qualisys track manager software and exported to Visual 3-D (C-Motion Inc., Germantown, USA) for processing. The durations of the braking and propulsive phases were based on anterior and posterior horizontal GRF. Peak GRF was determined for the following components: vertical, braking, propulsive. Vertical impulse was calculated as the area under the vertical force-time curve (using a trapezoidal function) minus body weight impulse over the time of ground contact. The braking and propulsive impulses were determined by integrating all the negative and positive values of horizontal GRF, respectively, over the time of ground contact (Kawamori, et al., 2014; Kawamori, et al., 2013). Net horizontal impulse was calculated as propulsive impulse minus the absolute value of braking impulse. All impulse measures were normalised to BM so they represent changes in velocity of centre of mass during ground contact (Mullineaux, et al., 2006). Similarly, mean values of vertical and net horizontal GRF were obtained by dividing respective impulse values by the contact time. Mean braking and propulsive GRF were calculated by dividing the respective impulse values by the time duration of the braking and propulsive phases, respectively. GRF measures were also normalised relative to BM (Kawamori, et al., 2014).

6.2.5. Statistical Analysis

Descriptive statistics were calculated and presented as mean ± SD. Dependant variables were examined using the uninhibited sprint trials. Test-retest reliability and within-subject variation was evaluated using ICC and CV%. Magnitudes of ICC were classified according to the following thresholds: 0.9 nearly perfect; 0.7–0.9 very large; 0.5–0.7 large; 0.3–0.5 moderate; and 0.1–0.3 small (Hopkins, 2002). One-way repeated measures ANOVA were used to compare the means of the different conditions (Uninhibited, 10, 15 and 20% V_{Dec}) with the different outcome measures (velocity, contact time, kinetics and kinematics). Post hoc pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment to control for type I error. Mauchly's test was used to confirm sphericity for each analysis. If the assumption of sphericity was violated, a Greenhouse-Geisser adjustment was used. Effect sizes were calculated using partial eta^2 ($p\eta^2$), in accordance with Cohen (1977) $p\eta^2 = 0.2$ considered small, $p\eta^2 = 0.5$ medium and $p\eta^2 = 0.8$ large. Significance levels were set at $p \leq 0.05$.

6.3. Results

6.3.1. Reliability of Measurement Variables

In addition to examining the reliability of the test-retest measurement variables (Pilot Study 2) the effect of fatigue on sprint performance over the repeated trials was also investigated (uninhibited, 10, 15 and 20% conditions). There were no significant differences in sprint velocity over the repeated trials ($p > 0.05$), thus indicating that fatigue had no impact on performance.

Table 6.2 presents the stance phase velocity and contact time data. The kinetic measures are presented in Table 6.3. Tables 6.4 – 6.7 present the 3-D kinematic parameters from the trunk, hip, knee and ankle joints. Figure 6.1 presents the mean sagittal plane angular kinematics during the stance phase.

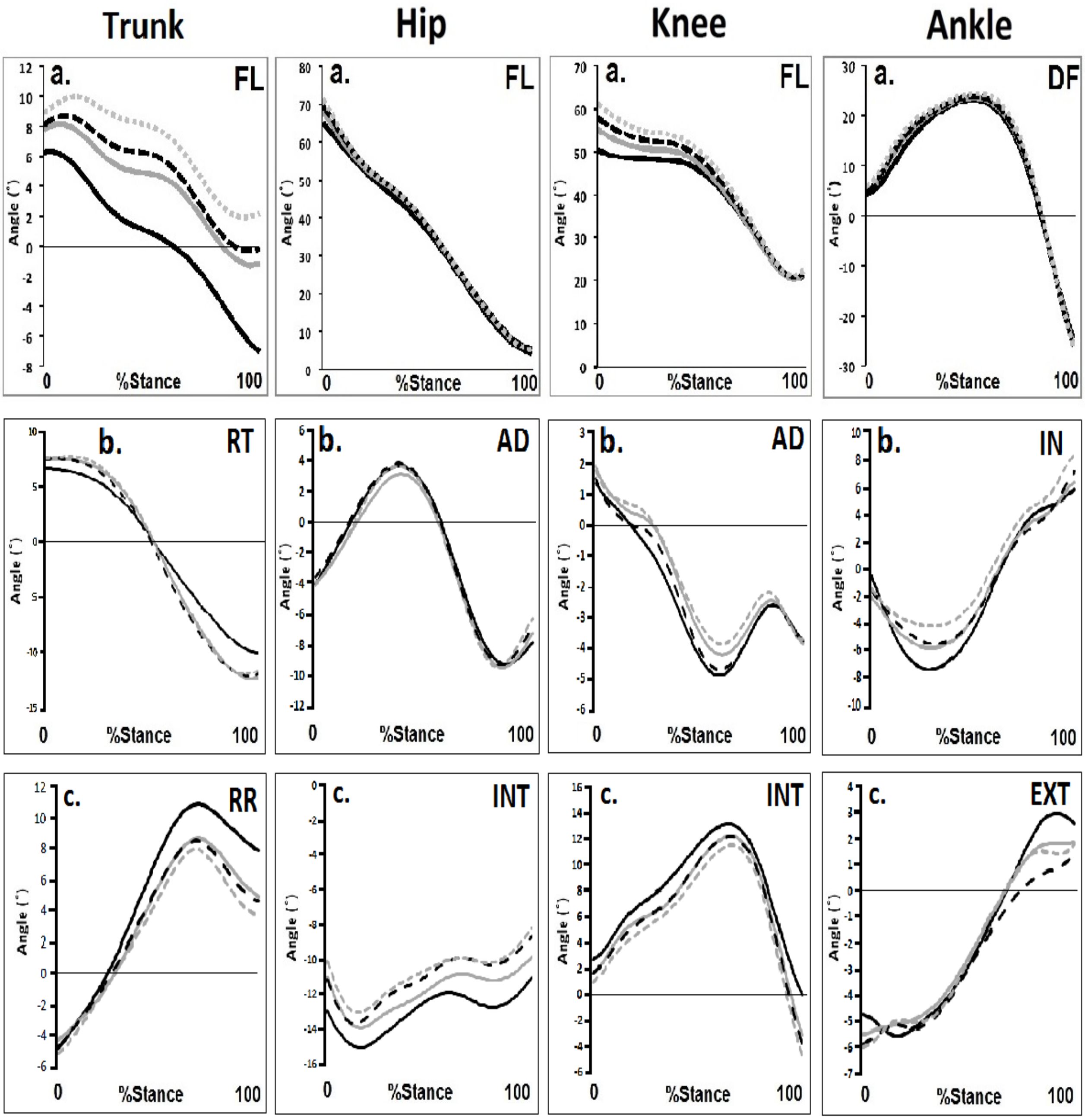

Figure 6.1: Mean trunk, hip, knee and ankle joint kinematics in the a) sagittal, b) coronal and c) transverse planes for the uninhibited (bold black line), 10% (bold grey line), 15% (dashed black line) and 20% (dotted grey line) conditions.

6.3.2. Velocity and contact variables

Table 6.2: Velocity and contact variables (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
Velocity (m.s-1)	5.49 ± .25**	4.94 ± .26**	4.69 ± .26**	4.44 ± .29**
Contact time (s)	.17 ± .01**	.19 ± .01**	.20 ± .01**	.21 ± .01**
Brake time (s)	.02 ± .01	.02 ± .01	.01 ± .01	.01 ± .01
Propulsive time (s)	.15 ± .01**	.17 ± .01**	.19 ± .01**	.20 ± .02**

** Significantly different from all other conditions $p \leq 0.05$

Table 6.2 presents the stance phase contact time and velocity data. There was a significant main effect for sprint velocity ($p < 0.001$, $p\eta^2 = 0.946$). Velocity was reduced significantly in all sled conditions as loading increased ($p = 0.001$). Similarly, a significant main effect was observed for the contact time of the stance leg ($p < 0.001$, $p\eta^2 = 0.807$). Contact times increased significantly in all sled conditions as loading increased ($p < 0.001$). The results showed a significant main effect for the duration of the propulsive phase ($p < 0.001$, $p\eta^2 = 0.767$). All sled conditions resulted in significantly greater propulsive times than uninhibited sprinting ($p < 0.001$), propulsive times increased with loading ($p < 0.05$).

6.3.3. Kinetic variables

Table 6.3: Kinetic variables (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
Vertical peak force ($N.kg^{-1}$)	9.53 ± 1.69	8.01 ± 1.80	8.33 ± 2.01	8.26 ± 1.87
Vertical mean force ($N.kg^{-1}$)	2.94 ± .94	2.19 ± 1.07	2.23 ± 1.19	2.03 ± .87*
Vertical impulse ($m.s^{-1}$)	.51 ± .16	.42 ± .21	.45 ± .24	.43 ± .20
Net horizontal mean force ($N.kg^{-1}$)	3.39 ± .27**	3.71 ± .26	3.83 ± .30	3.94 ± .36
Net horizontal impulse ($m.s^{-1}$)	.58 ± .03**	.71 ± .04**	.76 ± .05**	.83 ± .09**
Braking peak force ($N.kg^{-1}$)	3.09 ± 1.72	2.53 ± 1.50	2.19 ± 1.35	2.08 ± 1.23
Braking mean force ($N.kg^{-1}$)	1.43 ± 1.04	1.00 ± .78	.93 ± .70	.85 ± .63
Braking impulse ($m.s^{-1}$)	.02 ± .02	.01 ± .02	.01 ± .01	.01 ± .01
Propulsive peak force ($N.kg^{-1}$)	6.73 ± .42	6.84 ± .50	6.92 ± .58	7.00 ± .57
Propulsive mean force ($N.kg^{-1}$)	3.93 ± .29	4.17 ± .28	4.21 ± .40	4.31 ± .45*
Propulsive impulse ($m.s^{-1}$)	.61 ± .03**	.72 ± .05**	.77 ± .05**	.84 ± .09**

* Significantly different from uninhibited sprinting $p \leq 0.05$

** Significantly different from all other conditions $p \leq 0.05$

The results (Table 6.3) showed a significant main effect for vertical mean force ($p = 0.003$, $p\eta^2 = 0.346$). Vertical mean force during the 20% loading condition was significantly lower than the uninhibited trials ($p = 0.024$). There was a significant main effect for net horizontal mean force ($p < 0.001$, $p\eta^2 = 0.672$). Post hoc tests indicated that net horizontal mean force was greater in all ST conditions compared to the uninhibited trials ($p < 0.01$). There was no significant difference between ST conditions ($p > 0.05$). There was a significant main effect for the measure of propulsive mean force ($p = 0.002$, $p\eta^2 = 0.377$). The propulsive mean force recorded during the 20% loading was significantly higher than that of the uninhibited condition ($p = 0.032$). Again, there was no significant difference between ST conditions (p >

0.05). There was a significant main effect for the net horizontal impulse between conditions ($p < 0.001$, $p\eta^2 = 0.854$). Finally, a significant main effect was observed for propulsive impulse measures ($p < 0.001$, $p\eta^2 = 0.851$). Net horizontal and propulsive impulse measures were significantly greater as sled loading increased ($p < 0.05$).

6.3.4. Kinematic variables

Table 6.4: Trunk kinematics (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
		X (+=flexion/-=extension)		
Angle at foot-strike (°)	6.49 ± 7.28	8.02 ± 8.68	8.12 ± 8.24	9.04 ± 9.80
Angle at toe-off (°)	-6.60 ± 7.57**	-.95 ± 9.12	-.07 ± 8.68	2.49 ± 10.37
Peak flexion (°)	7.24 ± 6.91	9.35 ± 8.76	9.62 ± 8.28	11.47 ± 9.70
ROM (°)	13.09 ± 6.59	8.98 ± 4.70	8.19 ± 3.07	7.16 ± 3.20
Rel ROM (°)	.74 ± 1.41	1.33 ± 1.51	1.51 ± 1.57	2.43 ± 1.99*
		Y (+=right tilt/-=left tilt)		
Angle at foot-strike (°)	6.43 ± 4.15	7.68 ± 4.31	7.58 ± 4.02	7.64 ± 3.8
Angle at toe-off (°)	-10.51 ± 4.88	-12.33 ± 4.42*	-12.05 ± 4.03	-11.52 ± 4.73
Peak tilt (°)	-10.62 ± 4.96	-12.59 ± 4.58*	-12.33 ± 4.13	-12.0 ± 4.64
ROM (°)	16.93 ± 3.38	20.0 ± 4.39*	19.63 ± 4.5	19.16 ± 4.91
Rel ROM (°)	17.05 ± 3.48	20.27 ± 4.46*	19.91 ± 4.44	19.64 ± 4.62
		Z (+=right rotation/-=left rotation)		
Angle at foot-strike (°)	-4.93 ± 2.71	-4.31 ± 3.27	-4.52 ± 3.88	-4.7 ± 4.16
Angle at toe-off (°)	8.01 ± 3.93**	4.88 ± 3.23	4.52 ± 3.38	3.73 ± 3.5
Peak rotation (°)	11.4 ± 3.93**	9.21 ± 3.45	9.2 ± 3.22	8.53 ± 3.47
ROM (°)	12.94 ± 5.17**	9.19 ± 4.99	9.04 ± 6.0	8.63 ± 5.73
Rel ROM (°)	16.33 ± 5.3**	13.52 ± 4.9	13.72 ± 5.63	13.23 ± 5.6

* Significantly different from uninhibited sprinting p ≤ 0.05

** Significantly different from all other conditions p ≤ 0.05

The results (Table 6.4) indicate that in the sagittal plane there was a significant main effect for angle at toe-off for the trunk ($p = 0.006$, $p\eta^2 = 0.440$). Trunk angle at toe-off was significantly greater during ST than the uninhibited trials ($p < 0.05$). There was no significant difference between ST conditions ($p > 0.05$). A significant main effect was observed for the relative ROM of the trunk ($p = 0.010$, $p\eta^2 = 0.391$). Relative trunk ROM was significantly greater in the 20% loading condition compared to the uninhibited trials ($p = 0.035$). ST had a significant impact on trunk kinematics in the coronal plane. There was a significant main effect for angle at toe-off ($p = 0.039$, $p\eta^2 = 0.221$). Left tilt was significantly greater in the 10% condition when compared to the uninhibited trials ($p = 0.44$). There was no significant difference between ST conditions ($p > 0.05$). Similarly, there was a significant main effect for peak tilt ($p = 0.009$, pη2 = 0.295). In comparison to the uninhibited group the 10% ST caused greater left trunk tilt ($p = 0.019$), differences between the ST groups were negligible. The results show significant main effects for both ROM and relative ROM ($p = 0.008$, $p\eta^2 = 0.295$ and $p = 0.003$, pη2 = 0.339 respectively). Both ROM and relative ROM were significantly greater during the 10% ST trials compared to uninhibited sprinting ($p < 0.05$). Again, the differences between ST groups were negligible ($p > 0.05$). The results indicate that in the transverse plane there was a significant main effect for angle at toe-off for the trunk ($p < 0.001$, $p\eta^2 = 0.698$). Post hoc tests revealed that right rotation was significantly greater during uninhibited sprinting when compared to all ST groups ($p < 0.01$), whereas the differences between ST groups were negligible ($p > 0.05$). There was a significant main effect for peak rotation of the trunk ($p < 0.001$, $p\eta^2 = 0.530$). Peak rotation was greater during the uninhibited group compared to all ST conditions ($p < 0.05$). The results show significant main effects for both ROM and relative ROM in the transverse plane ($p < 0.001$, $p\eta^2 = 0.631$ and $p < 0.001$, $p\eta^2$

= 0.552 respectively). Both ROM and relative ROM were significantly greater during uninhibited trials compared to all ST conditions ($p < 0.01$).

Table 6.5: Hip kinematics (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
		X (+=flexion/-=extension)		
Angle at foot-strike (°)	64.85 ± 8.42	68.08 ± 7.92	69.90 ± 7.74	71.12 ± 9.84
Angle at toe-off (°)	3.44 ± 9.01	5.21 ± 10.70	5.72 ± 10.29	5.20 ± 11.26
Peak flexion (°)	64.85 ± 8.42	68.08 ± 7.92	69.90 ± 7.74	71.12 ± 9.84
ROM (°)	61.41 ± 9.22	62.87 ± 7.35	64.17 ± 6.46	65.91 ± 8.01
		Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	-4.03 ± 3.53	-4.06 ± 3.91	-3.5 ± 4.24	-3.74 ± 4.82
Angle at toe-off (°)	-8.14 ± 3.90	-7.14 ± 4.88	-6.64 ± 4.92	-5.81 ± 6.01
Peak adduction (°)	3.79 ± 3.84	3.43 ± 4.25	3.97 ± 4.80	4.2 ± 4.34
ROM (°)	4.3 ± 3.69	4.13 ± 1.93	4.72 ± 3.05	7.24 ± 3.29
Rel ROM (°)	7.82 ± 3.4	7.48 ± 3.19	7.47 ± 4.1	7.94 ± 4.85
		Z (+=internal/-=external)		
Angle at foot-strike (°)	-12.82 ± 7.51	-10.4 ± 11.89	-10.98 ± 11.05	-10.45 ± 13.86
Angle at toe-off (°)	-11.21 ± 7.56	-9.48 ± 9.81	-8.46 ± 9.52	-8.01 ± 9.97
Peak external rotation (°)	-17.68 ± 6.23	-15.9 ± 10.02	-15.63 ± 9.28	-16.6 ± 10.85
ROM (°)	6.36 ± 4.27	7.98 ± 4.27	7.28 ± 4.75	9.54 ± 4.96*
Rel ROM (°)	4.86 ± 3.46	5.5 ± 3.5	4.66 ± 4.02	6.14 ± 5.4

* Significantly different from uninhibited sprinting $p \leq 0.05$

** Significantly different from all other conditions $p \leq 0.05$

Hip joint measures can be observed in Table 6.5. ST had no significant impact on the sagittal or coronal plane kinematics of the hip joint. However, in the transverse plane there was a significant main effect for ROM at the hip joint ($p = 0.004$, $p\eta^2 = 0.421$). Hip joint ROM was lower in the uninhibited trials compared to the 10 and 20% ST conditions ($p < 0.05$).

