

**The Neuromuscular and Mechanical Control of the**  
**Knee Joint in Patellofemoral Pain Sufferers**

**By**  
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## Declaration

I declare that while registered as a candidate for the research degree, I have not been a registered candidate or enrolled student for another award of the University or other academic or professional institution

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## **Abstract**

### **Background**

Patellofemoral pain (PFP) is a condition that has been described as “the Loch Ness monster of the knee” and the “black hole of orthopaedics” due to its indefinable and expansive nature when addressing the aetiology, management and treatment. Although significant and clinically important changes have been observed with the joint biomechanics, psychosocial factors, brain activity and neuromuscular activity a lack of understanding of PFP still remains. The overall aim of the study was to provide a unique and multifaceted investigation into the motor unit control, biomechanical, neuromuscular and psychosocial factors in understanding the movement control of PFP subjects and the response to a common clinical intervention.

### **Method**

Non-symptomatic (n=13) and symptomatic subjects (n=13) performed a single limb isometric squat in two conditions, no tape and with a medial glide tape application. Motor unit data from the Vastus Medialis (VM) and Vastus Lateralis (VL) was recorded using sEMG Decomposition. Muscle activity of the Gastrocnemius (GAS), Rectus Femoris (RF), Biceps Femoris (BF) and Gluteus Medius (GMed) were collected using sEMG. Kinematic and kinetic data from the lower limb were recorded. All systems were synchronised for simultaneous data collection. Measures of conscious motor processing were made using the Movement Specific Reinvestment Scale and pain levels recorded using the Numerical Rating Scale.

### **Results**

*Grouped Tape Response:* The mean motor unit firing exhibited an increase in the VM firing rate and a decrease in the VL firing rate within the tape condition, across both subject groups, suggesting a modification in the load bias across the Vasti muscles. The common drive, a physiological phenomenon describing common fluctuations in the motor unit firings and consequently a measure of the nervous systems signals to control pools of motor units, increased in the VM and decreased for the VL in response to the tape condition in symptomatic subjects showing that the tape may be providing enhanced feedback to the nervous system that responded by modifying the ‘control’ to the motor units. There were no changes however in the non-symptomatic subject group, perhaps suggesting their motor units were already controlled efficiently. Motor unit recruitment analyses, through regression analysis of the motor unit firing rate and knee joint moment, showed the VM motor units in the non-symptomatic subjects were recruitment at a higher firing rate in the tape condition but interestingly no change in the VL and no change in the symptomatic subjects. Both non-

symptomatic and symptomatic subjects demonstrated significant reductions in transverse plane knee joint range of moment, illustrating a more controlled rotational knee joint after the application of tape. There were no significant changes found in the coronal or sagittal joint mechanics. Symptomatic subjects demonstrated a propensity to consciously control their movements, suggestively disrupting automatic motor control tasks. Symptomatic subjects presented with pain scores of 4.2/10 on the numerical rating scale.

*Individual Tape Response:* Exploration of individuals' response to tape, opposed to pooling data and treating as homogenous groups, exhibited a non-uniform response with variable increases, decreases and no changes across the different measurements taken. The exploration of the data with this method is in line with common clinical presentation of PFP subjects and presents rationale for new ways to view the data as to not mask the true physiological behaviours.

*Comparison of groups:* Motor unit recruitment analyses comparing the subject groups demonstrated that symptomatic subjects had a significantly different motor unit recruitment strategy for the Vasti muscles, where the larger motor units were firing faster compared to the non-symptomatics larger motor units in both VM and VL for the same level of force. Symptomatic subjects demonstrated a lower common drive to the VM and higher common drive in the VL compared to non-symptomatic subjects, which after the application of tape became the same level as the non-symptomatics. Symptomatic subjects also exhibited significantly lower muscle activity in the GAS, BF, RF and GMed, thus suggestively increasing the muscle activity bias to the Vasti muscles. No changes were seen in the joint biomechanics or mean motor unit firing rate between the groups.

## **Discussion**

These findings suggest that the nervous system offers a portfolio of solutions to control and distribute force, which can be manipulated through a common taping intervention. The results show that the motor unit firing rate in the VM increases and decreases in the VL, coupled with altered motor unit recruitment strategies thus inferring that there may be a re-distribution of force across the Vasti with the application of tape. This is interestingly complimented with an increase of common drive in the VM and decrease in the VL between subject groups. The presence and then change of common drive within the Vasti so that the motor units are firing in unison, more so with tape, and providing a tantalising prospect that the VM muscle is acting more efficiently and controlled with tape. The novel findings of the neuromuscular system and its modification were alongside the increase in torsional joint control. However, it is evident that the motor unit firing rate, common drive and motor unit recruitment present variable

responses amongst individuals, offering different solutions to achieve the same goal; increasing the force and its control within the muscle. The underlying mechanism for the observed findings are unable to be expressed definitively, however it can be deduced that the application of tape presents proprioceptive feedback to the muscle that alters the motor unit pool; consequently adjusting the force and its control within and across muscles leading to an increase in knee stability.

## **Conclusion**

The key implications from this work is that the application of tape can offer clinically meaningful changes to the sensory-motor control system, through the manipulation and alteration of the motor unit pool, suggestively from an enhanced proprioceptive feedback mechanism. However, researchers and clinicians should consider the individualistic responses and the potential to mask true physiological findings by assuming homogeneity within patient populations with data analyses and clinical decision processes respectively. This work offers unique and novel insights into both the behaviour of patients with Patellofemoral Pain and also the effects of a taping intervention, thus providing additional clinical understanding and also tantalizing opportunities for future work exploring musculoskeletal or neurological disorders and insight into the sensory-motor control strategies.

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## **Glossary of Terminology and Definitions**

Throughout the thesis various terms are used to describe physiological concepts or processes, although many of the terms are familiar they can be misrepresented or misunderstood across differing fields. Therefore to ensure no ambiguity exists a selection of pertinent terms are described and/or defined below.

### *Biomechanical System*

The 'Biomechanical system' is used as a descriptive term used to encompass the involvement of the joint mechanics and its mechanical interactions, measured in this context from a motion capture system.

### *Neuromuscular System*

The 'Neuromuscular system' is used as a term used to describe the combination of the muscles, the nervous system (central and peripheral) and its physiological interactions.

### *dEMG/Surface EMG Decomposition*

This term is used to describe the method of decomposing a surface EMG signal, using specialised and novel technology, into its constituent motor unit action potentials (MUAPs). This differs from the traditional method of surface EMG, which provides information about the composition of all detected MUAPs that is unable to provide the detailed information on the firing characteristics as dEMG is able to.

### *Proprioception*

This can be defined as the body's ability to sense stimuli from muscular, tendon and articular sources to detect position, motion and equilibrium.

### *Common Drive*

The physiological phenomenon that the firing rates of motor units fluctuate in unison with essentially no time delay between them, leading to a concept of common drive. Suggesting that the CNS has evolved a strategy for controlling motor units, rather than controlling the activity of each motor separately the CNS appears to control the excitation to the motoneuron pool.

### *Cross-Correlation*

The mathematical calculation used to provide a measure of common drive, showing motor units have correlated fluctuations in their firing within a  $\pm 100$ ms time lag.

### *Mean Firing Rate (MFR)*

The motor unit action potential train (MUAPT) passed through a low pass hanning filter provides the mean of the firing rate of a given motor unit. The mean firing rate provides behavioural information about the muscle and the force it generates.

### *Recruitment Threshold*

The Recruitment Threshold is the point at which a given motor unit begins to fire and is often presented in relation to an MVC, within the context of this thesis that is the maximum knee moment. The recruitment threshold is often regressed against another variable relating to the motor unit characteristics, in the case of this thesis it's related to the average MFR.

## **Glossary of Abbreviations**

MU – Motor Unit

MUAP – Motor Unit Action Potential

MUAPT – Motor Unit Action Potential Train

MFR – Mean Firing Rate

PPS – Pulses Per Second

Hz – Hertz

PFP – Patellofemoral Pain

VM – Vastus Medialis

VL – Vastus Lateralis

MRI – Magnetic Resonance Imaging

EMG – Electromyography

sEMG – Surface Electromyography

dEMG – Surface Electromyography Decomposition

## **1. Introduction**

Patellofemoral pain (PFP) is a condition that has been described as being “the Loch Ness monster of the knee” (Grelsamer et al. 2009) and the “black hole of orthopaedics” (Dye & Vaupel 1994) due to its indefinable and expansive nature when addressing the aetiology, management and treatment. A plethora of academic and clinical investigations has evolved the knowledge and understanding of PFP, however this has often provided inconsistent and varied information to researchers and clinicians alike. This can partly be explained by the complex mosaic of pathophysiological processes associated with PFP. Patellofemoral Pain has been reported as being a common complaint amongst a wide range of individuals, thought to be particularly prevalent in younger and physically active persons (Taunton et al. 2002). PFP has been attributed to several causes: traumatic, overuse, patellofemoral malalignment, degenerative and idiopathic (Sanchis-Alfonso & Roselló-Sastre 2005). Due to the suggested high prevalence of PFP much research has focused on identifying the true cause of the pain and dysfunction. The primary theory, at this current time, is that patellofemoral malalignment and/or maltracking results in PFP symptoms, however the mechanisms behind the pathomechanics are yet to be fully understood. Several factors have been theorized to contribute towards abnormal tracking and alignment of the patella, including; quadriceps weakness, quadriceps muscle imbalances, excessive soft tissue tightness, increased quadriceps angle (Q-angle), hip weakness and altered foot kinematics (Bolgla & Boling, 2011).

Conservative intervention and management has been as varied and multifaceted as the causative factors associated with PFP. Treatment often consists of various components designed to improve patella alignment, including: quadriceps retraining, stretching of the lower limbs, patella mobilization, correcting foot kinematics with foot orthoses and patellar taping (Bolgla & Boling, 2011). Since McConnell’s landmark paper (McConnell, 1986) there has been widespread acceptance in clinical practice for the use of tape. The proposed aim of McConnell taping is to create a medial realignment of the patella within the trochlea groove, consequently enhancing the tracking and control of the patella thus reducing pain and improving function to allow pain-free rehabilitation to be performed (McConnell, 1986). However, despite the clinical success of patellar taping at reducing pain and improving function the mechanisms are yet to be fully understood, which is certainly not reflective of the wealth of research that has focused on patellar taping. Various explanations of the clinical success

with patellar taping have been proposed and investigated (Crossley et al., 2000), with the neuromuscular system being a favoured area of study and specifically the role of the vasti muscles.

The neuromuscular system and its control of the knee joint musculature is perhaps the least understood variable associated with patellofemoral pain (Grabiner et al. 1994), however often the most cited factor in rehabilitation. Previous investigations have followed the clinical lead with the belief that the vasti muscles, being synergistic stabilizers of the knee, are important factors in patellofemoral control with the Vastus Medialis being “the only dynamic medial stabilizer of the knee” (McConnell, 1986). Extensive investigations have explored the neuromuscular control of the vasti muscles using electromyography (EMG), both invasively and non-invasively, using various EMG measurements and techniques. The majority of investigations have focussed on the postulate of delayed firing or ratio difference between the VM and VL in various conditions and environments (Neptune et al., 2000; Bowyer et al., 2008; Van Tiggelen & Med, 2009; Cowan et al., 2001; Wong, 2009; Sung & Lee, 2009; Chester et al., 2008; Smith et al., 2009). The lack of homogeneity amongst the protocols, methods and data processing techniques used in the literature has led to inconsistent and mixed findings (Wong, 2009). Therefore definitive neurophysiological evidence for a change in vasti coordination within a PFP population is limited. One method that may provide additional insight into this would be to study control at the motor unit (MU) level opposed to studying whole muscle behaviour.

Studying the neuromuscular system at a motor unit level is often achieved through invasive EMG procedures consisting of inserting fine-wire or needle electrodes into the muscle belly. These procedures provide information on the characteristics of a small yield (typically 2-5) of MUs, which can be described as being the smallest controllable muscular units in the body (Basmajian & De Luca, 1985). The study of the individual motor unit action potentials (MUAPs) provides desirable information on the timing of their discharges and therefore allowing a detailed description of the interpulse interval, firing rate and synchronisation characteristics (De Luca et al., 2006). From a clinical perspective this could provide invaluable information regarding the control of the muscles. Recent developments have allowed decomposition of surface EMG signals (De Luca et al. 2006; Nawab et al. 2010) providing new information on the hierarchical control of motor units during voluntary isometric contractions in non-symptomatic individuals (De Luca & Contessa, 2012), in elderly subjects (Erim et al.