Table 6.6: Knee kinematics (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
		X (+=flexion/-=extension)		
Angle at foot-strike (°)	50.74 ± 5.39**	55.03 ± 6.54**	57.82 ± 5.57**	60.78 ± 7.24**
Angle at toe-off (°)	20.97 ± 5.04	21.11 ± 4.28	21.76 ± 5.24	22.38 ± 4.94
Peak flexion (°)	51.99 ± 5.36**	56.04 ± 5.95**	58.61 ± 4.86**	61.70 ± 6.50**
ROM (°)	29.77 ± 6.70**	33.92 ± 8.09§	36.07 ± 7.69	39.32 ± 7.36
Rel ROM (°)	1.25 ± 1.91	1.01 ± 1.67	.78 ± 1.53	.93 ± 2.80
		Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	1.33 ± 6.51	2.45 ± 10.53	1.46 ± 12.03	1.32 ± 11.77
Angle at toe-off (°)	-3.85 ± 2.22	-3.86 ± 3.05	-3.81 ± 3.23	-3.94 ± 3.51
Peak abduction (°)	-5.96 ± 2.52	-6.0 ± 3.79	-7.03 ± 4.33	-6.88 ± 4.0
ROM (°)	5.83 ± 5.31	7.83 ± 7.51	8.38 ± 8.00	5.26 ± 10.31
Rel ROM (°)	7.28 ± 5.64	8.45 ± 7.59	8.48 ± 8.45	8.2 ± 8.50
		Z (+=internal/-=external)		
Angle at foot-strike (°)	2.45 ± 7.07	1.18 ± 8.63	1.8 ± 7.95	1.5 ± 8.67
Angle at toe-off (°)	-.03 ± 5.66	-3.33 ± 6.89	-3.64 ± 7.86	-4.32 ± 7.89*
Peak internal rotation (°)	13.58 ± 4.66	12.57 ± 5.88	12.81 ± 6.09	12.2 ± 5.67
ROM (°)	5.08 ± 3.43	6.79 ± 4.8	7.17 ± 4.32	5.82 ± 7.17
Rel ROM (°)	11.13 ± 5.14	11.39 ± 5.1	11.0 ± 4.77	10.7 ± 4.59

* Significantly different from uninhibited sprinting p ≤ 0.05

§ Significantly different from 20% loading p ≤ 0.05

** Significantly different from all other conditions p ≤ 0.05

The results (Table 6.6) indicate that in the sagittal plane there was a significant main effect for angle at foot-strike for the knee joint ($p < 0.001$, $p\eta^2 = 0.746$). Knee flexion at foot-strike was significantly greater as sled loading increased ($p < 0.05$). There was a significant main effect for peak flexion at the knee joint ($p < 0.001$, $p\eta^2 = 0.765$). Peak flexion was greater as loading increased ($p < 0.01$). There was also a significant main effect for the magnitude of ROM for the knee joint ($p < 0.001$, $p\eta^2 = 0.672$). ROM in all ST conditions were significantly greater than the uninhibited trials ($p < 0.01$). ROM in the 20% sled loading condition was also significantly greater than the 10% condition ($p = 0.001$). Results indicate that ST had no significant impact on the coronal plane kinematics of the knee joint. In the transverse plane there was a significant main effect for joint angle at toe-off ($p < 0.001$, $p\eta^2 = 0.443$). There was significantly greater external rotation at the knee in the 20% sled loading condition compared to the uninhibited sprint trials at toe-off ($p < 0.05$).

Table 6.7: Ankle kinematics (means and standard deviations) under the different conditions (uninhibited, 10%, 15% and 20% V_{Dec}).

	Uninhibited	**10%**	**15%**	**20%**
	X (+=dorsiflexion/-=plantarflexion)			
Angle at foot-strike (°)	4.25 ± 3.71	5.08 ± 3.31	5.12 ± 3.84	6.19 ± 3.78
Angle at toe-off (°)	-24.10 ± 6.20	-25.33 ± 6.06	-25.84 ± 6.85	-25.76 ± 7.11
Peak dorsiflexion (°)	23.62 ± 3.96	24.11 ± 4.23	24.27 ± 4.72	24.96 ± 5.14
ROM (°)	28.36 ± 5.26**	30.41 ± 5.55	30.96 ± 6.52	31.95 ± 5.79
Rel ROM (°)	19.37 ± 2.75	19.03 ± 3.19	19.15 ± 3.82	18.77 ± 2.72
	Y (+=inversion/-=eversion)			
Angle at foot-strike (°)	-.59 ± 4.53	-1.78 ± 4.5	-1.26 ± 5.57	-1.06 ± 5.25
Angle at toe-off (°)	5.98 ± 2.95	6.45 ± 2.9	7.1 ± 3.3	8.43 ± 2.79*
Peak eversion (°)	-7.84 ± 3.57	-6.78 ± 3.06	-6.53 ± 3.41	-5.75 ± 3.09
ROM (°)	6.83 ± 4.04	8.16 ± 3.97	9.07 ± 3.74	9.5 ± 4.75*
Rel ROM (°)	7.25 ± 4.01	5.0 ± 4.12	5.28 ± 5.31	4.68 ± 4.48
	Z (+=external/-=internal)			
Angle at foot-strike (°)	-4.75 ± 2.78	-5.43 ± 2.62	-5.75 ± 3.06	-5.98 ± 2.68
Angle at toe-off (°)	2.61 ± 4.31	1.68 ± 3.96	1.18 ± 5.03	1.51 ± 4.25
Peak external rotation (°)	4.1 ± 4.0	3.24 ± 3.07	2.76 ± 3.89	3.27 ± 2.5
ROM (°)	7.36 ± 3.63	7.28 ± 4.1	7.56 ± 4.46	7.5 ± 4.83
Rel ROM (°)	8.85 ± 3.26	8.67 ± 3.19	8.5 ± 3.9	9.26 ± 3.09

* Significantly different from uninhibited sprinting $p \leq 0.05$

** Significantly different from all other conditions $p \leq 0.05$

The results (Table 6.7) indicate that in the sagittal plane there was a significant main effect for magnitude of ROM for the ankle joint ($p < 0.001$, $p\eta^2 = 0.503$). Ankle ROM during all ST conditions was significantly greater than the uninhibited trials ($p < 0.05$). There was no significant difference between ST conditions ($p > 0.05$). The results show that at the ankle joint in the coronal plane there was a significant main effect at toe-off ($p = 0.002$, $p\eta^2 = 0.352$) and ROM ($p = 0.004$, $p\eta^2 = 0.332$). Post hoc analysis revealed that there was significantly greater ankle inversion at toe-off and ROM in the 20% condition compared to the uninhibited trials ($p = 0.042$ and $p = 0.040$ respectively). Results indicate that ST had no significant impact on the transverse plane kinematics of the ankle joint.

6.4. Discussion

This was the first ST study to examine trunk and lower body 3-D kinematics, contact time variables and kinetics during early acceleration in semi-elite team-sport athletes. Therefore, this study will provide a valuable insight for strength and conditioning practitioners looking to prescribe ST (% V_{Dec}) for team-sport athletes. The major findings of this study were that (a) as sled loadings increased trunk and sagittal plane lower body kinematics were altered to a greater extent, (b) there were no significant differences in propulsive peak force between any of the sled conditions and uninhibited sprinting, and (c) propulsive impulse measures in the 20% V_{Dec} sled trials were significantly greater than all other conditions.

In general, sprint 3-D kinematics were affected in all sled conditions when compared with uninhibited sprinting. This supports our previous research (Chapter 5) on harness attachment points and casts further doubt on the belief that lighter sled loadings (10% BM or 10% V_{Dec}) will not affect sprint kinematics. Previous investigations have suggested that when heavier sleds are utilised kinematic alterations to stride length and frequency are greater (Lockie, et al., 2013; Maulder, et al., 2008; Murray, et al., 2005). Although stride length and frequency were not measured in the present study, results indicate that velocity and contact time were affected to a greater extent when sled loadings were increased. The longer contact times were explained by an extended propulsive phase, as suggested previously (Kawamori, et al., 2014; Monte, et al., 2016; Murray, et al., 2005). The additional contact time allows the athlete to exert greater propulsive forces to overcome the extra resistance provided by the sled. This increased propulsive contact time may be beneficial for acceleration performance, in this instance more horizontal force can be applied to the ground (Kawamori, et al., 2013; Morin, et al., 2016).

ST with light to moderate loadings using a waist harness attachment appears to have no significant impact on sagittal plane hip joint kinematics. This finding differs from previous research by Monte et al. (2016) who reported significant kinematic alterations at the hip, knee and ankle joints at foot-contact and toe-off. However, the greater sled loadings utilised in their study (30 and 40% BM) likely explains the difference. The only sagittal plane kinematic alterations observed at the ankle joint in the present study was a significantly lower ROM in the uninhibited condition compared to all ST trials. The change in ROM during sled trials was explained by a trend of increased dorsiflexion at foot-strike and increased plantarflexion at toe-off. Kinematic adjustments of this nature appear to allow the athletes to increase their stance phase contact times, as discussed previously. Results show that there were several significant sagittal plane kinematic changes at the knee joint. Knee flexion at foot-strike and peak flexion were greater in all sled conditions and increased in line with loading. It is believed that such adjustments allow the athletes to lower their centre of mass and increase contact time, thus helping them overcome the added resistance of the sled by increasing their horizontal force application. However, in contrast, a study by Murphy et al., (2003) speculated that faster athletes would exhibit a reduced knee extension, thus allowing them to increase step frequency. Studies have highlighted the importance of trunk kinematics during ST and uninhibited sprinting alike (Alcaraz, et al., 2014; Lockie, et al., 2003). The results support this finding; extension of the trunk was significantly greater in the uninhibited condition compared to all sled conditions at toe-off. There was a trend for greater trunk flexion as sled loadings increased; however, this was not significant. Along with increased peak knee flexion, the authors believe the increased trunk flexion at toe-off enables the athlete to increase their horizontal force application. Adaptations of this nature have been reported after ST interventions, during acceleration such practice effects may lead to greater propulsive forces in the later stance phase (Alcaraz, et al., 2014; Kawamori, et al., 2013; Spinks, et al., 2007).

Although many of the kinematic alterations occur in the sagittal plane it is important to consider the coronal and transverse planes of motion. In accordance with our previous investigation (Chapter 5) into harness attachment points there were no coronal plane significant differences at the hip or knee joints. There were several alterations at the ankle joint, inversion at toe-off and ROM were greater in the 20% V_{DEC} condition compared to uninhibited sprinting. These adjustments likely occur as the participants struggle to overcome the added resistance provided by the sled. Surprisingly, only the 10% loading led to significant coronal plane kinematic alterations at the trunk. During the 10% V_{DEC} trials trunk tilt was different at toe-off, peak with larger ROM and Rel ROM measures when to uninhibited sprinting. Alterations of this nature may be a strategy to lower the centre of mass further or to compensate for the lack of rotations seen during all ST trials. It's somewhat surprising that trunk tilt did not increase with ST loading, however participants appear to stabilise the trunk to a greater extent as sled loadings were heavier (15 and 20% V_{DEC}).

In the transverse plane none of the sled loadings (10, 15 and 20% V_{DEC}) affected ankle joint kinematics when compared to uninhibited sprint acceleration. In comparison to uninhibited sprinting hip and knee joint kinematics were altered during the 20% V_{DEC} trials only. During which hip joint ROM was greater and there was more external rotation at the knee joint at toe-off. Such changes may be an indication that at the 20% loading and above athletes may be forced to compensate for the greater changes in sagittal plane kinematics. In agreement with our previous study (Chapter 5), uninhibited transverse plane trunk kinematics were significantly different to the ST trials. The reduced trunk rotations during ST are a concern, as mentioned previously. These rotations may help to minimise the displacement of centre of mass during the acceleration phase (Preece, et al., 2016). In general, trunk rotations and the resultant ROM measures were greater for the uninhibited condition. The reduced rotations were likely due to the increased trunk stabilisation required when towing the heavier sleds and may have resulted in the increased trunk tilt reported.

The authors hypothesised that propulsive peak force would be greatest in the 20% V_{Dec} sled condition. Results did not support this; there was however, a trend that as sled loading increased so too did propulsive peak force. It does appear that propulsive peak force may continue to increase with heavier sled loadings, as suggested in previous studies (Morin, et al., 2016). It is important to note that such increases are at the expense of much greater contact times, which after a certain point may become counterproductive (Maulder, et al., 2008). Additionally, previous research suggests that the magnitude of forces may not be as important as the direction of force application (Kawamori, et al., 2013; Morin, et al., 2011). Propulsive mean force was significantly higher and vertical mean force significantly lower in the 20% V_{Dec} sled condition when compare to uninhibited acceleration. These kinetic changes again highlight the increased horizontal force vector orientation when towing moderate sled loads.

Net horizontal and propulsive impulses are key determinants of early acceleration (Hunter, et al., 2005; Kawamori, et al., 2013). However, simply maximising these measures at the expense of other key variables such as contact times may not be beneficial (Kawamori, et al., 2013). The results indicate that both net horizontal and propulsive impulses were significantly greater in all sled conditions and increased in line with sled loading. This supports the findings of previous investigations that utilised similar sled loading strategies (Kawamori, et al., 2014). Again, the larger impulse measures reported can be explained by the increased contact times. As such, when rapid acceleration and shorter contact times are a priority, 20% V_{Dec} ST may not be the ideal loading strategy; during these specific pre-competition training periods, uninhibited sprinting might be more appropriate. However, during the general preparation phase of training practitioners may look to overload horizontal force application with this loading strategy. In this instance, ST may enhance the transition between high-strength and high-velocity exercises (Alcaraz, et al., 2014).

Unsurprisingly, heavier sled loadings led to a greater sprint velocity reduction (Petrakos, et al., 2016). In the present study sled loadings were determined using % V_{Dec} rather than % BM. Sled loadings adjusted based on % BM may not provide an optimal overload among all athletes because this method does not account for the athlete's muscular strength and sprint technique (Kawamori, et al., 2014). Greater individual differences were apparent when towing heavier sleds, highlighted in this investigation by larger standard deviations as sled loadings increased. The researchers believe that differences can be partly explained by training age, observations highlighted the breakdown in sprint technique of those individuals of a lower training age with a lighter sled loading compared to those with a higher training age. Although more time consuming, it is recommended that practitioners load sleds based on a % V_{Dec} rather than a % BM, this is more important as sled loadings increase.

Investigations have demonstrated that females exhibit distinct lower body kinematics when compared with males (Sinclair, et al., 2012). As such, the results are limited to this population and may not be applicable to female athletes. Similarly, the results are specific to the highly trained population and may not be appropriate for recreational athletes. The light to moderate sled loadings utilised in this study may be a limitation. Researchers have recently suggested that very heavy sled loadings may provide the optimal training stimulus by maximising peak power output (Cross, et al., 2017). It is beyond the scope of the present study to comment on such loading strategies. The results have highlighted a number of important 3-D kinematic alterations occurring at the trunk segment, studies have suggested that such alterations would have an impact on the shoulders and arms (Preece, et al., 2016). Unfortunately, a reduced upper-body marker set was utilised during testing which did not include the arms. As such, it is beyond the scope of this study to comment on the interaction between the trunk segment and arm drive during the acceleration phase of sprint running.

6.4.1. Conclusion

Overall, the results of this study have shown that a sled loading of 20% V_{Dec} enables practitioners to increase propulsive forces and impulses. However, a blanket application of such loads may not be the most appropriate strategy as some of the acute changes are potentially counterproductive, such as reduced velocity and increased contact times. Thus, a periodised approach should be adopted. For example, training with a 20% V_{Dec} sled loading will allow a greater emphasis on the horizontal application of forces then progressing to lighter sled loads or UST to allow greater transfer of potential adaptations (e.g., maintain force/impulse production whilst lowering contact times). The study therefore, highlights the effects of differential loads to help practitioners understand acute biomechanical changes to improve the planning of sprint training.

7. Study 3: The effect of in-season velocity-based sled towing on acceleration in semi-elite rugby league players

Conference Presentations

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7.1. Introduction

Sprint acceleration is defined as the capacity to generate as high a velocity as possible in as short a distance or time as possible (Lockie, Murphy, & Spinks, 2003), and is essential for success in the majority of sports (Duthie, et al., 2006; Murphy, et al., 2003). In team-sports, where the need to reach the ball first or be in position for play to develop is decisive, acceleration is a crucial factor (Lockie, Murphy, & Spinks, 2003 (Murphy, et al., 2003), and as such MV may not be as important as sprint acceleration in team-sport players (Murphy, et al., 2003).

Practitioners can improve acceleration in different ways; by focussing on either increasing an athlete's maximal strength or power (Cormie, McGuigan, & Newton, 2010), or by focusing on movement efficiency or force application (De Villarreal, et al., 2012; Cissik, 2004). Alternatively, practitioners may adopt a more combined approach (Comfort, et al., 2012). Sprint-specific training modalities may have a better transfer to performance compared to non-specific strength training (Brughelli, et al., 2010; Young, 2006). RST methods such as sled towing, parachutes, weighted vests, bungees and uphill running offer the practitioner an alternative approach to sprint training. RST modalities are performed in a horizontal direction, and involve the relevant muscles, velocities and ROM to those of uninhibited sprinting (Alcaraz, et al., 2014). ST provides an external load in the form of a sled towed via a shoulder or waist harness and cord, behind the athlete. The mass of the sled and the friction coefficient between the sled and the ground surface affect external load and the subsequent impact on performance (Linthorne & Cooper, 2013). Sleds are generally loaded based on a % BM or %

V_{Dec} (Kawamori, et al., 2014; Spinks, et al., 2007). However, loadings based on a % BM do not account for individual variations in strength, power or technical ability. As such, loading sleds based on V_{Dec} over a given distance is the preferred approach (Petrakos, et al., 2016).

Whilst acute studies can help the practitioner to understand the manner in which loading can alter sprint mechanics, longitudinal interventions are necessary to explore the adaptive responses to such modifications. Many studies have investigated the effects of ST over various training periods, however the majority have used active or recreational populations (Lockie, et al., 2012; Makaruk, et al., 2013; Spinks, et al., 2007; Zafeiridis, et al., 2005). A previous study by Harrison & Bourke (2009) investigated ST in semi-professional and professional rugby players over a six-week period. Players were assigned to a ST or control group and continued with a concurrent in-season training programme, the intervention group undertook two additional ST sessions per week. They reported significant improvements in the ST group over 5 m and improvements in various jumps. It is difficult to draw conclusions from this study as no UST protocol was used as a comparison and improvements may have been the result of increased training volume. A more recent study by West, et al., (2013) also investigated ST over a six-week period, their participants were professional rugby players. This study did include a UST comparison, they focussed on the pre-season phase and compared ST and UST combined with UST only. They reported significant improvements in 10 and 30 m sprint times for both intervention groups. Although the ST group promoted greater improvements these were not significant. Again, it is difficult to draw conclusions because this study combined ST and UST into a single protocol. Although this may prove to be the optimum strategy at present a ST only intervention would provide a useful insight. It appears

ST can enhance early acceleration, however these studies used light sled loading strategies. More recent investigations have suggested moderate to heavy sled loadings may be more approriate (Petrakos, et al., 2016).

Therefore, the purpose of this study was to compare the effects of 20% V_{DEC} ST versus UST in semi-elite rugby league players during the competitive phase of the season over a period of eight-weeks. It was hypothesised that (a) both intervention groups would significantly improve sprint performance, (b) the ST intervention would lead to significantly greater improvements over the initial 5 m compared to the UST group, and (c) the ST intervention would significantly improve performance in the CMJ testing compared to the UST group. Findings will allow practitioners to incorporate ST into their programmes more effectively.

7.2. Methods

7.2.1. Research design

This study used a randomised between-participants design to compare the longitudinal effects of ST and UST programmes. The intervention programmes involved 9 x 20 m unloaded sprints or sled tows. Sprint sessions were performed twice per week and built into the in-season concurrent training programme. Sleds were loaded to cause a 20% V_{Dec} over a 10 m distance. Participants were tested pre, mid and post (0, 4 and 8-weeks) intervention in a variety of performance tests (sprint, CMJ and change of direction).

7.2.2. Participants

Twenty-eight semi-professional male rugby league players participated in this study (Table 7.1). All participants were resistance trained (> 3 years) with ST experience (> 6 months). Participants gave written and informed consent before attending the initial testing session. All participants were ranked in order (from fastest to slowest) based on their 20 m sprint times measured during a familiarisation session undertaken one-week prior to the baseline testing session. Participants were then assigned to one of the intervention groups based on those times, thus allowing groups to be matched as evenly as possible. Any participants that missed more than three of the scheduled sessions were removed from the study. Two participants had to be removed from the study leaving twenty-six participants. Dropout largely resulted from injuries that occurred during match-play.

Table 7.1: Participant information (means and standard deviations).

	Uninhibited Sprint Group	**Sled Towing Group**
Number	13	13
Age (y)	18.7 ± 0.62	18.9 ± 0.52
Stature (cm)	182.48 ± 6.07	181.85 ± 5.07
BM (kg)	89.49 ± 11.44	85.75 ± 11.53

7.2.3. The training programme

The training interventions were incorporated into the in-season programme. All participants were exposed to the same standardised training programme in the four-weeks prior to this study. The interventions were scheduled over an eight-week period, during this window, normal training resumed (typically involving 3 x 45 minutes resistance and 3 x 70 minutes field-based sessions per week) and five league games were played. The ST interventions were built into an undulating concurrent training programme (Table 7.2).

Table 7.2: An overview of a typical training week.

<table>
<tr><th>Monday</th><th>Tuesday</th><th>Wednesday</th><th>Thursday</th><th>Friday</th><th>Saturday</th><th>Sunday</th></tr>
<tr><td>Gym</td><td>Gym</td><td rowspan="2">Off</td><td>Gym</td><td></td><td rowspan="2">Match</td><td rowspan="2">Off</td></tr>
<tr><td>Match review session</td><td>Field session</td><td>Field session</td><td>Field session (match preparation)</td></tr>
</table>

The programmes were identical other than the sled or sprint protocols and the participants self-selected exercise loadings (Figure 7.1). Once completed the four-week strength training programme was repeated with adjusted exercise loadings. The ST or UST protocols were undertaken twice per week for eight-weeks. All sessions began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several short sprints building up to maximum intensity (4 x submaximal and 2 x maximal). The intervention sprints were completed in an indoor sports hall with a hard rubber surface (μ = 0.38).

MONDAY (STRENGTH - FULL BODY)	Wk 1		Wk 2		Wk 3		Wk 4	
Exercise	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***
PISTOL SQUATS	3X6*		3X6*		3X6*		3X6*	
SB CURLS	3X6		3X6		3X6		3X6	
MILITARY PRESS	4X8		4X8		4X8		4X8	
WTD PULL UPS	4X8		4X8		4X8		4X8	
BANDED WALKS (TOES)	3X5M*		3X5M*		3X5M*		3X5M*	
BENCH BRIDGES	3X8		3X8		3X8		3X8	
ROLL OUTS	4X6		4X6		4X6		4X6	
Y-T-V	4X4		4X4		4X4		4X4	
TUESDAY (STRENGTH - FULL BODY)	**Wk 1**		**Wk 2**		**Wk 3**		**Wk 4**	
Exercise	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***
SPRINTS	**9X20M**	SLED OR NORMAL	6X20M	SLED OR NORMAL	6X20M	SLED OR NORMAL	6X20M	SLED OR NORMAL
SQUATS	4X8		4X6		4X6		4X5	
LATERAL LUNGES	4x4*	BW	4x4*	BW	4x4*	BW	4x4*	BW
DBELL BENCH	4X8		4X8		4X6		4X6	
BENT OVER ROW	4X8		4X8		4X6		4X6	
REVERSE FLYS	4X10		4X10		4X10		4X10	
BOX STEP UPS	3X6*		3X6*		3X6*		3X6*	
RDLS	3X6		3X6		3X6		3X6	
THURSDAY (POWER - FULL BODY)	**Wk 1**		**Wk 2**		**Wk 3**		**Wk 4**	
Exercise	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***	***SETS/REPS***	***SET 1, 2, 3, 4.***
SPRINTS	**9X20M**	SLED OR NORMAL	6X20M	SLED OR NORMAL	6X20M	SLED OR NORMAL	6X20M	SLED OR NORMAL
DROP SNATCH	4X5		4X5		4X5		4X5	
SQUAT JUMPS	4X5		4X5		4X5		4X5	
SL BOX DRIVES	4X6*		4X6*		4X6*		4X6*	
MED BALL SLAMS	5X6		5X6		5X6		5X6	
BENCH THROWS	5X6		5X6		5X6		5X6	
HANGING LEG RAISES (FULL)	5X4		5X4		5X4		5X4	

Figure 7.1: Strength programme (repeated once completed).

7.2.4. Sled towing group

Participants completed 3 x 20 m sled tows with 2 minutes recovery between each sprint. After the third sprint participants had 3 minutes recovery before repeating the procedure twice more. These sets and reps were similar to those of the ST studies on semi-elite or competitive-elite populations (Harrison & Bourke, 2009; West, et al., 2013). Compared to the other investigations (Clark, et al., 2010) which used a much higher volume of running, these strategies minimise fatigue and therefore suit the concurrent programme (Fyfe & Loenneke, 2018; Wilson, et al., 2012). Any players reporting or showing signs of fatigue during sprints were encouraged to have an extended recovery period. This only occurred on rare occasions as the players had previous ST experience and the programme was designed to minimise fatigue. Sleds were loaded to reduce uninhibited sprint velocity by 20% over 10 m, as recommended in the previous study (Study 6). Sled loadings were determined during a familiarisation session one-week prior to the baseline testing session and recalculated halfway through the intervention (Table 7.3).

Table 7.3: Sled loadings by % V_{Dec} (means and standard deviations).

Loading Strategy	Weeks 1-4	Weeks 5-8
% V_{Dec} (kg)	21.44 ± 2.88	23.08 ± 3.97
Equivalent % BM	25 ± 3.36	26.92 ± 4.63

7.2.5. Uninhibited sprint training group

Participants completed 3 x 20m uninhibited sprints with 2 minutes recovery between each sprint. After the third sprint, participants had 3 minutes recovery before repeating the procedure twice. Both intervention protocols were completed before the gym-based elements of the session.

7.2.6. Testing procedures

Identical protocols were followed before the pre, mid and post intervention testing. All tests were carried out during a single testing session, participants were given 2 minutes recovery within tests and 4 minutes between different tests. Testing commenced following a period of 24 hours rest, participants were instructed not to consume any alcohol during this period and continue with their typical training day diet. As mentioned previously, all participants completed a familiarisation session during which all testing protocols were practiced until participants were confident. The baseline and intervention testing sessions were identical (0, 4 and 8-weeks). BM and stature were recorded during the testing sessions.

Five, ten and twenty-meter splits

The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and a number of short sprints building up to maximum intensity (4 x submaximal and 2 x maximal). On completion of the warm up participants completed 3 x 20 m sprints from a standing staggered stance with their non-dominant foot forward through the electronic timing gate system (Fusion Sports, SmartSpeed, Australia). Participants started 0.3 m behind the starting point, timing gates were positioned on 0, 5, 10 and 20 m. Participants were instructed to start when they were ready and to sprint through the 5 m past the final gate. The fastest time out of the attempts was used in the data analysis.

Counter movement jump

The CMJ began with participants standing tall with hands on their hips. They were instructed to perform a countermovement by simultaneously flexing the hips and knees to a self-selected height then to explosively jump as high as possible. Participants were instructed to land in the same position on the mat with a toe first contact. The jumps were performed on the electronic jump mat (Fusion Sports, SmartSpeed, Australia) which utilised flight time to calculate jump height. All participants performed 3 jumps with adequate rest between (3 min). The largest jump was recorded and utilised in the data analysis.

505-agility test

Participants were assessed using a single timing gate (Fusion Sports, SmartSpeed, Australia). During the 505-agility test the participants started 10 m from the timing gate (15 m from the turning line) and they sprinted through the timing gate before turning on the following line and accelerating back through the timing gate (Figure 7.2). Participants were instructed to place one foot over the line as they performed the 180 degree turn. Each participant performed 2 trials turning on each leg (4 total). An aggregate of the fastest trial for each leg was used during data analysis.

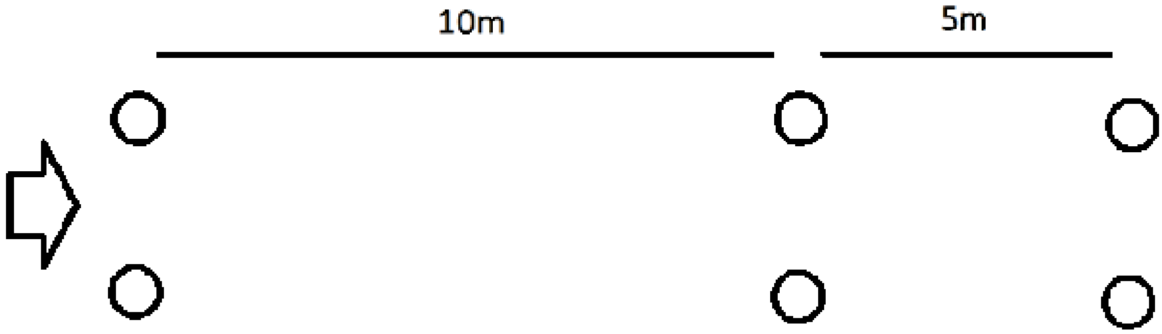

Figure 7.2: 505-agility test set up.

7.2.7. Statistical analysis

Descriptive statistics were calculated and presented as mean ± SD. A 2 x 3 mixed ANOVA was used to compare the means of the different conditions throughout the intervention (group x time) for each of the performance measures (sprint time, CMJ and agility time). Post hoc pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment to control for type I error. Mauchly's test was used to confirm sphericity for each analysis. If the assumption of sphericity was violated, a Greenhouse-Geisser adjustment was used. The significance level was set at $p \leq 0.05$. Effect sizes were calculated using partial eta^2 ($p\eta^2$), in accordance with Cohen (1977) $p\eta^2 = 0.2$ considered small, $p\eta^2 = 0.5$ medium and $p\eta^2 = 0.8$ large.

7.3. Results

The results (Table 7.4) indicate that there were significant main effects for time at all sprint distances (5, 10 and 20 m). Over 5 m, sprint times decreased significantly ($p < 0.001$, $p\eta^2$ =

0.284). Further analysis highlighted that acceleration improvements occurred over the initial four-week period (pre to mid and pre to post), differences from mid to post were not significant ($p > 0.05$). Over 10 m, sprint times decreased significantly ($p = 0.002$, $p\eta^2 = 0.230$). Again, performance improvements took place over the first four-weeks of the intervention, as opposed to the later part ($p > 0.05$). The 20 m sprint times decreased significantly over the interventions ($p < 0.001$, $p\eta^2 = 0.398$). Significant improvements occurred over the full intervention period ($p < 0.05$). The results indicate that there was no significant effect for condition over any of the sprint distances ($p > 0.05$).

Table 7.4: Performance tests pre, mid and post interventions (means and standard deviations).

Performance test	Uninhibited Sprint Group	% Improvement (from Pre-testing)	Sled Towing Group	% Improvement (from Pre-testing)
		5m Sprint (s)		
Pre	1.019 ± .057		1.032 ± .071	
Mid	.998 ± .066	2.1	.992 ± .046	3.9
Post	.993 ± .062	2.6	.975 ± .049	5.5
		10m Sprint (s)		
Pre	1.759 ± .083		1.772 ± .064	
Mid	1.737 ± .083	1.3	1.725 ± .07	2.7
Post	1.737 ± .068	1.3	1.701 ± .066	4.0
		20m Sprint (s)		
Pre	3.030 ± .119		3.043 ± .114	
Mid	3.011 ± .112	0.6	2.990 ± .101	1.7
Post	2.993 ± .110	1.2	2.946 ± .087	3.2
		CMJ (cm)		
Pre	39.181 ± 6.586		40.429 ± 3.869	
Mid	39.343 ± 6.696	0.4	42.023 ± 5.177	4.8
Post	39.489 ± 6.747	0.8	43.066 ± 4.550*	6.1
		505 Agility (s)		
Pre	2.449 ± .0712		2.432 ± .111	
Mid	2.435 ± .071	0.6	2.397 ± .084	1.4
Post	2.416 ± .062	1.3	2.369 ± .058	2.6

* Significantly different to the Pre-testing $p \leq 0.05$

The results (Table 7.4) highlight that there were significant main effects for both time ($p = 0.001$, $p\eta^2 = 0.237$) and condition ($p = 0.014$, $p\eta^2 = 0.164$) in the CMJ testing. CMJ height was increased significantly in the ST group ($p = 0.012$), there were no significant changes in CMJ height in the UST group (0.79% increase; $p > 0.05$). In agreement with the sprint times, results indicate that improvements occurred over the initial four-week period of the intervention ($p < 0.001$).

The results (Table 7.4) indicate that was a significant main effect for time in the 505-agility test ($p = 0.005$, $p\eta^2 = 0.197$). Further analysis revealed that significant improvements occurred over the full eight-week intervention period ($p = 0.14$). There were no significant differences between the intervention groups ($p > 0.05$).

7.4. Discussion

This is the first study to investigate the long-term adaptations to velocity-based ST in semi-elite team-sport athletes during the competitive phase of the season. Therefore, this study will provide a valuable insight for strength and conditioning practitioners looking to prescribe ST (% V_{Dec}). The major findings of this study were (a) an eight-week ST or UST can be incorporated into the training programme of team-sport players to enhance acceleration, (b) there were no significant differences between intervention groups, and (c) the ST group improved CMJ height significantly.

Results indicated that both ST and UST can be employed to improve acceleration over 5, 10 and 20 m. These findings are consistent with those of previous investigations by West et al., (2013) and Harrison & Bourke (2009) who reported similar improvements following six-week interventions on semi-elite rugby players. Although results in this study were similar, there were some distinct methodological differences as mentioned previously. Sleds in the current study were loaded at 20% V_{Dec}, this was the equivalent of 25 and 26.9% BM in weeks 1-4 and 4-8 respectively. This loading strategy was heavier than the 12.6 and 13% used in the investigations mentioned previously (Harrison & Bourke, 2009; West, et al., 2013). A recent review by Petrakos et al., (2016) suggested that heavier sled loadings should be utilised when targeting acceleration. Our results would support this; the 4% improvement reported was greater than the 2.4% found previously (West, et al., 2013).

ST led to greater but non-significant enhancements compared to the UST intervention. The performance difference between interventions was largest over 5 m, were the ST and UST groups improved 2.6 and 5.5% respectively. Although not significant in semi-elite team-sport athletes small improvements in acceleration performance may differentiate between successful and unsuccessful actions (Petrakos, et al., 2016). The effectiveness of ST over UST remains unclear at present, however, we can be confident that loads between 10 - 30% V_{Dec} are not detrimental to acceleration performance (Petrakos, et al., 2016).

In-season programming ST for team-sport athletes can be challenging. Concurrent training programmes have many different elements, such as technical, tactical and physical training components (Jeffreys & Moody, 2016). The twice-weekly approach incorporated in this study appears sufficient for adaptations and was easier to schedule than a three sessions per week approach. Players completed a total of 180 m ST or UST each session; this distance is lower than suggested by some investigations (Petrakos, et al., 2016). However, during the in-season phase it is imperative to minimise fatigue, thus allowing optimal performance during match play (Jeffreys & Moody, 2016). The ST intervention in the present study did not include any UST other than the build-up sprints completed during the warm-up. However, both intervention groups were involved in speed and agility drills, which formed part of the warm-up for the field-based rugby sessions. Training and match play would also typically involve numerous high intensity sprints of 10 – 20 m (Gabbett, et al., 2012). Previous investigations have suggested that a combined approach of ST and UST would improve acceleration more than either strategy alone (West, et al., 2013). It is entirely possible that acceleration would have been further enhanced if such an approach were taken.

The CMJ is a measure of slow-stretch shortening cycle performance; this measure has been found to have a strong relationship with acceleration (0 - 30 m) (Cronin & Hansen, 2005). As predicted, our results suggest CMJ height was significantly increased in the ST group only; these findings support those of Harrison & Bourke (2009). However, these findings are in contrast to other investigations (Alcaraz, et al., 2014) (Lockie, et al., 2012), who suggested that the increased horizontal force application of ST might not enhance CMJ performance. However, we believe that in terms of movement velocity ST and the CMJ actions were similar. Research suggests that exercise velocity is key to optimise performance and that training at a specific velocity improves strength at that velocity (Cronin, McNair, & Marshall, 2002). Both

ST and CMJ actions are more force-based than acceleration, which may be the reason that the ST group improved significantly over the intervention and had less impact on acceleration.

Change of direction performance was assessed using the 505-agility test, unsurprisingly; in agreement with other studies on semi-elite team-sport athletes, the marginal improvements were not significant (Hoyo, et al., 2016). Performance in change of direction activities is more complex than sprinting or jumping alone and other factors such as technique, muscle qualities and anthropometry might also have some or more impact (Hoyo, et al., 2016; Gabbett, et al., 2008; Sheppard & Young, 2006). Thus, strategies focused on improved acceleration should only form part of the solution when enhancing change of direction performance.