1999), muscular fatigue (Adam & De Luca, 2003; Contessa et al., 2009), strength training (Beck et al. 2011) and stroke sufferers (Suresh et al. 2011), however no previous work has explored any musculoskeletal conditions. To date, previous investigations using decomposition methods have used isometric open kinetic chain exercises to explore MU behaviour. Although these methods allow for highly repeatable and reliable contractions they tend to lack the clinical relevance for most musculoskeletal conditions, such as patellofemoral pain, as it lacks a stability challenge and functional relevance. A task that offers stability challenges and functional relevance for patellofemoral pain, without compromising the use of the surface EMG decomposition method, could provide tantalizing insights into MU control. Such information allows the study of the neuromuscular system, however the functional interaction between the intrinsic biomechanics of the knee joint and the surrounding musculature that drives the movements (Andriacchi et al. 1984), is yet to be fully understood.

Previous research exploring the role of biomechanics in PFP has focussed on the sagittal plane or used too simplistic modelling techniques (Gilleard et al., 1998; Salsich et al., 2001; Brechter & Powers, 2002; Salsich et al., 2002; Crossley et al., 2004), however the knee joint is significantly more complex than singular plane movements. Kowalk et al. (1996) highlighted the importance of the abduction-adduction moment in medio-lateral stability. Selfe et al. (2008) also emphasized this significance of studying the coronal and transverse planes when exploring the control of the knee during step descent, being further highlighted in a PFP population (Selfe et al. 2011). The authors showed that the discrete and significant changes in the coronal and transverse plane knee kinetics and kinematics could be observed with varying therapeutic interventions, with no changes seen in the sagittal plane. Clinically it seems logical to explore the coronal and transverse planes of movement as most common therapeutic interventions are directed medially, as in the medial glide with the McConnell taping technique (McConnell, 1986).

The last decade has seen an exponential rise in inter-disciplinary research with kinetics, kinematics and sEMG being applied to musculoskeletal and neurological conditions, providing further insight into the interaction of the neuromuscular system on the biomechanical system. However, studying motor unit level control of the neuromuscular system coupled with detailed 3-dimensional biomechanics remains both technically challenging and conceptually complex. The application of such investigations could provide new insights or clarifications into common musculoskeletal conditions and consequent treatment efficacies, further representing significant contributions to the apparent knowledge gap.

## **2. Literature Review**

### 2.1 Patellofemoral Pain Aetiology

#### 2.1.1 “Patellofemoral Pain”

The term Patellofemoral Pain is a descriptive diagnosis that is often, and sometimes inaccurately, synonymous with Anterior Knee Pain (AKP), idiopathic anterior knee pain, Patellagia, Patella compression syndrome, overuse patellofemoral pain and Chondromalacia (Näslund et al. 2006). Historically, Chondromalacia Patellae was the first term and diagnosis used by Koenig (1924) to describe all-inclusive knee pain associated with the patellofemoral joint. It was not until 1977 that a differential diagnosis of knee pain was exposed (Ficat & Hungerford 1977) and Chondromalacia Patella was restricted to describing articular cartilage defects. The term Patellofemoral Pain is the current descriptive diagnosis that has, and will no doubt, continue to evolve over time as more is understood about the condition. However, there is evidently a lack of homogeneity in the definition of PFP which becomes apparent in the reported incidence and prevalence of the condition.

#### 2.1.2 Prevalence and Incidence

Patellofemoral pain is frequently claimed and described as a ‘common complaint’ amongst a wide range of groups and settings (Cavazzuti et al. 2010; Cook et al. 2010; Cowan et al. 2000; Crossley et al. 2001). Various population groups have been investigated, including; adolescents (Rathleff et al. 2013), military (Boling et al. 2009), athletic (Witrouw et al. 2000), females (Boling & Padua 2010) and the general population (Wood et al. 2011). Authors have attempted to be more specific with the incidence of PFP by stating a popularised, yet unsubstantiated, ratio of 1:4 or 25%. However, such statements are often lacking source data or are biased to specific populations, as highlighted in a review by Callaghan and Selfe (2007) whom explored the reported incidence and prevalence rates for PFP. It was stated that 40/136 papers reviewed cited a numerical rate or ratio, with 15 of these papers citing the 1:4 ratio or 25% value. The 40 papers that offered a numeric value cited many papers for justification, with four citations being most popular (Devereaux & Lachmann 1984; DeHaven & Lintner 1986; Kannus et al. 1987; Milgrom et al. 1991). These and much of the literature is based upon convenient and/or accessible populations such as sports medicine clinics and military populations, yet the incidence and prevalence rates from these settings are often inaccurately inferred to the adult general population. Wood et al. (2011) is the only author to investigate

the prevalence of PFP within the United Kingdom in the general adult population. During one year (2006) and across 8 general practices there were 1782 knee-related consultations held, of which 303 or 1:6 were classified as being a patellofemoral disorder. Although PFP is reported as having a relatively high incidence and being a prevalent condition it is evident that caution should be sought when considering and inferring this across different population groups. A factor which further hazes the prevalence and incidence of PFP is its presentation, consequent clinical examination and classification.

### 2.1.3 Symptoms and Clinical Examination

PFP is commonly described as retropatellar or peripatellar pain which can present itself, and often is exacerbated, during activities such as walking, running, stair ascent and descent, squatting, kneeling and sitting. Naslund et al. (2006) reviewed the wide spectrum of the PFP symptomatology that has been reported, concluding that there is a clear lack of consensus on the definition or classification, and that PFP is often a diagnosis made by exclusion. Consequently there exists a plethora of methods and criteria that researchers and clinicians use to assist the clinical examination of PFP that include: detailed evaluation of complaints of pain, identification of origin of symptoms, assessment of performance deficits, and imaging investigation (Cook et al. 2012).