Unfortunately, the performance tests (sprint, CMJ, COD) incorporated in this study did not allow the authors to identify which specific physiological adaptations induced improvements. However, as the greatest performance enhancements were seen in the initial four-weeks of the programme. Performance improvements of this nature over a relatively short period of time are likely neuromuscular in nature (Alcaraz, et al., 2014). Such neuromuscular adaptations have been well documented previously (e.g., selective recruitment of high threshold motor units, increased firing frequency and synchronisation) (Cormie, McBride, & McCaulley, 2009). Thus, four-week training blocks would seem appropriate when looking to enhance acceleration.

There were a number of limitations associated with this investigation; a third group with a combined ST and UST approach would have helped inform the programming of team-sport athletes. More detailed testing procedures (biomechanical, physiological and performance tests) pre, mid and post might have enabled us to identify adaptations and subsequently to better inform practitioners. The lack of a horizontal bound or hop test has been identified as a limitation, testing of this nature would have proved more useful than the standard CMJ testing undertaken. Thus, future research in the area should look to embed a combined approach of moderately loaded ST with detailed testing pre, mid and post intervention. Investigations have demonstrated that females exhibit distinct lower body kinematics when compared with males (Sinclair, et al., 2012). As such, the results are limited to this population and may not be applicable to female athletes. Similarly, the results are specific to the highly trained population and may not be applicable to recreational athletes. Finally, the eight-week intervention period might not have been long enough for all the training adaptations to occur. Any muscle fibre and contractile adaptations generally only transpire in the later stages of a training programme (Campos, et al., 2002; Costill, et al., 1979; Deschenes & Kraemer, 2002). However, longer interventions in team-sports during the competitive phase may prove challenging due to changing schedules etc.

7.4.1. Conclusion

Overall, the results indicate that the inclusion of ST in an eight-week training programme improves explosive power, but these adaptations did not transfer through to acceleration as distinctly as they did to executing a CMJ. This is likely to be because of the difference between tasks, as CMJ demands are principally force-based, whereas increasing sprint distances tend more towards velocity-based demands. As such, for semi-elite rugby league players, ST appears to provide marginal benefits over UST when implemented as part of an in-season training programme.

8. Synthesis of Findings

Due to a lack of recommendations regarding the optimal sled setup and consensus over loading strategies it is difficult for practitioners to integrate ST into the training programme. As such, the key objectives of this thesis were to investigate the 3-D kinematics and kinetics of ST with different harness attachment points, thus to determine whether a waist or shoulder harness attachment point should be utilised during ST. Secondly, to examine the 3-D kinematics and kinetics of different sled loadings to suggest the optimum strategy for the acceleration phase of sprinting. Sleds were loaded to reduce velocity by 10, 15 and 20% over a 6 m sprint and compared to uninhibited sprint acceleration. Finally, to investigate the benefits of an eight-week in-season ST intervention. Sled loadings were based on the outcomes of the previous studies and performance measures were taken pre, mid and post to (a) determine whether a ST or an uninhibited sprint intervention would be more effective at improving sprint acceleration, and (b) investigate whether the interventions impact other performance measures. This chapter will provide a summary of the key findings from the three main studies of this thesis. Findings will be discussed in relation to the original contribution to knowledge. Finally, recommendations for additional research and the implications for the applied practitioner will be considered.

8.1 Important findings from the developmental methods

The developmental studies were undertaken prior to the main studies and were essential, as well as informing all subsequent testing protocols the results of these experiments may have implications for researchers or practitioners.

The results from the force platform targeting study on a semi-elite rugby league population (Pilot Study 1) provided an insight into the deliberate striking of the force plate during acceleration. The results indicated that force plate targeting had no significant impact on the participant's subjective comfort and most of the kinematic measures of the lower extremities. This study also highlighted that recreationally active individuals and semi-elite athletes differ in their visual cueing and technique consistency. Therefore, any data collected using recreationally active individuals should not be used to inform programming or practice on individuals competing at a higher level and vice versa.

The test-retest reliability of all dependant variables (e.g. velocity, contact, kinematic and kinetic measures) was investigated (Pilot Study 2) as participants accelerated across the force platform. The results of this study were crucial to the interpretation of data in the subsequent investigations. Results indicated that reliability was generally high across the different variables and within the accepted ranges. However, there are a few measures which fell outside these ranges and therefore any changes in these measures may need to be interpreted with caution. All testing protocols in the main studies were designed to minimise errors, such as providing coaching cues to players during the familiarisation session. Thus, allowing all data to be interpreted with greater confidence.

The weekly variation in sprint performance of semi-elite rugby league players during the competitive phase of the season was investigated (Pilot Study 3). The results of this study highlighted the low variability of weekly sprint performance (10 and 20 m) meaning that any performance improvements would be identifiable. As such, practitioners should be able to assess performance improvements with pre and post intervention sprint testing. These findings had important implications not only for the final intervention of this thesis but also any practitioners carrying out training programmes on semi-elite athletes.

8.2. Summary of main findings

Sprint-specific training modalities are generally preferred in the later stages of the periodised programme when strength training should be more specific to competition (Brughelli, et al., 2010; Young, 2006). ST is very specific when compared to uninhibited sprinting with similar contact times, direction of force application, muscles, velocities and ranges of motion (Keogh, et al., 2010; Kristensen, et al., 2006). The results of this thesis support these findings, however, specificity and transfer to performance may decrease as sled loadings increase. The optimal sled setup, loading strategies as well as the sets and repetitions used to implement ST have been investigated previously (Alcaraz, et al., 2008; Cronin, et al., 2008; Lockie, et al., 2003; Maulder, et al., 2008; Murray, et al., 2005).

Whilst there is an ongoing discussion around sled loading strategies, there has been clear lack of research around the practicalities of ST, notably regarding the attachment point for the harnesses. Although no previous studies have examined the harness attachment points in ST during the acceleration phase of sprint running Lawrence et al., (2013) investigated the effects (shoulder and waist) on walking sled pulls. They reported kinematic differences and concluded that the shoulder harness would challenge the knee extensors more, and the waist harness the hip extensors. Therefore, the purpose of the first main study was to investigate different harness attachment points (waist and shoulder) and compare them to uninhibited sprint acceleration.

The results of this study indicated that ST, with the commonly prescribed loading to cause a 10% V_{Dec} in velocity, will alter sprint velocity, contact time as well as the 3-D kinematics of the trunk, hip, knee, and ankle joints. It is not surprising that both ST conditions led to reduced velocity and increased contact times, as participants must overcome the additional resistance provided by the mass of the sled and the coefficient of friction between the sled and the surface. The sagittal plane kinematics were typically altered more than the coronal or transverse planes. During all ST conditions peak flexion was significantly greater at the knee and ankle joints when compared to the uninhibited condition. It was proposed that such changes may enable participants to increase contact time and lower their centre of mass. Although there were fewer adaptations in the coronal and transverse planes, both ST conditions significantly reduced trunk rotations when compared to uninhibited sprint acceleration. Similarly, both ST conditions led to significant GRF alterations when compared to uninhibited sprinting. Net horizontal mean force, net horizontal impulse, and propulsive impulse were all increased. However, such measures may be explained simply by longer ground contact times, thus allowing more time to apply horizontal GRF.

The kinematic and kinetic alterations observed in this study differed depending on the harness attachment point. Firstly, the sagittal plan kinematic alterations at the trunk appear important. ROM was significantly lower in the shoulder trials which although not significantly different resulted from a greater trunk extension at foot-strike and greater flexion at toe-off. The shoulder attachment also led to significantly greater peak knee flexion when compared to the waist harness and a larger ROM than the uninhibited condition. It was speculated that such adaptations might enable the participants to lower their centre of mass to overcome the more upright trunk position at foot-strike. The GRF measures were affected differently also. The waist harness attachment led to significantly greater net horizontal impulse compared to the shoulder attachment trials and greater propulsive means when compared to the uninhibited sprint condition. Importantly, none of the ST contact time measures between ST conditions were significantly different.

Any practitioners incorporating ST into their training programme will benefit from this study, thereby allowing them to adjust their sled setup accordingly. The results indicate that the waist harness attachment point is the most suitable when training for the acceleration phase of sprinting. ST with this attachment led to fewer 3-D kinematic alterations and greater net horizontal impulses when compared to the shoulder harness attachment condition.

Sled loadings and the strategies of determining them have varied greatly among the different investigations. Studies have used light loads of 5% BM (Petrakos, et al., 2016) whereas others have opted for much heavier loads, such as 80% BM (Morin, et al., 2017). Findings indicate that as sled loadings increased, sprint kinematics were altered to a greater extent (Lockie, et al., 2003; Monte, et al., 2016; Murray, et al., 2005). As such, other investigations have recommended sled loadings of approximately 10% BM or 10% V_{Dec} to minimise the alterations to sprint kinematics (Maulder, et al., 2008). However, more recent investigations have reported that moderate to heavy loadings may be required to provide an optimal kinetic overload (Monte, et al., 2016). Therefore, the purpose of the second main study was to investigate the kinetics and 3-D kinematics of ST during the early acceleration phase of sprinting with a range of different sled loads (10, 15 and 20% V_{Dec}) compared to uninhibited trials.

Firstly, in agreement with the initial harness attachment study, 3-D kinematics were altered in all ST conditions when compared with uninhibited sprinting. Results indicated that velocity, contact times as well as trunk and lower body kinematics were affected more when sled loadings were increased. The longer contact times were explained by an extended propulsive phase, as suggested previously (Kawamori, et al., 2014; Monte, et al., 2016; Murray, et al., 2005). This increased propulsive contact time may be beneficial for acceleration performance, in this instance more horizontal force can be applied to the ground (Kawamori, et al., 2013; Morin, et al., 2016). There were several key sagittal plane kinematic changes at the trunk, knee and ankle joints. Ankle ROM was greater during sled trials, explained by a trend of increased dorsiflexion at foot-strike and increased plantarflexion at toe-off. Kinematic adjustments of this nature appear to allow the athletes to increase their stance phase contact times, as discussed previously. At the knee joint, flexion at foot-strike and peak flexion were greater in all sled conditions and increased with loading. It is believed that such adjustments allow athletes to lower their centre of mass and again increase contact time, thus increasing their horizontal force application. As discussed previously, trunk adaptations appear critical to overall sprint performance. It is believed that the greater trunk flexion at toe-off may enable athletes to further increase their horizontal force application.

Although ST investigations generally focus on the sagittal plane kinematics it is also important to consider the coronal and transverse plane adaptations. In the transverse plane, only the 20% V_{DEC} trials resulted in hip and knee joint kinematic changes when compared to uninhibited acceleration. Hip joint ROM was greater and there was more external rotation at the knee joint at toe-off. Such changes may be an indication that at the 20% loading and above athletes may be forced to compensate for the greater changes in sagittal plane kinematics, it is postulated that the break down in technique could be quite rapid at 25% V_{DEC} and beyond. The reduced trunk rotations during ST are a concern, as mentioned previously. In general, trunk rotations and the resultant ROM measures were greater for the uninhibited condition. Such rotations may help to minimise the displacement of centre of mass during the acceleration phase (Preece, et al., 2016), therefore, adaptations of this nature may not enhance sprint acceleration in the longer-term.

Increased sled loadings did not impact peak GRF as expected, there was only a trend for larger peak propulsive forces and although these may continue to rise with heavier loading it is at the expense of much longer contact times. However, as previous research suggests that the magnitude of forces may not be as important as the direction of force application (Kawamori, et al., 2013; Morin, et al., 2011). Results highlighted positive changes to propulsive and vertical mean force measures during the 20% V_{Dec} sled condition when compare to uninhibited acceleration. Such changes may highlight an increased horizontal force vector orientation when using sleds with a 20% V_{Dec} loading. In correspondence, both net horizontal and propulsive impulses were significantly greater in all sled conditions and increased with greater sled loadings.

The results of this study have shown that a sled loading of 20% V_{Dec} should be recommended to improve propulsive forces and impulses for the acceleration phase. The increased contact times during the 20% V_{Dec} trials may have helped to improve body positioning and resulted in the greater horizontal force vector orientation. Although, all ST conditions reduced trunk rotations the heavier loadings did not significantly increase these measures, whereas, the kinetic alterations significantly improved during the 20% V_{Dec} trials. Therefore, based on the positive kinetic changes it was concluded that the kinematic adjustments were beneficial during the acceleration phase.

Whilst cross-sectional studies can help the practitioner to understand the way loading can alter kinetics and kinematics, longitudinal interventions are necessary to explore the adaptive responses to such modifications. Many studies have investigated the effects of ST over various training periods, however the majority have used active or recreational populations (Lockie, et al., 2012; Makaruk, et al., 2013; Spinks, et al., 2007; Zafeiridis, et al., 2005). Several studies have examined the effects of ST on semi-elite or competitive-elite rugby league players (Harrison & Bourke, 2009; West, et al., 2013). Results indicate that ST can enhance acceleration performance, however methodological issues surrounding the studies mean it is difficult to either compare or employ the strategies utilised. Therefore, the purpose of this study was to compare the effects of 20% V_{DEC} ST versus UST in semi-elite rugby league players during the competitive season.

ST and UST can be employed to improve acceleration over 5, 10 and 20 m. These findings are consistent with those of previous investigations by West et al., (2013) and Harrison & Bourke (2009) who reported similar improvements following six-week interventions on similar testing populations. Although, differences between ST and UST were not significant practitioners can include 20% V_{DEC} ST into their programmes without fear of reduced performance. Therefore, ST may also be incorporated to provide some exercise variety which has been highlighted as being important to avoid performance plateaus and increase athlete motivation (Rhea, et al., 2002).

As predicted, CMJ height increased significantly in the ST group only; supporting previous research by Harrison & Bourke, (2009). These findings are in contrast to other investigations (Alcaraz, et al., 2014) (Lockie, et al., 2012), who suggested that the increased horizontal force orientation of ST would not transfer to CMJ performance. However, research suggests that exercise velocity and specificity of movement kinematics are also key for performance transfer, as such therefore training at a specific velocity should improve strength at that velocity (Cronin, McNair, & Marshall, 2002). As such, it is believed that the similar movement velocities of ST and CMJ led to performance enhancements. Change of direction performance did not improve significantly during either intervention group. Performance in change of direction activities is more complex than sprinting or jumping alone and other factors such as technique, muscle qualities and anthropometry might have some or more impact (Hoyo, et al., 2016; Gabbett, et al., 2008; Sheppard & Young, 2006).

The intervention study highlighted that the inclusion of ST in an eight-week in-season training programme for semi-elite rugby league players did provide benefits over UST. Although ST improved explosive power, such adaptations did not transfer through to the acceleration phase as distinctly as they did to executing a CMJ. This is likely to be because of the difference between tasks, as CMJ demands are principally force-based, whereas increasing sprint distances tend more towards velocity-based demands with considerably shorter contact times.

8.3. Original contribution to knowledge

Firstly, this thesis has enabled a greater understanding of the impact of force plate targeting during the acceleration phase of sprinting in a semi-elite rugby league population (Pilot Study 1). The findings highlighted that force plate targeting had minimal impact on these participants who regularly carry out sprint training. Results of this nature emphasise the importance of specificity, practitioners and researcher should consider the training age of the participants when analysing research or implementing different training strategies.

The investigation into the kinetic and 3-D kinematic impact of ST utilising different harness attachment points (Study 1) enhanced the existing knowledge around the optimal sled setup. Results indicated that the waist attachment point appears to be the most suitable when training for the acceleration phase of sprinting utilising a 10% V_{DEC} loading. ST with this attachment led to fewer 3-D kinematic alterations and greater net horizontal impulses when compared to the shoulder attachment condition. Alterations of this nature are likely beneficial when training for sprint acceleration, in this phase great emphasis is placed on horizontal force application which is enhanced by the longer contact times.

Throughout this thesis sleds were loaded based on a percentage of velocity decrement (V_{DEC}). However, to provide a comparison the equivalent BM percentages were reported also. The sled loading study (Study 2) highlighted the importance of employing the correct loading strategy when implementing ST. As sled loadings increased the standard deviations increased also, this increased variation most likely highlights the differences in strength and technical ability between participants. Therefore, V_{DEC} sled loading is the recommended approach, this technique accounts for strength and technical ability as well as the different dynamic friction coefficients of the various surfaces.

The investigation on the impact of ST with a range of different loadings prescribed using the V_{DEC} method (Study 2) provided an original contribution to knowledge. This was the first ST study to examine trunk and lower body 3-D kinematics, contact time variables and kinetics during early acceleration in semi-elite team-sport athletes. The major findings of this study were that as sled loadings increased trunk and sagittal plane lower body kinematics were altered to a greater extent. The propulsive impulse measures in the 20% V_{Dec} sled trials were also significantly greater than all other conditions. As such, a sled loading of 20% V_{Dec} was recommended as it enables practitioners to increase propulsive forces and impulses. It is further speculated that heavier sleds may not prove superior as 3-D kinematic compensations could outweigh the positive kinetic alterations.

The final investigation (Study 3) of this thesis examined the longer-term performance benefits of ST during the competitive phase of the season in semi-elite rugby players. This study contributed to the current knowledge base in several ways, no other investigations have used V_{DEC} ST on semi-elite athletes during the competitive phase of the season. All the previous intervention studies on semi-elite or competitive-elite team-sport athletes have used lighter sled loading strategies, as such the results from this intervention were unique. As discussed previously, for semi-elite rugby league players, ST appears to provide marginal benefits over UST when implemented as part of an in-season training programme.

8.4. Recommendations for the applied practitioner

The findings of this thesis may be used by practitioners to inform ST strategies and improve performance. The key recommendations are as follows:

- Practitioners should look to employ a V_{DEC} sled loading strategy. Ideally V_{DEC} will be examined using a timing gate system, however, although not as accurate other methods may also be utilised e.g. stopwatch. This will enable practitioners to not only utilise different training surfaces effectively but also load the sleds based on the athlete's strength and technique capabilities.

- The waist is the preferred attachment point when training for the acceleration phase of sprinting (0 – 20 m). ST with this attachment led to fewer 3-D kinematic alterations and greater net horizontal impulses when compared to the shoulder harness attachment condition.

- There doesn't appear to be one optimal sled loading strategy, heavier sleds may benefit from a kinetic point of view whereas lighter loaded sleds are closer to the kinematics of uninhibited sprinting. Therefore, a blanket application of a single load may not be the most appropriate strategy.

- The 20% V_{DEC} sled loading is an effective strategy for the acceleration phase of sprinting. However, the increased propulsive forces and impulses were at the expense of velocity, contact time and 3-D kinematic alterations which should be considered.

- Practitioners should adopt a periodised approach to ST. For example, training with a 20% V_{Dec} sled loading will allow a greater emphasis on the horizontal application of forces before progressing to lighter sled loads or UST to allow a greater transfer to performance.