Due to the multifactorial aetiology of PFP a battery of clinical examination techniques are frequently used to substantiate the rule-out, rule-in probabilistic model. Cook et al. (2010) individually and collectively explored the diagnostic accuracy and disability relationship of a selection of routinely used measures, including: manual compression of the patella, palpation of patella borders, isometric quadriceps contraction, squatting, stair climbing, kneeling, and prolonged sitting. The authors found that no single physical examination test or functional activity is helpful in the diagnosis of PFP, however they did state that any two of three: pain with quadriceps contraction, pain during squatting, and/or pain during palpation of the postero-medial or postero-lateral borders resulted in a moderate shift towards a PFP diagnosis. These findings are in agreement with similar studies who also found that no single physical or functional test is sensitive or specific enough to diagnose PFP but positive findings from multiple tests could indicate a PFP diagnosis (Haim et al. 2006; Nijs et al. 2006). The lack of definitive physical examinations and functional tests, which are able to diagnose or assist in the diagnosis, could be due to the various suggested paradigms of PFP.

#### 2.1.4 Patellofemoral Pain Paradigms

PFP has historically been widely accepted as being a mechanical problem with the patella incorrectly aligned in the trochlear groove, Patellofemoral Malalignment and/or the patella incorrectly tracking in the trochlear groove during the flexion-extension cycle, Patellofemoral Maltracking. First proposed by Insall (1979) as “Patellar Malalignment Syndrome”, it was thought that the lateral loading of the patella was increased with malalignment. The patella maltracking theory suggests that the abnormal tracking of the patella changes the contact zones and thus causes a noxious stimulus (Fulkerson 2004), which is then subjectively and individualistically inferred as pain by the patient. This proposal was, and frequently still is, met with a surgical intervention (Lateral Retinacular Release) to ‘correct the malalignment’, however this theory has also provided many conservative non-invasive modalities. The malalignment and/or maltracking theory has been investigated by many authors in an attempt to provide empirical evidence and justification, most commonly through various imaging techniques. Plain radiographs (Teitge 2001), computed axial tomography (Biedert & Gruhl 1997) and magnetic resonance imaging (MRI) (Noehren et al. 2012) are common techniques which have been used in an attempt at providing insight into the mechanical aspects of the malalignment/maltracking theory with homogeneous findings. In more recent years it has been highlighted that the malalignment and maltracking theories may not be the sole cause of PFP and that several contributory components may be ascribed to causing pain. A complimentary component of the biomechanical approach is the psychosocial element to movement related pain and an individual’s conscious perception of their movement. Masters and Maxwell (2008) have proposed that psychological, physiological, environmental and mechanical events are a function of an individual’s propensity to consciously control movements, coined ‘The Theory of Reinvestment’. The psychosocial component of PFP is one of which compliments the biomechanical and neuromuscular elements of PFP and consequently the malalignment/maltracking theory.

Various other paradigms have been suggested to be responsible and/or contribute to PFP, a summary of which can be seen in Table 2-1. Although these paradigms evidently present complementary and alternative information to the understanding of PFP they are beyond the scope of this thesis and will not be investigated but held in consideration.

**Table 2-1 Summary of other proposed PFP paradigms**

<b>PFP Paradigm</b>	<b>Key Information</b>	<b>References</b>
Tissue Homeostasis	Envelope of load acceptance and function leading to loss of tissue homeostasis. Theory suggesting coexistence of multiple causative factors leading to PFP.	(Dye 2005) Pathophysiology of Patellofemoral Pain
Fat Pad	The involvement of the highly innervated and vascular fat pad as a source of pain in PFP.	(McConnell 2013) Management of a difficult knee problem
Vascular	Concept that poor vascularisation of the patella and knee surrounding arteries	(Sanchis-alfonso 2010) Pathophysiology of Anterior Knee Pain

## 2.2 Neuromuscular Involvement

### 2.2.1 Background

The knee joint is not only comprised of complex articulating anatomical structures but has an equally intricate neuromuscular system, in producing both power and control leading to the generation of force and stability at the joint. A plethora of classic texts have investigated the quadriceps muscles in an attempt at understanding the role and function of the knee joint (Lindahl & Movin 1967; Haffajee et al. 1972; Carlsoo et al. 1973; Wahrenberg et al. 1978), where the historical view being that the Quadriceps main function is the sole contributor in extension of the knee. Even though the Quadriceps muscles has been described as being “the most beautiful muscles” (Last 1952) other muscles have shown their contribution to the function of the knee. The work of Andriacchi et al. (1984) demonstrated the significant roles the Vastus Medialis, Vastus Lateralis, Vastus Intermedius, Rectus Femoris, Gracilis, Sartorius, Biceps Femoris, Semitendinosus, Semimembranosus, tensor fasciae latae, medial and lateral heads of Gastrocnemius all have in the control of the knee at different knee angles and external moments. In addition to the Quadriceps role in knee extension it has been postulated that the Vasti components hold significant contributions in the control of the patella and knee joint (Lieb & Perry 1968; Makhsoos & Lin 2004; Wilson & Sheehan 2009; Lin et al. 2010). Explicitly, the role of the Vastus Medialis has held the focus of researchers and clinicians for its purported role in acting as a medial stabiliser of the patella (McConnell 1986) and its possible dysfunction in terms of strength (Neptune et al. 2000), disbalance (Petersen et al. 2013), force direction (Tucker & Hodges 2010) and control (Toumi et al. 2013).

### 2.2.2 Muscle Activity and Patellofemoral Pain

Electromyography (EMG) provides a detailed measurement and quantification of the behaviour of the muscle, consequently offering key insights into the neuromuscular system and its behaviour. The advent of surface EMG technology has offered a repeatable, accurate and non-invasive method to measure the behaviour of a muscle and also the ability to measure multiple muscles simultaneously from the surface of the skin. This has stimulated a host of investigations into the neuromuscular involvement in Patellofemoral Pain, where a key focus has been to attempt to understand the behaviour of the muscles surrounding the knee and explicitly the Vasti muscles (Tang et al. 2001; Cowan et al. 2001; Christou 2004; Sacco et al. 2006; Bowyer et al. 2008; Patil et al. 2011; Lee & Cho 2013). By far, the majority of the

studies investigating PFP and its neuromuscular components have done so by observing the gross changes of the surface EMG signal, predominantly through investigations of the signal amplitude or activation timing of the muscles. The heterogeneous findings and purported relationships between and within the Vastus Medialis and Vastus Lateralis have long been studied in an attempt to understand the ‘control’ of the muscles and their respective behaviour (Cowan et al. 2001; Herrington et al. 2005; Rainoldi et al. 2008; Cowan & Crossley 2009; Cavazzuti et al. 2010).

Quadriceps muscle imbalances is one of the most popularised areas of investigation in the neuromuscular explorations within PFP research. This follows a seemingly logical concept that if there is a load bias across the differing portions, specifically the Vastus Medialis and Vastus Lateralis, then it may cause maltracking of the patella within the trochlear groove and perhaps being a causative factor in PFP (see section 2.3.3). The imbalance of the Quadriceps has historically been thought to be down to two main possibilities; a reduction in the force producing ability of the Vastus Medialis (Ahmed & Burke 1987) or due to an altered temporal control of the Vasti in PFP patients (Voight & Weider 1991). The altered onset of the Vastus Medialis (temporal control) has been considered to be of particular importance due to the hypothesis from Grabiner et al. (1994) that the VM should be activated earlier than the VL to be able to optimally track the patella, as the VM has a smaller cross-sectional area in combination with the dominant laterally directed force contribution of the VL. Neptune et al. (2000) used musculoskeletal modelling to simulate running and the effects of two treatments, foot orthoses and VM strengthening, and the functional significance to VM onset timing had on the estimated patellofemoral joint loads. It was found that both treatments significantly reduced the average patellofemoral joint load and the VM strengthening also significantly reduced the peak patellofemoral joint load. Interestingly when the VM timing was delayed and advanced relative to the VL onsite there was a significant increase and decrease in patellofemoral joint load respectively. Many other investigations have explored the temporal characteristics of the Vasti muscles in relation to PFP and therapeutic interventions (Cowan et al. 2002; Wong 2009; Sung & Lee 2009; Chester et al. 2008; Van Tiggelen et al. 2009; Dixon & Howe 2007; Cavazzuti et al. 2010; Cowan et al. 2001). However, there exists controversy as to the ‘normal’ relationship in the EMG onsets of the Vasti muscles, and if there actually exists any differences in a PFP population. The controversies present themselves in various forms; through processing techniques, measurement error, in reference to non-physiological events and sample sizes. There exist many methods of determining the onset of a muscle

contraction through varying processing techniques, with the most commonly cited methods being manual/visual determination, onset relative to the number of standard deviations away from the baseline noise (using automatic processing methods) and cross-correlation yet there is no consensus within the literature which may be the most sensitive and reliable. Uliam Kuriki et al. (2011) collected sEMG data from the two Vasti muscles with 33 subjects, 11 of which had PFP, during a stair climbing task. The same data set was then processed using three different techniques at determining the onset of the muscle, namely cross-correlation, automatic detection and visual inspection. The results demonstrated the cross-correlation technique had the lowest variation but the results were not able to elicit a difference between the PFP and control group, unlike the other techniques that showed significantly larger standard error of measurement but could distinguish between the different subject groups. Interestingly the authors also reported that the variability was higher in the PFP patients, indicating that the multifactorial aetiology of PFP can also affect the results (Cavazzuti et al. 2010). It can be seen from this paper and others that using the same samples from the same subjects, varying only the technique used to obtain the onset, the results can be significantly manipulated and potentially leading to gross misinterpretation. Wong and Ng (2006) examined the effect of electrode positioning on the EMG recordings of VM and VL with respect to the onset timing during quadriceps stretch reflex and voltage during voluntary isometric contraction. They revealed that different positioning of the VL electrodes would significantly affect the EMG onset time, VL relative to VM, and the electrical signal strength during the same activity. These highlighted points can be seen within the diversity and lack of consensus in the literature about EMG onset and the methodology of determining the onset is a crucial aspect when interpreting the results.

In addition to the processing and measurement problems that seem to plague the investigations into the onset timing it is seemingly common to present the onset timing as percentage of a gait cycle (Powers et al. 1996), in relation to changes in force (Morrish & Woledge 1997) or simply reporting the time difference between the onset (Cowan et al. 2002) rather than considering the joint biomechanics which are suggestively more sensitive and applicable. Often talked within the same scope are papers that have investigated the Vasti onset timing in relation to a reflex task (Voight & Weider 1991; Witvrouw et al. 1996; Karst & Willett 1995), which should be approached with caution due to the different physiology behaviour between a reflex based onset timing and voluntary contraction onset timing, with the former offering the question about the clinical relevance to such work. These critiques and literature explicitly bring into question the validity and applicability of the plethora of texts exploring the onset time of the Vasti and

the purported delay, which seems to have become a dogmatic belief within both the literature and clinical practice. Although the imbalance between the Vasti muscles is a logical concept the confusion amongst the literature perhaps taints the understanding, where new methods of exploring the load bias across these structures may be able to offer further detail and insight.

Andriacchi et al. (1984) demonstrated many years ago the significance in the role of a number of the lower limb muscles involved in the control of the lower limb and specifically the knee. As often with investigations into musculoskeletal conditions there is a keen focus on the musculature that surrounds the joint of interest, in the case of PFP then the majority of the work has exerted great effort in attempting to understand the Vasti muscles during various movement tasks and under differing interventions, but with less exposure often found for the other involved muscles around the ankle, knee and hip. The control, strength and consequent muscular behaviour of the hip has gained much attention in recent years with the theory that that diminished gluteal muscle function could cause increased hip joint adduction and internal rotation when carrying out activities such as running, squatting and stair ascent/descent. The excessive and aberrant hip motion has been proposed to increase the patellofemoral joint stress, which is considered to be associated the development of PFP (Powers 2010). Following on from this a host of strengthening programmes have been devised which have provided positive clinical outcomes (Mascal et al. 2003; Fukuda et al. 2010). However, despite this support for the efficacy of gluteal strengthening it has been documented that the development of PFP is not predictive through hip strength testing (Prins & van der Wurff 2009) but at the same time it's also been reported that greater hip external rotational strength could be predictive (Boling et al. 2009). The method of measuring 'muscle strength' is done through isometric testing and can only loosely be associated with the functional and dynamic movements, and in addition does not take into account any of the other lower limb muscles, kinematics, or joint forces and these should be considered when evaluating the reported involvement and importance of the hip. A recent systematic review by Barton et al. (2013), with 10 case-control studies and no prospective studies, concluded that the gluteal muscle activity with PFP is limited due to an absence of prospective research, low sample sizes and heterogeneity in methodological design including procedures, data reduction and analysis and participant inclusion and exclusion criteria. It was identified that moderate-to-strong evidence suggests Gluteus Medias muscle activity is delayed and of shorter duration during stair negotiation in PFP patients, but in running there is limited evidence indicating that Gluteus Medius muscle activity may be delayed and of shorter duration.