- The twice-weekly ST programme incorporated with all other forms of training (gym, technical and tactical sessions) appears sufficient for performance adaptations in semi-elite rugby league players. Further ST sessions may be difficult to fit into the concurrent training schedule and may increase the risk of overtraining.

- Practitioners should utilise four-week long ST training interventions when looking to enhance acceleration. Not only were performance improvements over the initial four-week training period greater but interventions of this length are much easier to schedule and plan effectively.

8.5. Limitations and recommendations for future research

It is important to consider and acknowledge the limitations of any research or thesis. This in turn allows for appropriate conclusions to be drawn and future research recommendations be devised.

The lab-based experiments implemented as part of this thesis often shared the same methodological issues. Firstly, the lack of multiple force plates in the biomechanics laboratory meant that testing protocols had to be adjusted. Starting positions were adjusted so participants contacted the force plate on their third foot-strike. As such, it was not possible to examine the GRF of any other step during acceleration. As discussed previously, the use of a single force plate positioned approximately 3 m into the sprint start also increased the chances of targeting and altered lower-body kinematics (Challis, 2001; Sinclair, et al., 2014). Pilot studies informed all subsequent testing protocols which were amended to minimise any force plate targeting. Future investigations should look to examine the whole early acceleration phase using a series of embedded force plates.

Secondly, the range of sled loadings examined may be seen as a limitation. The common sled loading of 10% V_{DEC} was selected during the harness attachment point study (Chapter 5) and a range of light to moderate (10, 15 and 20% V_{DEC}) loadings were used in the sled loading study (Chapter 6). The harness attachment point study was used to inform the sled loading study, as such the loading was selected based on previous recommendations (Maulder, et al., 2008). Unfortunately, it was not possible to select a wide range of sled loading as testing comprised of multiple conditions (uninhibited, waist and shoulder) with repeated trials. Similarly, the sled loading study involved participants sprinting in four different conditions on a number of occasions. All sprints were completed at high-intensity; therefore any additional trials would have increased participant fatigue and may have impacted on the kinematic and kinetic data obtained. Recent investigations have placed an emphasis on heavier sled loadings (Monte, et al., 2016; Morin, et al., 2016), however at the time of data collection there was little suggestion such loadings would be appropriate. Therefore, future investigations should examine heavier sled loadings e.g. 30, 40 and 50% V_{DEC}. Such studies would help to determine whether heavier sled loading strategies would have a greater kinetic benefit to outweigh more kinematic alterations.

Finally, a reduced marker set (CAST) was used during all lab-based experiments. This marker set meant that the 3-D kinematics of the trunk, stance leg kinematics of the right thigh, right shank, and right foot could be determined. However, the trunk was analysed as a single rigid section and it was not possible to obtain kinematic data on the other leg or the arms. Kinematic data on the arms and a more detailed marker set on the trunk would have enabled a more in-depth analysis of sprint acceleration. For example, it is clear there were important interactions between the transverse plane trunk kinematics and the arm drive. Unfortunately, it is beyond the scope of this thesis to discuss such interactions. Therefore, future studies should utilise a full marker set (CAST) providing data on full-body kinematics with a multi-segment trunk model.

There were also several limitations associated with the final intervention study, as discussed previously (Chapter 7). Unfortunately, the sprint times, CMJ and change of direction measures completed pre, mid and post intervention only highlight performance improvements. More detailed testing procedures (biomechanical, physiological and performance tests) might have enabled the identification of important adaptations. For example, the lab-based testing utilised in the earlier studies may have provided some interesting information regarding the kinematic and kinetic adaptations following ST. As such, all future intervention studies should incorporate detailed testing (biomechanical, physiological and performance tests) pre, mid and post training. The eight-week intervention period might not have been long enough for all the training adaptations to occur. Any muscle fibre and contractile adaptations generally only transpire in the later stages of a training programme (Campos, et al., 2002; Costill, et al., 1979; Deschenes & Kraemer, 2002). Therefore, if the training period was extended by four-weeks then further adaptations might have occurred. Although this study had its limitations it must be noted that this is a semi-elite training population and testing had to fit in with the typical training routine. As such, compromises had to be made to the programming as well as the testing procedures. Future studies should look to extend the intervention period beyond eight-weeks.

Although questions still remain unanswered, the literature base on the acute changes to ST is fairly extensive. In contrast, there is a clear lack of quality intervention studies on semi-elite, competitive-elite and successful-elite athletes/teams (Swann, et al., 2015). Such studies would provide further insight into important factors such as programming, as well as the overall effectiveness of ST. For example, the final intervention study (Chapter 7) compared the longitudinal effects of 20% V_{DEC} ST and UST programmes using a randomised between-participants design. Although, the ST condition resulted in marginal benefits over UST alone a combined approach may be more effective again. Therefore, future investigations should attempt to manipulate the different programming variables and look to identify optimal strategies e.g. the frequency, sets, reps, recovery periods along with a combined ST and UST approach.

8.6. Conclusion

Overall, the findings from this thesis have provided new insights into the optimal sled setup, loading strategies and programming variables affecting a ST training intervention. It is recommended that sleds should be attached using a waist belt. Sleds should be individually loaded based on acceleration performance (V_{DEC}) and incorporated into the periodised programme accordingly. The 20% V_{DEC} may be used to increase propulsive forces and impulses, although such kinetic changes are at the expense of reduced trunk rotations. This ST strategy led to benefits over UST following an eight-week training intervention. As such, a twice-weekly ST intervention is recommended for semi-elite rugby league players during the competitive phase of the season.

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Appendices

Appendix A: Calibration of the 3-D motion analysis system

Appendix B: Intrarater and test-retest reliability of the anatomical model and marker set

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Appendix I: A sample of the journal matrix produced during the systematic review process

Appendix A: Calibration of the 3-D motion analysis system

Introduction

The accuracy of the data collected from 3-D motion analysis systems is largely dependent on the calibration procedure (Richards, 2008). A dynamic calibration is the most common method employed, during which a static frame is positioned in the zero position and the wand is moved dynamically to define the global coordinate system (Figure A1). The global coordinate system refers to the capture volume created by the dynamic wand movements, this space must be large enough for the whole activity to be performed in (Figure A2) (Robertson, et al., 2014). Lower average residuals and standard deviation of wand length are associated with fewer errors, thus improving the subsequent data collection (Richards, 2008). The aim of this study was to compare different calibration techniques to discover the most suitable method.

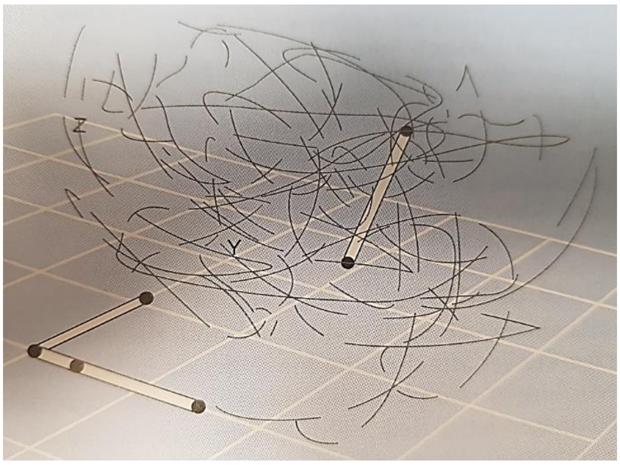

Fig A1: A representation of the static frame position and dynamic wand movements (Richards, 2008).

Methods

Procedures

Ten 30 s calibrations were completed for three different wand movement techniques; straight brushing movements (side to side, up and down wand movements), rotations (spinning the wand in different directions) and a combination technique (straight and rotational wand movements). During calibrations the static frame was positioned on the embedded force plate (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments, Winterthur, Switzerland).

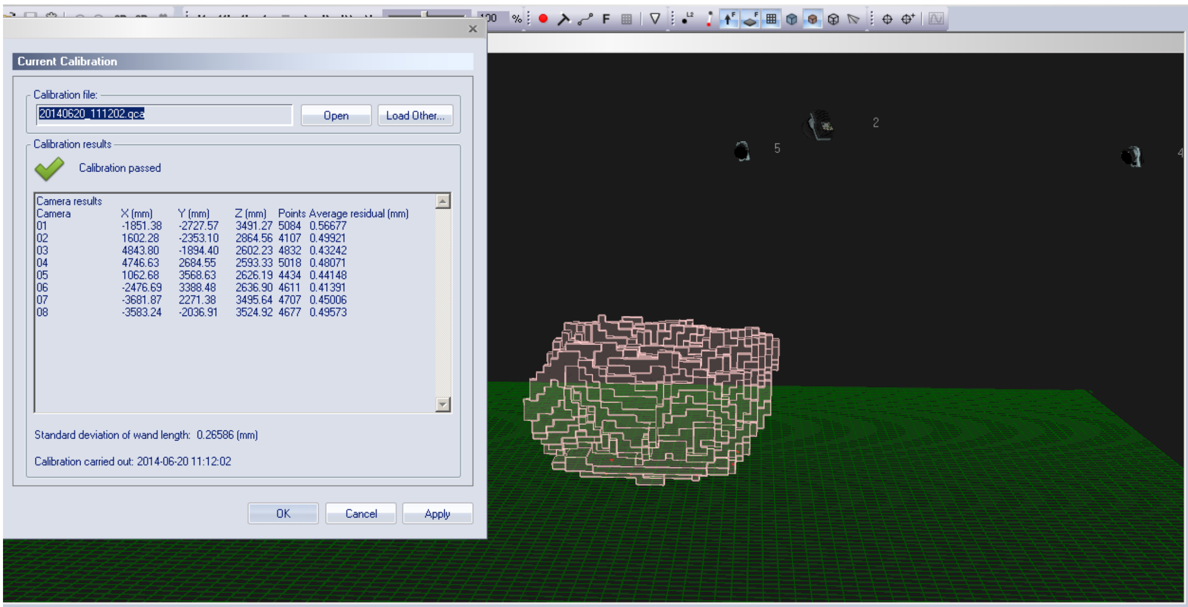

Figure A2: An example of the calibration results (points, average residuals and calibrated space).

Statistical analysis

One-way between subject's ANOVA was used to compare the means of the different conditions (straight, rotations and combination) with the different outcome measures (average points, average residuals and standard deviation of wand length) (means ± SD). The significance level was set at $p \leq 0.05$. Post hoc pairwise comparisons were conducted on all significant main effects using a Bonferroni adjustment to control for type I error. All statistical procedures were conducted using SPSS 20.0 (SPSS Inc, Chicago, USA).

Results

The results (average points, average residuals and standard deviation of wand length) are presented in Table A1.

Table A1: Analysis of the different wand movement calibration techniques.

Calibration Technique	Points	Residuals	Standard Deviation of Wand Length
Linear	4803.60 ± 353.29	0.37 ± 0.05	0.28 ± 0.03*
Rotations	4655.90 ± 285.36*	0.39 ± 0.05	0.26 ± 0.02*
Combination	5052.40 ± 313.20	0.35 ± 0.04	0.23 ± 0.01

* Significantly different from the combination technique ($p < 0.05$).

The combination technique produced significantly lower standard deviation of wand length when compared to the rotations and straight movements alone ($p < 0.05$). The combination technique also resulted in higher average points when compared to the rotation technique ($p < 0.05$).

Discussion

The combination technique of straight movements and rotations was more effective than straight or rotational movements alone. Calibrating using this technique resulted in significantly lower standard deviation of wand length, this measure has been linked to fewer errors in data collection (Richards, 2008). As a result of this experiment the motion analysis system was calibrated using the combination of straight and rotational movements throughout this thesis.

Appendix B: Intrarater and test-retest reliability of the anatomical model and marker set

Introduction

3-D motion camera systems are used extensively during gait analysis in both clinical and research settings. The CAST method is considered the gold standard for 3-D kinematic analysis (Sinclair, et al., 2012). This technique relies on the identification of anatomical landmarks through external palpation and allows researchers to model each body segment in six degrees of freedom (Cappozzo, et al., 1995).

Previous studies have not only highlighted kinematic reliability differences from lab to lab, but have also shown that reliability among researchers can also be an issue (Gorton, et al., 2009). This is of importance when undertaking gait analysis, were multiple participants will be assessed for each research study. Therefore, reliability and validity of such measurements should be known, thus allowing 3-D analysis to be used appropriately (Rothstein & Echternach, 1993). The aim of the current study was to assess the primary researcher's marker placement reliability.

Methods

Participants

Twelve male participants (age: 26.7 ± 3.5 years; BM: 82.7 ± 9.4 kg; stature: 173.8 ± 7.4 cm) volunteered for this study. All participants were free from injury at the time of data collection. All participants gave written and informed consent before attending the testing sessions.

Procedures

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. The system was calibrated before every testing session. Participants walked across the 22 m laboratory, striking an embedded force platform (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd.) sampling at 1000 Hz. Each participant completed three trials, in order to be deemed successful their whole right foot (right leg) had to contact the force platform.

In order to determine stance leg kinematics (foot, shank, thigh and trunk segments) retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1st metatarsal head, 5th metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle, acromion process (both), T12 and C7 (Cappozzo, et al., 1995). The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell, et al., (1989) equation utilising the positions of the PSIS and ASIS markers. During walking trials the foot segment was tracked using the calcaneus, 1st and 5th metatarsal heads. Rigid cluster tracking markers were comprised of four 19 mm reflective markers mounted on a carbon fibre plate with a length to width ratio of 1.5 - 1, they were positioned on the right shank and thigh segments (Cappozzo, et al., 1997). The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. The trunk was tracked using markers at both acromion processes, as well as the T12 marker.

Two static calibration trials were collected with the participants standing in the anatomical position. The first static calibration was taken before the walking trials were recorded. During all walking trials anatomical markers were removed. All tracking markers (foot, pelvis, trunk and cluster markers) remained in place for the duration of the data collection, thus allowing the test-retest reliability of the anatomical marker placement to be examined. Following the walking trials the anatomical markers were reapplied and the second static calibration trial was conducted, similar to the methods used in the study by Sinclair et al., (2012).

Data processing

Motion files were exported as C3D files and quantified using Visual 3-D (C-Motion Inc., Germantown, USA) and filtered at 6 Hz using a Butterworth 4^{th} order filter. 3-D kinematics of the lower extremities and trunk were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). The relevant segments (thorax, thigh, shank and virtual foot) and reference segments (pelvis, thigh and shank) were used to calculate joint angles of the trunk, hip, knee and ankle joints respectively. All kinematic waveforms were normalised to 100% of the stance phase. Contact time was determined as time over which 20 N or greater of vertical force was applied to the force platform (Sinclair, et al., 2011). Various kinematic measures from the trunk, hip, knee and ankle joints were investigated: angle at foot-strike, angle at toe-off and peak angle. These variables were extracted from each of the three trials for each joint, data were then averaged within participants for a comparative statistical analysis.

Statistical analysis

Descriptive statistics were calculated and presented as mean and standard deviations. Paired samples t-tests were utilized to examine the kinematic parameters ($p \leq 0.05$). ICC (3, k) were undertaken to investigate the test and retest waveforms (sagittal, coronal and transverse) of the trunk, hip, knee and ankle joints. Magnitudes of ICC were classified according to the following thresholds: > 0.9 nearly perfect; 0.7–0.9 very large; 0.5–0.7 large; 0.3–0.5 moderate; and 0.1–0.3 small (Hopkins, 2002). All statistical procedures were conducted using SPSS 20.0 (SPSS Inc, Chicago, USA).

Results

Tables A2 – A5 present the 3D kinematic data at each of the joints investigated for the test and re-test conditions. The overall patterns of the resultant 3-D kinematic waveforms were qualitatively similar (Figure A3), with no statistical differences observed at the trunk, hip, knee or ankle joints.

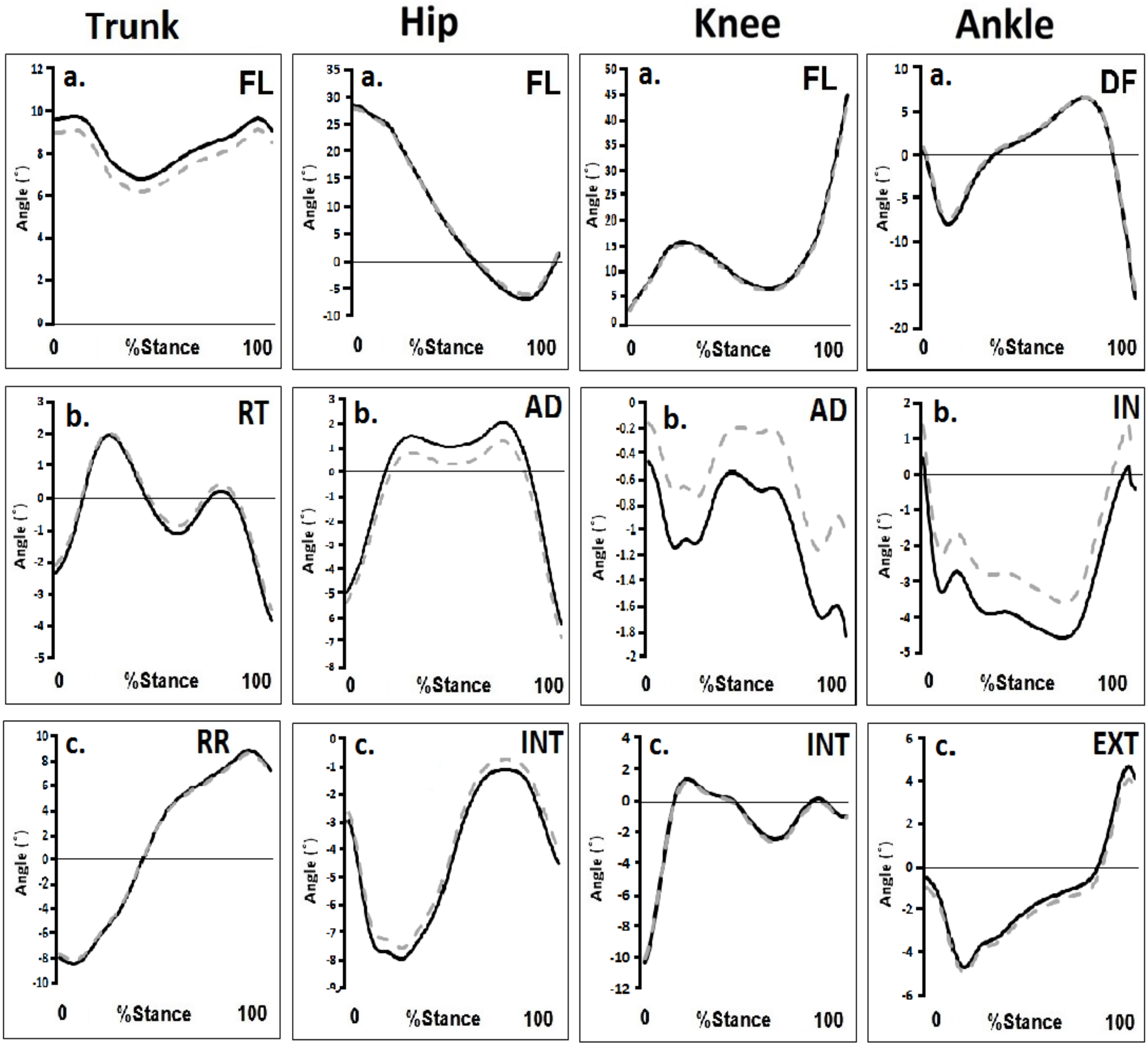

Figure A3: Mean trunk, hip, knee, and ankle joint kinematics in the a) sagittal, b) coronal, and c) transverse planes for the test (bold black line) and retest (dashed grey line) conditions.