Regardless if there is a true relationship, simply exploring the gluteal muscle activity of hip strength in isolation will likely not provide a complete picture of the PFP patient and the influence of the gluteal muscle function, where more parts of the pathophysiological puzzle are needed.

In general more than a single muscle is required to produce a joint moment and the joints consequent movements. This is certainly the case when investigating a closed chain exercise, such as squatting, walking and stair negotiation where multiple joints and consequently multiple muscles are involved. However, a limiting factor in our understanding of movements in general is that there is no consensus or good understanding on what is expected or 'normal' for a muscle or groups of muscles in a given task. Frequently the literature focusses on manipulating the muscles and movements through various forms of therapeutic interventions with little thought to what other muscle groups or structures have also been manipulated in the process. To the authors knowledge no other work has considered the relative muscle activity between PFP patients and non-symptomatic individuals, even though a plethora of work has focussed on physical therapy treatments directed at these muscle groups (Crossley et al. 2002; Sacco et al. 2006; Kaya et al. 2010). Further work should perhaps direct the focus to attempting to understand, or at least consider, a more complex pattern of the involved muscle groups in the lower limb, compare how they may differ across subject groups, how differing tasks can influence the results and the importance of measures other than amplitude or muscle onset timing.

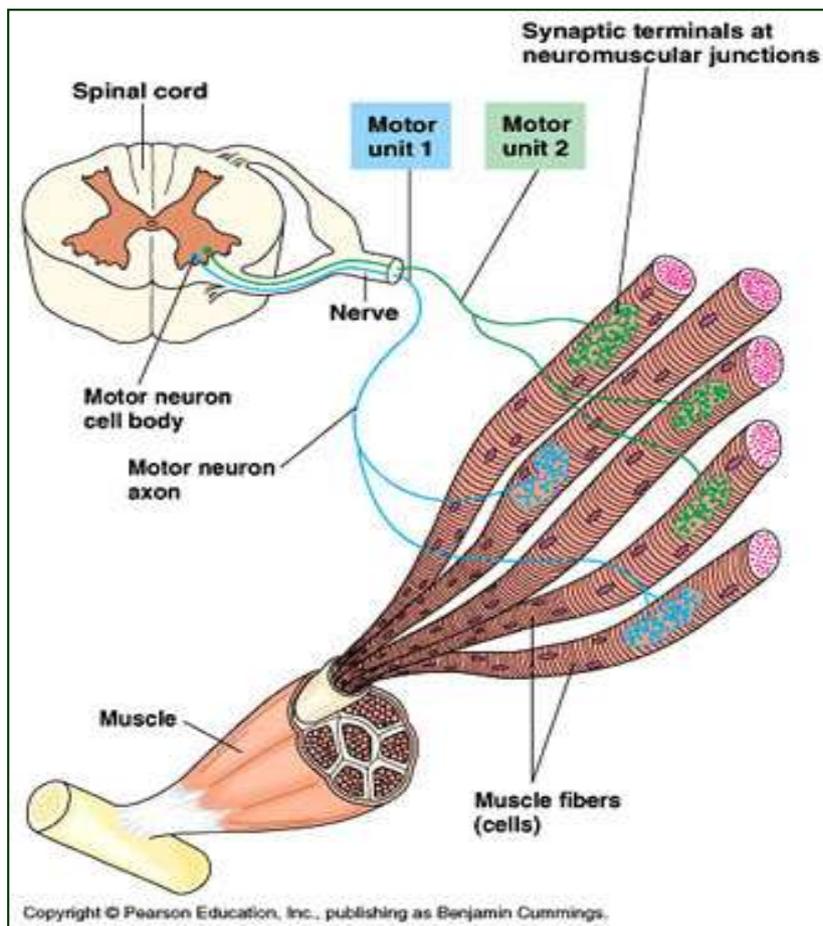
### 2.2.3 Motor Unit Measurement

Typical sEMG measurements provide gross information of the muscle behaviour in that the represented signal is a composition of all the motor unit action potentials within the measured area. It is suggested that this may not be sensitive enough to understand the intricate and discrete changes in motor unit control that may be occurring. It has been reported that there are many intrinsic and extrinsic factors that can affect the sEMG signal (De Luca 1997) with it being demonstrated that different inter-electrode spacing and different electrode configurations can have significant effect on the fidelity of the signal (De Luca et al. 2012). Although sEMG can offer key insights into the muscle activity the extracted variables, the inferred outcome and the consequent conclusions should be in consideration to the factors that can affect the fidelity of the signal.

Another method of measuring the behaviour of the muscles involved in Patellofemoral Pain and many other situations is through invasive EMG procedures, which is typically achieved through inserting fine-wire into the muscle belly, where less signal fidelity problems arise. Many investigators have applied the fine-wire EMG technique in an attempt access more detailed information on the behaviour of individual motor units and consequently the behaviour of the muscles in PFP patients (MacGregor et al. 2005; Mellor & Hodges 2005b; Mellor & Hodges 2005a). The study of the individual motor unit action potentials (MUAPs) can provide desirable information of the timing of their discharges, thus allowing a detailed description of interpulse interval, firing rate and synchronisation characteristics (De Luca et al., 2006). From a clinical perspective this could provide invaluable information regarding the control of the muscles from the nervous system.

#### 2.2.3.1 Anatomy and Physiology

In order to appreciate where the EMG signal originates, and remove any ambiguities, the anatomy and physiology of the processes involved in the decomposition of an EMG shall be covered in brief. The structural unit of a muscular contraction is the muscle cell or muscle fibre, which are supplied by the terminal branches of one nerve fibre or axon. The neural structure whose cell body is located in the anterior horn of the spinal cord, through its relatively large diameter axon and terminal branches, innervates a group of muscle fibres. The term used to describe the single smallest controllable muscular unit, is a Motor Unit (MU). The motor unit consists of a single alpha-motoneuron, its neuromuscular junction, and the muscle fibres it innervates (as few as 3, as many as 2000) (Basmajian & De Luca 1985). An illustration of the relevant anatomy can be seen below in Figure 2-1.