Table A2: Trunk kinematics (means and standard deviations) during test and re-test marker placement conditions.

	Test	Re-test	Mean Difference (°)
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	9.78 ± 7.84	8.93 ± 8.84	.85
Angle at toe-off (°)	9.17 ± 5.84	8.47 ± 7.23	.70
Peak flexion (°)	12.58 ± 6.84	11.51 ± 7.99	1.07
	Y (+=right tilt/-=left tilt)		
Angle at foot-strike (°)	-2.33 ± 2.78	-1.92 ± 3.11	.41
Angle at toe-off (°)	-4.16 ± 4.17	-3.59 ± 3.86	.57
Peak tilt (°)	2.53 ± 2.75	2.71 ± 3.10	.18
	Z (+=right rotation/-=left rotation)		
Angle at foot-strike (°)	-8.27 ± 6.25	7.88 ± 4.67	.39
Angle at toe-off (°)	7.86 ± 6.17	7.52 ± 7.35	.34
Peak rotation (°)	9.66 ± 6.56	9.28 ± 7.89	.38

* Significantly different from the test condition $p \leq 0.05$

There were no significant differences ($p > 0.05$) in trunk kinematics in the sagittal, coronal and transverse planes between the test and re-test conditions. Comparisons between test and retest kinematic waveforms revealed strong correlations for the sagittal (ICC = 0.76), coronal (ICC = 0.95) and transverse (ICC = 0.98) planes at the trunk.

Table A3: Hip joint kinematics (means and standard deviations) during test and re-test marker placement conditions.

	Test	Re-test	Mean Difference (°)
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	28.89 ± 6.21	28.01 ± 6.85	.88
Angle at toe-off (°)	1.41 ± 5.25	2.07 ± 5.84	.93
Peak flexion (°)	29.27 ± 5.99	28.38 ± 6.70	.89
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	-5.29 ± 7.35	-5.51 ± 6.24	.22
Angle at toe-off (°)	-6.41 ± 5.33	-6.84 ± 4.39	.43
Peak adduction (°)	3.31 ± 5.23	2.54 ± 4.41	.77
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-2.90 ± 7.75	-3.21 ± 7.17	.31
Angle at toe-off (°)	-3.64 ± 14.24	-3.62 ± 9.86	.02
Peak internal rotation (°)	2.94 ± 12.50	2.71 ± 9.30	.23

* Significantly different from the test condition $p \leq 0.05$

There were no significant differences ($p > 0.05$) in hip joint kinematics in the sagittal, coronal and transverse planes between the test and re-test conditions. Comparisons between test and retest kinematic waveforms revealed strong correlations for the sagittal (ICC = 1.00), coronal (ICC = 1.00) and transverse (ICC = 0.99) planes at the hip joint.

Table A4: Knee joint kinematics (means and standard deviations) during test and re-test marker placement conditions.

	Test	Re-test	Mean Difference (°)
X (+=flexion/-=extension)			
Angle at foot-strike (°)	2.56 ± 3.94	2.19 ± 3.40	.37
Angle at toe-off (°)	44.95 ± 6.01	42.50 ± 8.09	2.45
Peak flexion (°)	44.95 ± 6.01	42.50 ± 8.09	2.45
Y (+=adduction/-=abduction)			
Angle at foot-strike (°)	-.17 ± 4.92	.17 ± 4.92	.34
Angle at toe-off (°)	-1.66 ± 4.92	-1.08 ± 3.71	.58
Peak adduction (°)	1.99 ± 3.29	1.91 ± 3.57	.08
Z (+=internal/-=external)			
Angle at foot-strike (°)	-10.76 ± 6.63	-10.35 ± 4.71	.41
Angle at toe-off (°)	-1.05 ± 7.50	-1.22 ± 4.36	.17
Peak internal rotation (°)	2.77 ± 7.62	2.60 ± 4.95	.17

* Significantly different from the test condition $p \leq 0.05$

There were no significant differences ($p > 0.05$) in knee joint kinematics in the sagittal, coronal and transverse planes between the test and re-test conditions. Comparisons between test and retest kinematic waveforms revealed strong correlations for the sagittal (ICC = 1.00) and transverse (ICC = 1.00) planes at the knee joint. Comparisons in the coronal (ICC = 0.67) plane revealed moderate correlations.

Table A5: Ankle joint kinematics (means and standard deviations) during test and re-test marker placement conditions.

	Test	Re-test	Mean Difference (°)
X (+=dorsiflexion/-=plantarflexion)			
Angle at foot-strike (°)	.93 ± 4.98	1.18 ± 4.22	.25
Angle at toe-off (°)	-16.18 ± 8.98	-15.55 ± 8.26	.63
Peak dorsiflexion (°)	8.00 ± 4.92	7.84 ± 3.94	.16
Y (+=inversion/-=eversion)			
Angle at foot-strike (°)	.65 ± 2.74	1.52 ± 3.12	.87
Angle at toe-off (°)	-.08 ± 4.75	.98 ± 3.44	.90
Peak eversion (°)	2.88 ± 3.11	3.58 ± 2.96	.70
Z (+=external/-=internal)			
Angle at foot-strike (°)	-.31 ± 2.63	-.91 ± 1.84	.60
Angle at toe-off (°)	4.51 ± 4.95	3.71 ± 3.21	.80
Peak internal rotation (°)	5.68 ± 4.62	4.80 ± 3.08	.88

* Significantly different from the test condition $p \leq 0.05$

There were no significant differences ($p > 0.05$) in ankle joint kinematics in the sagittal, coronal and transverse planes between the test and re-test conditions. Comparisons between test and retest kinematic waveforms revealed strong correlations for the sagittal (ICC = 1.00), coronal (ICC = 0.83) and transverse (ICC = 1.00) planes at the ankle joint.

Discussion

The aim of this study was to assess the test re-test reliability of the primary researcher's marker placement skills (CAST method). This represents was an important study, as many participants were tested during the lab-based experiments of this thesis.

The results show that there were no significant differences between the kinematic data extracted from the test and re-test static trials. This finding is in line with those of Sinclair et al., (2012). The ICC analyses highlight very strong relationships (ICC > 0.9) for the majority of joints in all planes (sagittal, coronal and transverse). Results indicate that agreement was only lower (ICC < 0.9) for the sagittal plane trunk (ICC = 0.76) waveforms as well as the knee (ICC = 0.67) and ankle (ICC = 0.83) joints in the coronal plane.

Previous research has suggested that angular differences of less than 2° are highly likely to be classed as acceptable in a clinical setting. Errors of between 2 and 5° were classed as reasonable whereas errors of 5° or more could misinform clinical analyses and were classed as excessive (McGinley, et al., 2009). As such, the marker placement technique used by the primary researcher appears to be acceptable as the majority of errors were less than 2°. Knee joint sagittal plane peak flexion and angle at toe off were greater than 2°, although these errors were greater the guidelines suggest they were still reasonable in a clinical setting (McGinley, et al., 2009).

Conclusion

The results of this investigation suggest that the primary researcher's marker placement skills (CAST technique) were reliable and can be repeated accurately.

Appendix C: Coefficient of friction of different testing surfaces

Introduction

When implementing ST exercises the coefficient of friction (μ) between the base of the sled and the running surface has a huge impact on the load placed on the athlete (Cronin & Hansen, 2006; Halliday, et al., 2001). As discussed previously, practitioners often set the loading of the sled as a percentage of the athlete's BM so as to account for the fact that larger athletes tend to have greater muscular strength and can generate greater muscular power (Kawamori, et al., 2014; Spinks, et al., 2007). However, to precisely account for strength, power or technical ability then loadings should be determined by V_{Dec} (Petrakos, et al., 2016). The sled loadings utilised in this thesis will be determined by the V_{Dec} strategy as recommended previously (Cronin & Hansen, 2006). When implementing % BM ST it is good practice to know the coefficient of friction of the surface, as this allows accurate replication during training or testing. Although, not as important when loading sleds via the V_{Dec} strategy, such knowledge does allow comparison with other research studies. Therefore, the aim of this study was to investigate the dynamic coefficient of friction for a number of surfaces that were used during testing, thus enabling comparison with other studies, particularly those which have employed a % BM loading strategy.

Methods

The dynamic μ of four different surfaces was examined (e.g. hard indoor sports hall, natural grass, 3G AstroTurf pitch and a synthetic laboratory floor) using the 'friction sled' method as used previously (Linthorne & Cooper, 2013). These commonly used surfaces could have been utilised during the laboratory-based or field-based studies of this thesis (Figure 4.3).

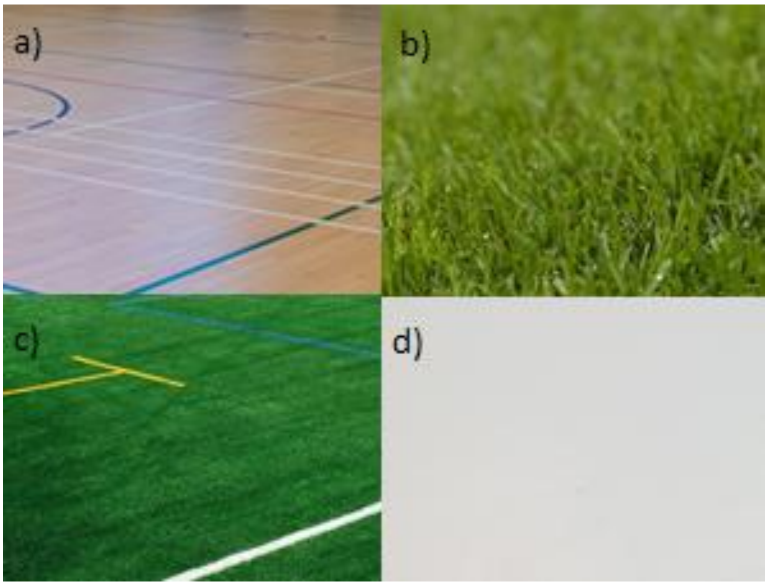

Figure A4: Examples of the different surfaces used during this thesis; a) hard indoor sports hall, b) natural grass, c) 3G AstroTurf pitch, and d) synthetic laboratory floor.

In this method, a normal force is applied to the body and the tangential towing force required to move the body at constant velocity across a surface is measured. The gradient of the (linear) relation between the normal force and the tangential towing force gives the coefficient of kinetic friction (e.g. $F = \mu N$) (Linthorne & Cooper, 2013). The sled had a mass of 7.5 kg and an additional load of 45 kg was also added, giving a total mass of 52.5 kg (514.85 N). The sled was towed by hand at a constant velocity of about 0.5 $m.s^{-1}$ while the towing force on the sled was measured through the Delsys S-shaped load cell (Delsys Trigno Wireless System, Massachusetts, USA) (Figure 4.4). Two timing gates were placed 5 m apart and the velocity of the sled was calculated from the elapsed time obtained from the two gates. When towing the sled, the towing force and S-shaped load cell were horizontal to within about 5°. The subsequent force–time data were recorded as a mean value for a 2 s period, like the methods used by Linthorne & Cooper (2013) (Figure 4.5). Three trials were completed in each condition and the average was used in further analysis. Dynamic coefficients of friction were calculated and presented as mean and standard deviations.

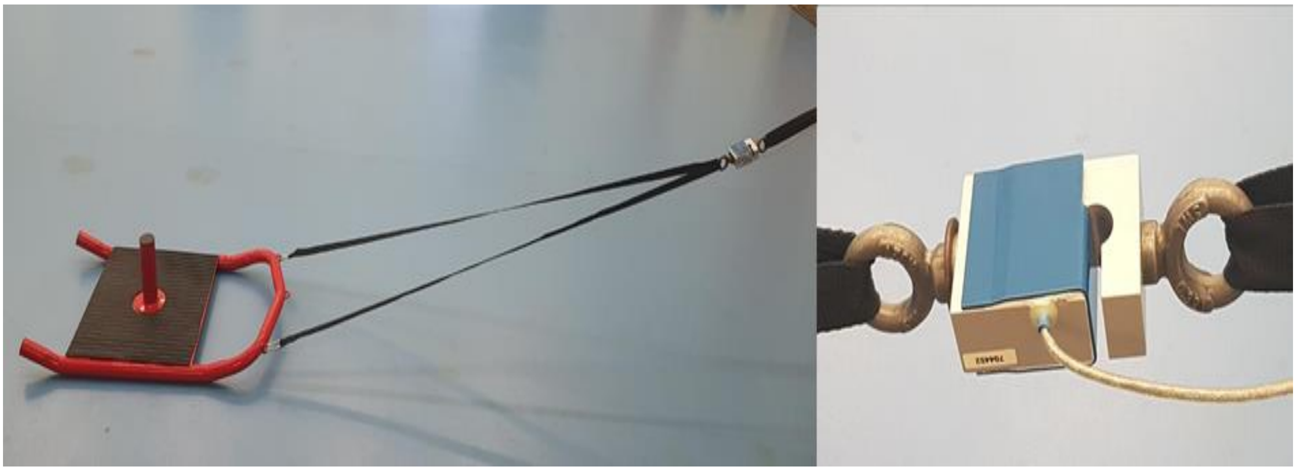

Figure A5: Examples of the S-shaped load cell position between the sled attachment cords.

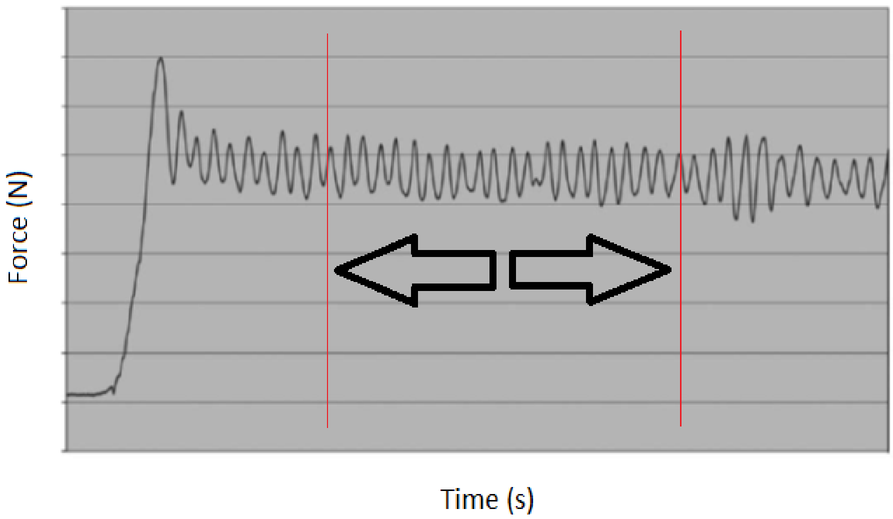

Figure A6: A sample trace from the S-shaped load cell (capture zone highlighted in red).

Results

Table A6 presents the coefficient of friction for the different surfaces investigated.

Table A6: The coefficient of friction (μ) (means and standard deviations) of the different surfaces utilised during testing.

Surface Type	Coefficient of Friction
Hard indoor sports hall	.38 ± .01
Natural grass	.56 ± .03
3G AstroTurf	.50 ± .02
Synthetic laboratory floor	.41 ± .01

Discussion

The dynamic coefficient of friction of the four different surfaces measured in this study were quite diverse. This is in line with the findings of similar research by Linthorne & Cooper (2013) who also measured a number of different sports playing surfaces. Although similar there were distinct differences in the dynamic coefficients of friction between these investigations, this is likely due to variation between the surface characteristics or environmental conditions (e.g. between 3G AstroTurf manufacturers or whether or not it was raining during testing etc.). As such, studies have advised against using published equations to determine the sled weight for an athlete (Linthorne & Cooper, 2013). Such equations were developed on a specific surface and may not transfer accurately to other surfaces.

The variation of coefficient of friction between the different surfaces can also have an impact on the behaviour of the sled during trials. Observations throughout testing highlighted that the sleds bounced more as the coefficient of friction increased. These sled behaviours were minimised by standardising the starting protocol, such as getting into a low a 3-point position and taking up all of attachment cord slack prior to setting off. These adjustments were implemented throughout the thesis.

Conclusion

All sled loading calculations in this thesis were prescribed using the V_{Dec} strategy which eliminates many of the problems associated with testing across different surface types. However, the dynamic coefficient of friction was still reported for all surface types, thus allowing a comparison with previous research using % BM loading strategies.

Appendix D: Force platform targeting in a recreationally active population

Introduction

The analysis of kinetics and kinematics during walking or running in a laboratory setting generally requires the participants to make foot contact with an embedded force plate (Challis, 2001; Sinclair, et al., 2014). Participants have been known to alter their natural running gait to ensure contact with the device, such deliberate striking is known as targeting (Challis, 2001). When participants adjust their running gait to target the force platform the resulting data may be compromised (Sinclair, et al., 2014).

During walking trials, embedded force plate targeting has been shown to have no significant impact on ankle joint kinematics (Greenhalgh, et al., 2014). The majority of variables measured at the hip and knee joints were also similar to those of uninhibited walking. However, the researchers identified differences in hip abduction, knee flexion/extension and knee abduction (Greenhalgh, et al., 2014). Sinclair et al., (2014) investigated how running across an embedded force plate affected the kinematics of the lower extremities. They found negligible differences between the embedded force plate and uninhibited running conditions at the hip and knee joints. Only sagittal plane ankle kinematics were significantly altered during the targeting trials. Various kinematic differences were apparent when embedded force plates were used for walk/run studies. However, researchers suggest such alterations are acceptable in a research setting when the results are interpreted with some caution (Greenhalgh, et al., 2014; Sinclair, et al., 2014).

To the researcher's knowledge, no studies have investigated how sprinting across a force plate may impact on the kinematics of the lower extremities. Therefore, the aim of the current investigation was to examine the influence of force plate striking on 3-D kinematics of the lower extremities and participant's subjective perceptions during the early acceleration phase sprinting.

Methods

Participants

Thirteen participants (10 males and 3 females) volunteered to take part in this investigation (age: 26.2 ± 3.8 years; mass: 76.5 ± 8.9 kg; stature: 174.8 ± 8.2 cm). All participants were injury free and were involved in recreational sport at the time of data collection. All participants gave written and informed consent before attending the testing session.

Procedures

Participants were asked not to participate in any physical activity 24 hours before the testing session. No food was allowed to be consumed during testing, though water was allowed throughout. The testing session began with a standardised warm-up consisting of jogging (5 minutes), dynamic stretching (5 minutes) and several sprints building up to maximum intensity (4 x submaximal and 2 x maximal).

Participants sprinted 6 m in two conditions, 1) over an embedded force plate, and 2) uninhibited sprinting to the side of the force plate without concern for striking it. Participants had two minutes recovery between each of the sprint trials. Five trials were collected for each condition in a randomized order. The embedded force plate (model 9281CA; dimensions = 0.6 x 0.4 m, Kistler Instruments Ltd.) which sampled at 1000 Hz was positioned approximately 3 m from the starting position. In order for the trials to be deemed successful, the whole foot had to contact the force platform. Starting positions were adjusted so that the dominant (right) foot contacted the force plate (during striking trials) on their third step following the starting stance. This adjustment typically took several practice accelerations. All participants chose to start with their left foot leading in the 3-point starting position. Regardless of the starting point, participants sprinted a total distance of 6 m before decelerating.

An eight-camera motion analysis system (Qualisys Medical AB, Gothenburg, Sweden) was used to capture kinematic data at 250 Hz. The system was calibrated before every testing session. In order to determine stance leg kinematics (foot, shank and thigh segments) retro-reflective markers were placed on the following bony landmarks; the right calcaneus, 1^{st} metatarsal head, 5^{th} metatarsal head, medial malleolus, lateral malleolus, medial epicondyle, lateral epicondyle (Cappozzo, et al., 1995). The pelvis segment was defined, using additional markers on the ASIS and PSIS. Hip joint centre was determined based on the Bell et al., (1989) equations via the positions of the PSIS and ASIS markers. During dynamic trials the foot segment was tracked using the calcaneus, 1^{st} and 5^{th} metatarsal heads. Rigid cluster tracking markers were also positioned on the right shank and thigh segments (Cappozzo, et al., 1997). The ASIS, PSIS and greater trochanters were used as tracking markers for the pelvis. A static calibration was completed and used as reference for anatomical marker placement in relation to the tracking markers. After which all non-tracking markers were removed.

As force data were not available in both conditions, foot-strike and toe-off were determined using kinematic based methods, identical to those used by Nagahara & Zushi, (2013). This method relied on a kinematic detection method using the marker placed on the 1st metatarsal head. Peak vertical acceleration was used to determine the initial foot-strike, and toe-off was identified when the marker reached its lowest point (towards the end of the stance phase) (Nagahara, et al., 2014). After the testing session participants were asked to rate their subjective comfort in striking the force plate in relation to uninhibited sprinting next to the plate using a 10-point Likert scale, 10 representing totally comfortable and 0 being totally uncomfortable.

Data processing

Trials were digitized using Qualysis track manager, exported to Visual 3-D (C-motion, Germantown, USA) and filtered at 12 Hz using a Butterworth 4th order filter. Lower extremity kinematics were calculated using an XYZ cardan sequence of rotations (X represents the sagittal plane, Y represents the coronal plane and Z the transverse plane). All kinematic waveforms were normalised to 100% of the stance phase and then processed trials were averaged. Various stance phase 3-D kinematic parameters (hip, knee and ankle) were extracted for statistical analysis; angle at foot-strike, angle at toe-off, peak angle during stance, range of motion (the angular displacement from foot-strike to toe-off during stance) and the relative range of motion (Rel ROM) (the angular displacement from foot-strike to peak angle).

Statistical analysis

Descriptive statistics were calculated for each of the sprint conditions (mean ± SD). Differences between kinematic, velocity and subjective parameters were examined using multiple paired samples t-tests ($p \leq 0.05$). No alpha level adjustments were made, in line with the analysis methods suggested previously (Sincair, et al., 2013). All statistical procedures were conducted using SPSS 20.0 (SPSS Inc, Chicago, USA).

Results

Table A7 presents the velocity data from the uninhibited and targeting conditions. Tables A8 – A10 show the 3-D kinematic data at the different joints under both conditions. Table A11 presents the subjective ratings of comfort for the uninhibited and targeting conditions.

Table A7: Velocity (means and standard deviations) observed during uninhibited and force plate sprint trials.

	Uninhibited	**Force Plate**	**Mean Difference ($m.s^{-1}$)**
Velocity ($m.s^{-1}$)	5.50 ± .50	5.51 ± .52	.01

* Significantly different from uninhibited sprinting $p \leq 0.05$

The results show that there was no significant difference in velocity between conditions ($t_{(12)} = 0.33$, $p = 0.747$).

The overall patterns of the resultant 3-D kinematic waveforms were qualitatively similar (Figure A7), although statistical differences were observed at the hip, knee and ankle joints (Tables A8 – A10).

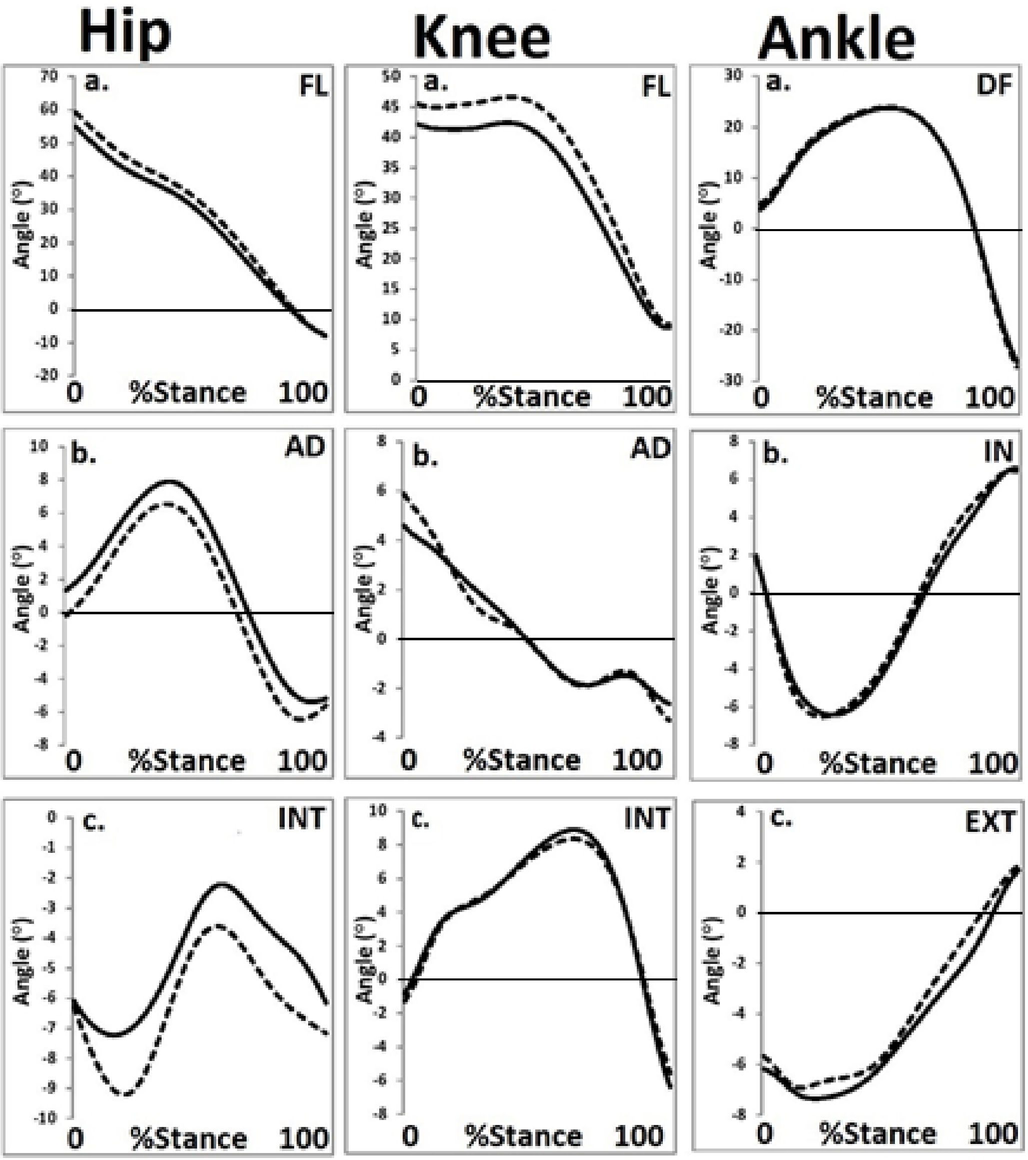

Figure A7: Mean hip, knee and ankle joint kinematics in the a) sagittal, b) coronal and c) transverse planes during force plate striking (dashed line) and uninhibited (black line) sprint trials.

Table A8: Hip joint kinematics (means and standard deviations) observed during uninhibited and force plate sprint trials.

	Uninhibited	Force Plate	Mean Difference (°)
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	59.10 ± 15.15	54.98 ± 14.82*	4.12
Angle at toe-off (°)	-8.12 ± 8.66	-7.69 ± 9.00	.43
Peak flexion (°)	59.10 ± 15.15	54.98 ± 14.82*	4.12
ROM (°)	67.22 ± 9.25	62.66 ±8.19*	4.56
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	-.12 ± 6.78	1.34 ± 6.95*	1.22
Angle at toe-off (°)	-5.52 ± 4.49	-5.12 ± 4.06	.40
Peak adduction (°)	7.08 ± 6.5	8.52 ± 6.38*	1.44
ROM (°)	5.79 ± 4.12	6.87 ± 5.69	1.08
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-6.31 ± 8.81	-6.25 ± 7.67	.06
Angle at toe-off (°)	-7.26 ± 10.29	-6.3 ± 10.36	.96
Peak rotation (°)	-.68 ± 7.89	.79 ± 8.61	.11
ROM (°)	7.05 ± 5.48	5.25 ± 4.33*	1.8

* Significantly different from uninhibited sprinting p ≤ 0.05

Results show that hip joint kinematics (Table A8) were significantly affected by the different sprinting conditions. In the sagittal plane, angle at foot-strike ($t_{(12)} = 3.60$, $p = 0.004$), peak flexion ($t_{(12)} = 3.60$, $p = 0.004$), and ROM ($t_{(12)} = 3.87$, $p = 0.002$) were all significantly greater in the uninhibited sprinting condition when compared to the force plate striking condition. In the coronal plane, there was significantly greater adduction at foot-strike ($t_{(12)} = 3.04$, $p = 0.010$) and peak adduction during the force plate striking condition compared to uninhibited sprinting ($t_{(12)} = 4.93$, $p < 0.001$). In the transverse plane, ROM was significantly larger in the uninhibited sprinting condition compared to the force plate striking condition ($t_{(12)} = 2.23$, $p = 0.046$).

<u>Table A9: Knee joint kinematics (means and standard deviations) observed during force plate and uninhibited sprint trials.</u>

	Uninhibited	**Force Plate**	**Mean Difference (°)**
	X (+=flexion/-=extension)		
Angle at foot-strike (°)	45.49 ± 5.30	42.10 ± 6.90*	3.39
Angle at toe-off (°)	9.19 ± 3.53	8.73 ± 3.79	.46
Peak flexion (°)	48.35 ± 5.00	44.94 ± 5.71*	3.41
ROM (°)	36.30 ± 7.27	33.37 ± 7.79	2.93
	Y (+=adduction/-=abduction)		
Angle at foot-strike (°)	5.78 ± 6.78	4.56 ± 6.54*	1.22
Angle at toe-off (°)	-3.29 ± 2.67	-2.6 ± 2.34*	.69
Peak abduction (°)	-4.63 ± 3.09	-4.01 ± 3.17*	.62
ROM (°)	9.12 ± 6.27	7.53 ± 5.74*	1.59
	Z (+=internal/-=external)		
Angle at foot-strike (°)	-1.26 ± 6.36	-0.86 ± 6.23	.4
Angle at toe-off (°)	-5.56 ± 6.94	-6.40 ± 6.46	.84
Peak internal rotation (°)	9.59 ± 6.44	10.15 ± 6.51	.56
ROM (°)	6.09 ± 3.74	6.55 ± 4.34	.46

* Significantly different from uninhibited sprinting $p \leq 0.05$

Knee joint kinematics (Table A9) were impacted significantly by the different sprinting conditions. In the sagittal plane, knee joint angles were significantly greater at foot-strike in the uninhibited condition when compared to the force plate striking condition ($t_{(12)} = 3.03$, p

= 0.010). Similarly, peak flexion in the sagittal plane was also significantly larger in the uninhibited sprinting condition ($t_{(12)} = 4.11$, $p = 0.001$). In the coronal plane, knee joint adduction was significantly increased at foot-strike in the uninhibited sprinting condition compared to the force plate striking condition ($t_{(12)} = 3.10$, $p = 0.009$). In contrast, knee joint abduction at toe-off was significantly larger in the uninhibited condition when compared to the force plate striking condition ($t_{(12)} = 2.86$, $p = 0.014$). Peak abduction ($t_{(12)} = 2.42$, $p = 0.033$) and ROM ($t_{(12)} = 3.26$, $p = 0.007$) were significantly larger in uninhibited sprinting condition compared to the force plate striking trials.

Table A10: Ankle joint kinematics (means and standard deviations) observed during force plate and uninhibited sprint trials.

	Uninhibited	**Force Plate**	**Mean Difference (°)**
	X (+=dorsiflexion/-=plantarflexion)		
Angle at foot-strike (°)	4.78 ± 5.12	3.70 ± 6.61	1.08
Angle at toe-off (°)	-27.23 ± 7.4	-26.16 ± 7.83	1.07
Peak dorsi-flexion (°)	24.21 ± 5.57	24.02 ± 5.49	.19
ROM (°)	32.01 ± 5.81	29.85 ± 6.16*	2.16
	Y (+=inversion/-=eversion)		
Angle at foot-strike (°)	1.93 ± 4.33	1.79 ± 4.35	.14
Angle at toe-off (°)	6.34 ± 5.91	6.59 ± 6.69	.25
Peak eversion (°)	-7.46 ± 4.59	-7.19 ± 5.12	.27
ROM (°)	5.06 ± 2.89	5.47 ± 3.76	.41
	Z (+=external/-=internal)		
Angle at foot-strike (°)	-5.70 ± 5.80	-6.18 ± 5.38	.48
Angle at toe-off (°)	1.92 ± 3.55	1.81 ± 4.25	.11
Peak internal rotation (°)	-8.76 ± 4.65	-9.00 ± 4.56	.24
ROM (°)	7.80 ± 3.71	8.01 ± 2.94	.21

* Significantly different from uninhibited sprinting $p \leq .05$

Similarly, ankle joint kinematics (Table A10) were found to be significantly influenced by the different sprinting conditions. It was shown that ROM was greater during the uninhibited sprint condition compared to the force plate striking condition in the sagittal plane ($t_{(12)} = 2.24$, $p = 0.045$).

Table A11: Subjective ratings of comfort (means ± standard deviations) for uninhibited and force plate trials.

	Uninhibited	**Force Plate**	**Mean Difference**
Subjective rating of comfort	9.92 ± .28	9.30 ± .75*	.62

* Significantly different from uninhibited sprinting $p \leq 0.05$

Results indicate that a significant difference exists between conditions. The subjective comfort ratings were significantly higher in the uninhibited sprinting condition compared to force plate striking condition ($t_{(12)} = 2.89$, $p = 0.014$).

Discussion

The aim of the current investigation was to examine the influence of force plate targeting on the kinematics of the lower extremities and participants subjective perceptions during early acceleration. To the authors knowledge this is the first study to compare lower limb kinematics during force plate striking and uninhibited sprinting.

In contrast to previous research into running by Sinclair et al., (2014), the current results highlighted significant decreases in hip and knee flexion at foot-strike in the force plate striking condition. Similarly, peak flexion was significantly reduced in the force plate striking condition. Such decreases in hip and knee flexion at foot-strike have been associated with a reduced stride length (Sincair, et al., 2013; Wank, et al., 1998). As reported previously (Challis, 2001; Sinclair, et al., 2014), the kinematic alterations in the current study are likely due to force plate targeting. During the force plate striking condition participants had to make slight adjustments to their sprinting gait to ensure contact with the force plate. Force plate targeting appears to have less impact on ankle joint kinematics in comparison to the hip and knee joints. Only one significant difference existed between conditions at the ankle joint; sagittal plane ROM was significantly larger in the uninhibited sprint condition.

The subjective responses revealed that participants felt more comfortable during the uninhibited sprint condition compared to the force plate striking condition. Although subjective this finding relates to the kinematic observations and is clearly a concern for researcher's looking to measure kinematics and GRF in this way.

All the participants in this study were involved in recreational sport at the time of data collection. These participants may not have had any coaching on their sprint technique or ever undertaken a structured training programme before. As such, the results may not be transferable to a semi-elite testing population. These athletes would likely receive some sprint coaching in their training programme and would regularly perform maximal efforts in training.

Conclusion

This study provides an insight into force plate targeting during the acceleration phase of sprinting in recreational participants. The results indicate that force plate targeting could have a significant impact on participant's subjective comfort and the kinematic measures of the lower extremities, particularly at the hip and knee joints. Future research is required to investigate whether additional coaching cues, familiarisation trials or the participants training age or level of competition could reduce the occurrence of targeting.

Appendix E: Ethical approval

27th February 2014

Chris Edmundson and Ian Bentley
School of Sports Tourism & the Outdoors
University of Central Lancashire

Dear Chris & Ian

Re: BuSH Ethics Committee Application
Unique Reference Number: **BuSH 202**

The BuSH ethics committee has granted approval of your proposal application 'Can Resisted Sled Training be used as an Efficient Method to Improve Force application, Acceleration and Maximum Velocity?'

Please note that approval is granted up to the end of project date or for 5 years, whichever is the longer. This is on the assumption that the project does not significantly change, in which case, you should check whether further ethical clearance is required

We shall e-mail you a copy of the end-of-project report form to complete within a month of the anticipated date of project completion you specified on your application form. This should be completed, within 3 months, to complete the ethics governance procedures or, alternatively, an amended end-of-project date forwarded to roffice@uclan.ac.uk quoting your unique reference number.