**Figure 2-1 Illustration of the anatomy and physiology of the motor unit**

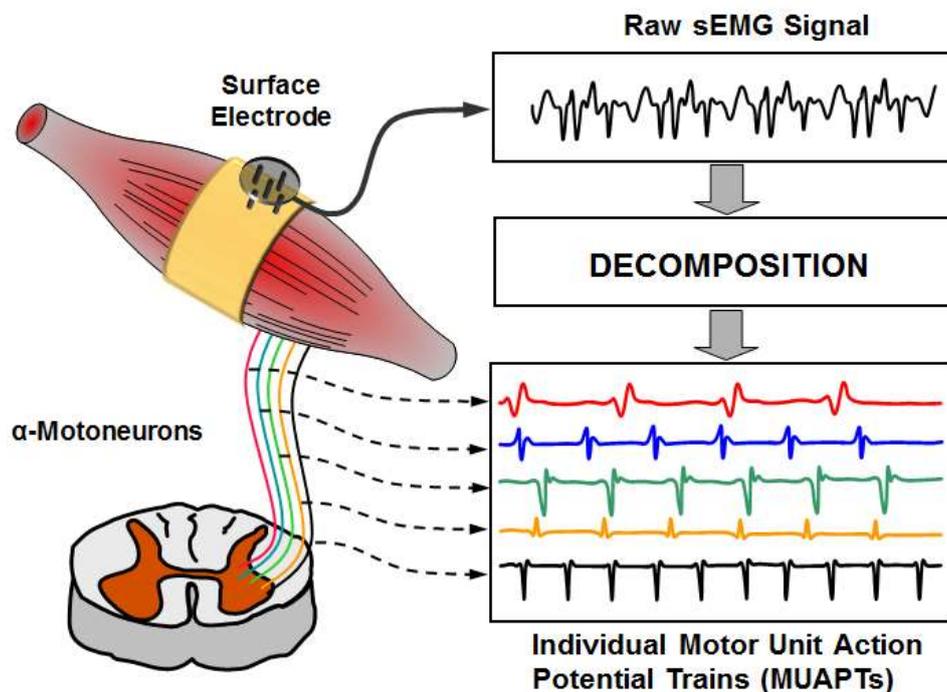
When an excitation occurs within the cell body it propagates down a motoneuron, down all the branches and to all the muscle fibres that are connected together as a motor unit. Each of said muscle fibres generate a force twitch, relative to the muscle fibre characteristics, and the motor unit overall generates the motor unit force twitch. If the motor unit force twitches fire fast enough and in close enough succession a tetanic force is produced, a process called tetanisation, and the muscle produces a voluntary controlled force. Understanding and measuring the motor unit functional characteristics is one of the most seductive muses of physiology, so that we have a fuller understanding on force production and control from a muscle. However, the task at hand has historically been a challenging one as has required using invasive methods to directly measure the electrical potentials from within the muscle, and further complicated by the very nature of a muscular contraction in that the motor units fire concurrently and thus cause a superposition of motor units.

### 2.2.3.2 Decomposition Techniques

As first described by LeFever & De Luca (1982) the process of decomposing an EMG signal into its constituent components is able to present information on the firing characteristics and morphology of the MUs, consequently detailed information on the behaviour of the muscle. The process is achieved by manually identifying individual MUAPs and allocating them, by their shape and amplitudes, to a specific motor unit action potential train (MUAPT). Although this process could provide a unique insight into the behaviour of the muscle its application is limited. Due to the selective nature of the invasive detection electrode only a small number of motor units could be detected, with 2-5 MUs typical for most measurements, which significantly limits the representative information that can be gained from a muscle contraction where hundreds of MUs could be active. A further limiting factor with invasive EMG decomposition is that the signal becomes redundantly complex when the force contraction increases, this is because the additional force the muscle requires to contract requires additional motor units and their firing behaviour changes thus the superposition of the MUs becomes near impossible to resolve in to the MUAPTs at all or with much confidence. Therefore the invasive measurements have typically been conducted with low force levels (1-10 % MVC), which again limits its application when larger force contractions are wanting to be explored. Another pragmatic but important limitation is the measurement procedures whereby a needle or fine-wire is required to be inserted into the muscle. This primarily brings about concerns with the ethics and safety of the process, and secondary the physiological effect of inserting foreign objects into the muscle belly and its potential for altering the behaviour. With the above points in consideration, although invasive EMG decomposition offers detailed information about the motor unit characteristics the relevance to the behaviour of a representation portion of the muscle and at such low force levels should be considered whether it's clinically applicable.

Decomposition of a surface EMG signal is an attractive notion that has been considered for many years (Masuda et al. 1985), however the complexity of a sEMG signal with multiple superimposed MUAPs and noise contamination make it a difficult task to resolve. Recent developments towards a non-invasive surface EMG decomposition solution have shown impressive results (De Luca et al., 2006) which are evolving (Nawab et al., 2010) to provide a solution for investigating MU properties from the surface of the skin. Artificial intelligence based algorithms have been developed (De Luca et al., 2006; Nawab et al., 2010), which can automatically decompose sEMG signals from isometric contractions at force levels up to 100%

maximal voluntary contraction (MVC). Figure 2-2 below illustrates an overview of the method behind decomposing a surface EMG signal and accessing the MU firing information. A surface EMG sensor (see section 3.4.2.2) is placed onto the surface of the muscle whereby it collects 4-channels of raw EMG data, after which it is processed by sophisticated algorithm (see section 4.2 for details) and provides the firing characteristics of individual motor unit action potentials.