Yours sincerely

Gill Thomson
Vice Chair
BuSH Ethics Committee

NB - Ethical approval is contingent on any health and safety checklists having been completed, and necessary approvals as a result of gained.

Appendix F: Examples of the Qualisys Track Manager software

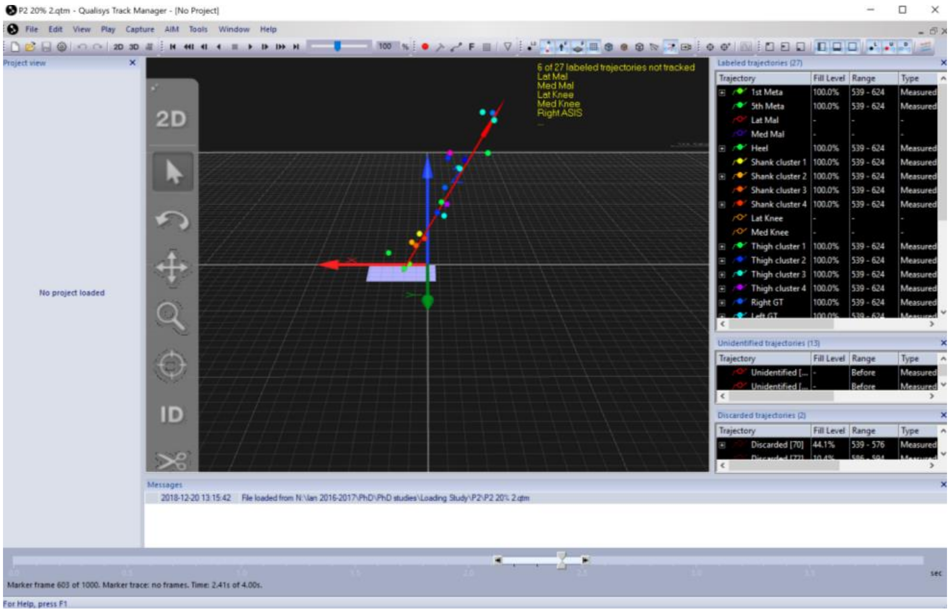

Figure A8: An example of the sagittal view of the marker set during sled trials.

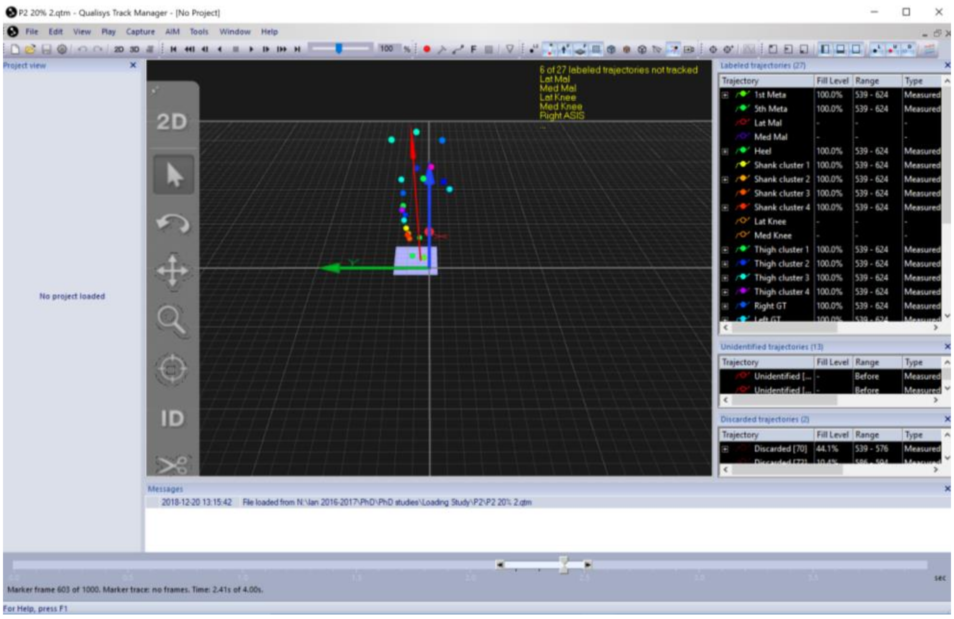

Figure A9: An example of the frontal view of the marker set during a sled trial.

Appendix G: Examples of the Visual 3-D software

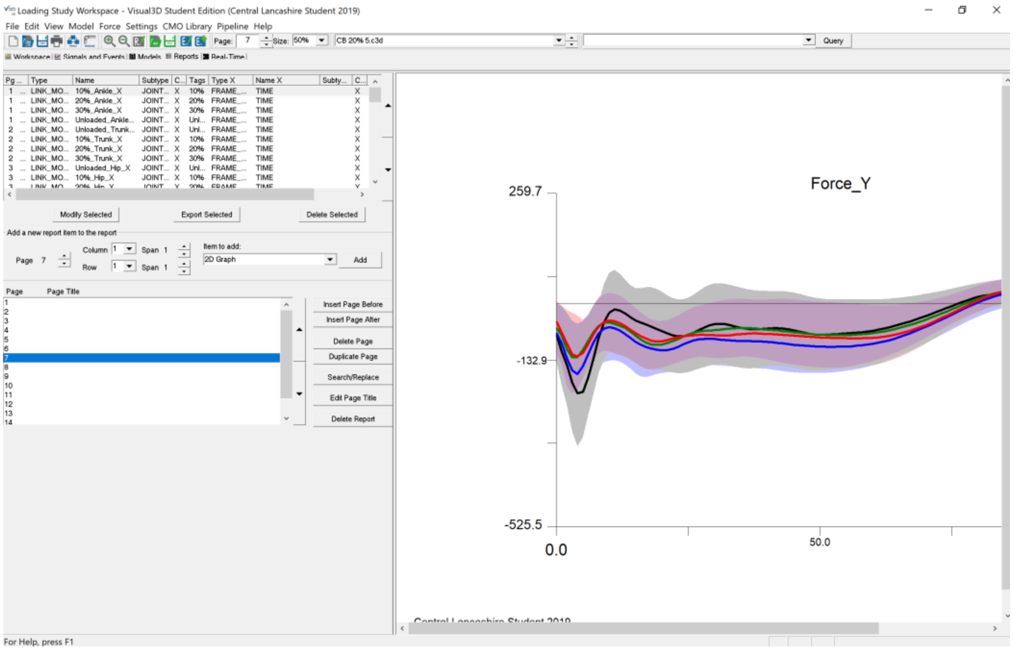

Figure A10: The anterior-posterior GRF.

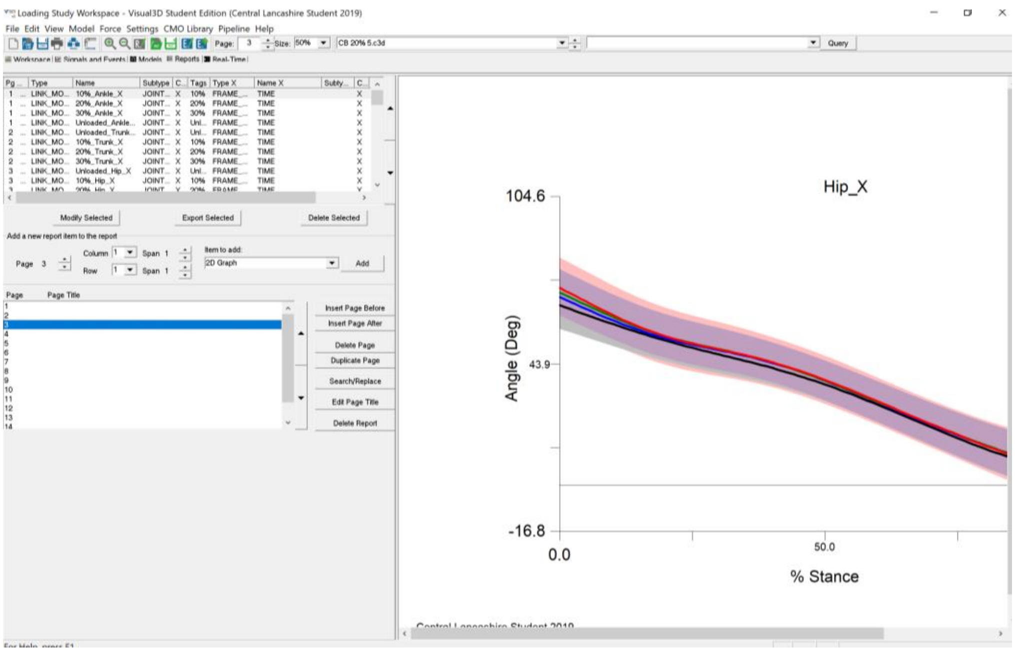

Figure A11: Hip joint kinematics in the sagittal plane.

Appendix H: Heel marker motion in the Visual 3D software

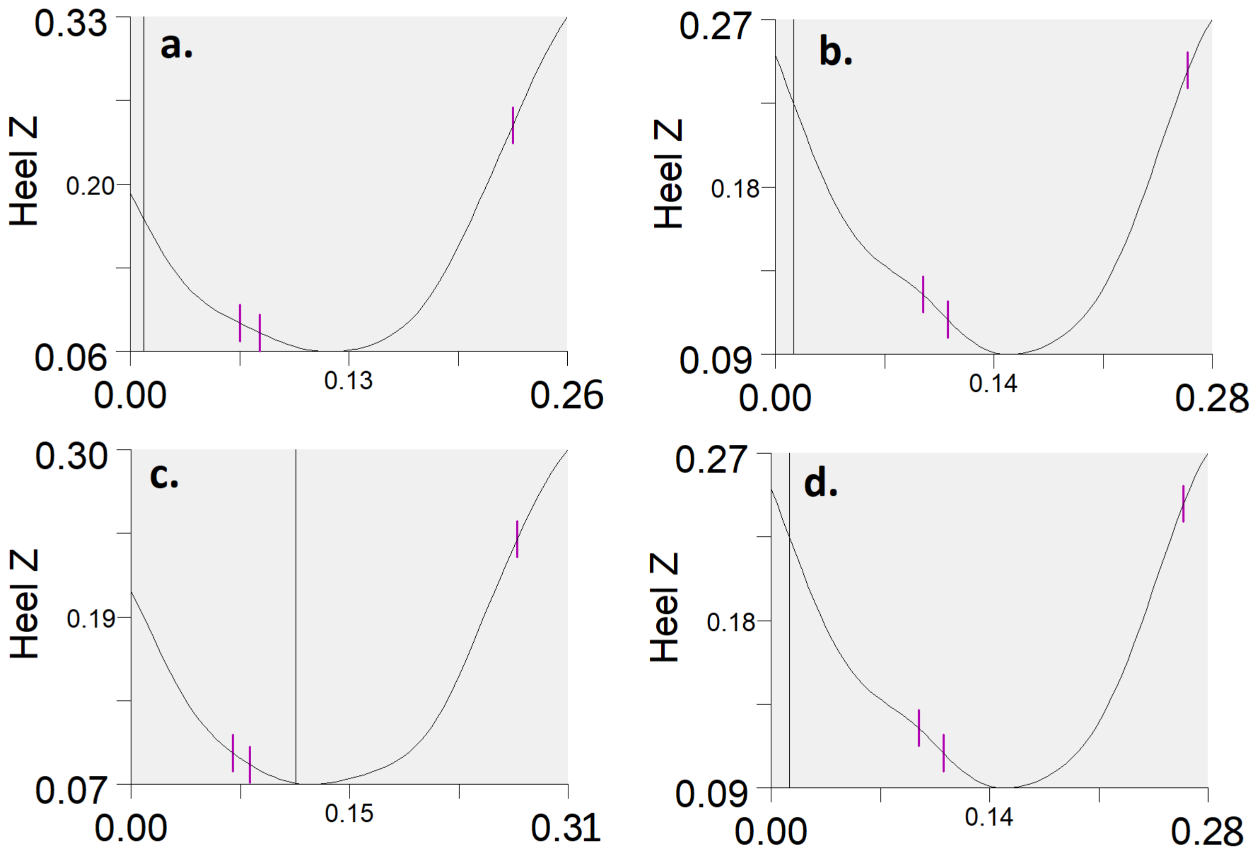

Figure A12: An example of heel marker motion during a) uninhibited, b) 10%, c) 15% and d) 20% V_{DEC} sled towing.

Appendix I: A sample of the journal matrix produced during the systematic review process

	Purpose of the study	Participants & data collection period	Data collection tools and tests	Results of analysis	What, why, how is it developed, how is it implemented	Implications for practice	Important conclusions	Personal
				Sprinting				
)10) Sprint Start. Modern ł Coach, 48 (1) 10-12.	Step-by-step breakdown of a sprint start by an experienced coach.	N/A	N/A	N/A	Step-by-step coaching points with the relevant photo stills.	Coaching points with relevant explanations.	N/A	Useful reference to points and a
, Kerwin, D.G. and Salo, Lower-limb mechanics ɔport phase of maximum-print running. Applied Biodynamics, 707-715.	Improve understanding of sprint technique in well-trained sprinters through the comprehensive analysis of joint kinematics during the support phase of maximum velocity.	Four high level sprinters completed the testing. The athletes were tested during one sprint session.	2D video analysis was used linked with force plate data. They used a 20 point model to determine velocity and centre of mass. A 5 point model was used to calculate joint kinematics and kinetics.	There are a number of tables and graphs to present the data. A large magnitude and consistent pattern was seen in the ankle and hip. Less magnitude and consistency seen in the knee.	Some interesting points to look at, particularly the presentation of data. Key; the knee doesn't produce large amounts of power.	The acceleration phase has greater horizontal force in relation to the vertical forces.	Major periods of both positive and negative work in the hip and ankle joints.	The knee did not p power pro
nmani, A., Dufour, A.B., . and Lacour, J.R. (2002) and stiffness as ability m sprint running. Journal Medicine and Physical s, 42 (3) 274-281.	To determine the importance of leg strength and stiffness relative to a) 100m sprint performance b) mean speed on the three phases of the 100m race and c) the speed differences between these phases.	19 male junior to senior sprinters competing at regional to National levels participated. All participants competed in an official race, in the month following the event they completed 3 different lab tests.	The tests completed were; concentric half squats, counter-movement jump and a hopping test. They also filmed the different phases and worked out mean velocities etc.	The height of the CMJ was significantly correlated to velocity during the 100m sprint. Leg stiffness was the predictor of the second and third phase.	Some useful parts to this paper. Indicates that the different phases of the sprint require different characteristics.	Leg stiffness plays an important role in the second phase and can be tested using the hopping test.	The results indicate that maximal leg strength is related to mean velocity during each phase of the 100m sprint.	This underlines producing great fo initial acce Longer contact ti acceleration pha stiffness is not neec
and Vescovi, J.D. (2012) beed: Misconceptions of rength and Conditioning ıal, 34 (2) 37-41.	Discussion of 3 areas; 1) achieving maximum speed over short distances, 2) role of the Gastrocnemius-Soleus-Achilles complex in sprint performance and 3) the phase of the sprint cycle that likely plays a dominant role in achieving maximum speed.	N/A	Literature review.	A large eccentric action during the early support phase is primarily responsible for preventing negative vertical displacement of the centre of mass.	A very useful paper that discusses some key point relating to my investigations.	The upright position and jogging starts of sprints during team sports means athletes reach maximum speed quicker than track athletes. Sprint programmes for field athletes should mimic the most common distances, often between 15 and 35m.	The GSAC provides a way to minimise the vertical displacement rather than contribute substantially to horizontal propulsion. Increased forces generated during the support phase are the underlying mechanism for faster sprint performance.	Slower individua support phases exerted les Possible that a fast during the flight p more horizontal because the next gr occur sc
ıs, L., Irwin, G., Bezodis, vin, D. (2012) Lower limb ınd ankle joint stiffness in art push-off. Journal of ciences, 30 (1) 1-9.	The aim of this study was to quantify and explain lower limb net joint moments and mechanical powers, ankle stiffness during the first stance phase of the push-off.	1 elite male sprinter performed 10 sprint starts. Testing was completed during one session.	They used force plates and kinematics to calculate the inverse dynamics at the hip, knee and ankle joints.	The hip extended throughout the stance phase. The knee extended until the final 5% were a flexion occurred. The ankle dorsi-flexed during the first 30% of stance and plantar flexed for the remainder.	This paper is useful but will not be key to my investigations.	The knee had much smaller joint moments than the hip and ankle joints, although it still plays a key role.	This paper indicated that lower limb joint kinetics of the first stance are similar to those previously reported for the second stance phase of the sprint start, the key difference being the smaller angular velocity.	No relationship wa ankle stiffness a perform
S., Heidersheit, B.C. and Ꞩ. (2007) The effect of influence of individual hamstring mechanics wing phase. Journal of ınics, 40, 3555-3562.	The purpose was to characterise the effect of speed and influence of individual muscles on hamstring stretch, loading and work during the swing phase of sprinting.	19 athletes participated in the study. They just say the athletes have experience sprinting on a treadmill. Testing was completed during a single testing session.	Whole body kinematics was recorded using 40 markers on 21 anatomical landmarks. Surface EMG was taken on the following; biceps femoris, medial hamstrings, vastus lateralis, rectus femoris and medial gastrocnemius.	The researchers use and present the EMG data. This would be worth another look.	This paper although interesting is not that useful to my investigation other than looking how they used the Delsys system.	The EMG activations were peak during the late swing phase of the sprint. The increase significantly with speed.	Results support the idea that acute hamstring strain injury may be related to performance of large amounts of negative work over repeated strides and or changes in neuromuscular coordination that induce excessive stretch of the hamstrings.	The hip and kne activated prior to c swing phase in ord the limb befo
ınd Bracic, M. (2010) ynamic and EMG factors art. Track Coach, 6172-6176.	Aim was to analyse and identify the major kinematic and dynamic parameters as well as the emg activation of the muscles of the sprint start.	1 female participant completed 8 sprint starts. Completed during 1 testing session.	The emg was placed on the erector spinae, gluteus maximus, rectus femoris, vastus medialis, vastus lateralis, biceps femoris and gastrocnemius muscle.	The results of the study clearly indicate the importance of the force produced in the starting blocks.	A useful paper especially now I will be looking at emg also. Muscle force depends on number of motor-units recruited during the contraction, motoneuron excitability and the type of recruited motor units.	The higher rigidity of the muscles results in better use of the elastic force stored in the serial elastic elements of the muscle.	The sprint start requires high muscle activation. Maximum emg was at the transition of the braking phase into the propulsive phase.	The execution of related to high forc specifically high po as a consequer inclination of th direction of t