**Figure 2-2 Illustration of the process of decomposing the surface EMG signal**

The advent of this technology has provided ground-breaking new insights into the hierarchical control of the neuromuscular system, whereby it has been documented that, at any time and force during voluntary constant-force contractions, earlier-recruited motor units maintain higher firing rates than later-recruited ones, providing an inverse orderly hierarchy of nested firing rate curves resembling the layers of the skin of an onion (De Luca et al. 2006). These recent developments in the ability to decompose a sEMG signal up to a maximum contraction and accurately observe high yields of motor units (typically 30-50 motor units) has provided new information on the nervous systems hierarchical control of motor units. The surface EMG decomposition outputs the firing instances and MU morphology which can be processed to extract information about the firing rate, MU recruitment and de-recruitments, morphological changes in action potentials, correlations in MU firing, firing rate variability within and across MUs all

of which can be applied to a wide range of fields in exercise physiology, kinesiology, motor control or rehabilitation. These variables can inform the researcher and clinician alike with regards to the behaviour and control of the neuromuscular system, and potentially how we can manipulate this to alter the force and consequent movements of the body. These insights provide significant advances compared to the ability of exploring a normal sEMG signal for its amplitude, timing or fatigue. The advances have led to a greater understanding in various population groups and situations; during voluntary isometric contractions in non-symptomatic individuals (De Luca & Contessa, 2012), in elderly subjects (Erim et al. 1999), during muscular fatigue (Adam & De Luca, 2003; Contessa et al., 2009), strength training (Beck et al. 2011) and stroke sufferers (Suresh et al. 2011).

The advantages of the ability to decompose a surface EMG signal are vast, but specifically the ability to measure up to 60 MUs from a single contraction, with force contractions up to 100% MVC and all from the surface of the skin far outweighs the aforementioned limitations of invasive EMG decomposition methods. However, the measures extracted should be contextualised within the validation and accuracy of the technology.

#### 2.2.3.3 Surface EMG Decomposition Validity

As with any new technological and methodological advancement it quite rightly leads to questions regarding the validity and accuracy, which have been raised within the literature (Farina & Enoka 2011). In the landmark paper by Nawab et al. (2010) details of the surface EMG decomposition algorithm are presented, along with a method to validate the output of the motor unit firing instances described as the reconstruct-and-test procedure. Farina and Enoka (2011) in a letter to the editor, firstly casted doubt on the ability of the decomposition algorithm to resolve  $N$  overlapping action potentials due to the complexity of the signal segment. Secondly, Farina and Enoka (2011) question the validity of using the proposed Reconstruct-and-Test in evidence for the decomposition output. In their rebuttal, De Luca and Nawab (2011) clearly demonstrate the misunderstanding and unsubstantiated arguments as proposed by Farina and Enoka (2011), which is backed up by a host of technical peer-reviewed and empirical evidence (Mambrito & Luca 1984; Lesser et al. 1995; Chang et al. 2008; Nawab et al. 2009; Nawab et al. 2010; De Luca & Hostage 2010). In addition, the sEMG decomposition algorithm (Nawab et al. 2010) has undergone significant independent validation and verification of the technique and consequent output (Hu, et al. 2013a; Hu, et al. 2013b; Hu, et al. 2013c). The substantial peer-reviewed publication, complimented by decades of internal

developments and evolutions, provides confidence in the measures extracted from the technology, which is reflected by the high-level of literature exploring the neuromuscular system and its application.

#### 2.2.4 Neuromuscular Control

Quadriceps weakness, dysfunction and control are all thought to be involved in the development and presentation of PFP (Bolgia & Boling 2011), which have often been quantified through measuring isokinetic strength (Citaker et al. 2011) and sEMG measurements (Sacco et al. 2006; Cowan & Crossley 2009; Cavazzuti et al. 2010; Patil et al. 2011; Aminaka et al. 2011). Although measurements of isokinetic strength offer potentially useful information to the clinician and researcher about the subjects' knee extension strength and possible weakness, it may not be sensitive enough to provide information on the contributing components of knee extension; such as Vasti weakness or dysfunction. sEMG has long been used in an attempt to both understand and quantify the involvement of the muscles around the knee. In particular the Vastus Medialis and Vastus Lateralis have often been key focusses in attempting to understand the 'control' of the muscles and their respective behaviour, purported through the onset timing of the two muscles (Cowan et al. 2001; Herrington et al. 2005; Rainoldi et al. 2008; Cowan & Crossley 2009; Cavazzuti et al. 2010). However, the proposed relationships between and within the Vasti are not well substantiated, which is clear by the presentation of the array of heterogeneous findings and conclusions. Wong et al. (2009) demonstrated these heterogeneous findings by highlighting the methodological issues and opposing results of the Vasti onset timing in PFP populations, concluding that only 6/12 studies demonstrated a distinguishable difference in onset timing with the other 6 studies showing the contrary. Considering various methodological differences between the studies the heterogenetic findings are not entirely surprising; although the variability could be considered a true finding in that PFP subjects may present with different Vasti control mechanisms.

A perhaps more sensitive measure of muscle behaviour and one that could provide more detailed insight is through the investigation of the motor unit control strategies. Macgregor et al. (2005) demonstrated, through intramuscular EMG, that the application of various patellar taping techniques increased the firing rate in the majority of the Vastus Medialis motor units. Although this provides evidence that tape can alter the firing rate of the muscle, suggesting an increase in force within the muscle, it is limited in its application as only 5 motor units per subject were identified during a low force level contraction (4 N). Considering the Vastus

Lateralis is thought to have approximately 300 motor units (Rich et al. 1998), this would mean only a 1.7% representation of the muscle was measured and shown to increase the motor unit firing rate by 1-2 Hz. The clinical significance of this change should be considered as such a small representation of the muscle under investigation at a low level of force would not demonstrate a 'real-world' situation. The motor unit firing rate, although a determinate of producing force within the muscle (Burke 1981), does not provide a full description or understanding of the control of the motor unit pool.

Motor unit synchronisation describes the greater than chance tendency for concurrently active motor units to discharge within a few milliseconds of each other (Semmler et al. 1997), which could offer insight into the control of a muscle. Mellor and Hodges (2005a) presented, through intramuscular EMG and at low levels of force, that subjects with anterior knee pain may present with a reduced motor unit synchronisation across the Vasti. However, it has been shown that motor unit synchronisation can vary considerably and even within the same muscle (Bremner et al. 1991). Although Mellor and Hodges (2005a) present an interesting finding of possible strength and control dysfunction within anterior knee pain subjects, the relevance of a small representation of the motor unit pool, low level force contractions and the variability of motor unit synchronisation should be considered. The common drive, as first described by De Luca et al. (1982), describes a remarkable and eloquent scheme of the nervous system to control groups of the motor unit pool within and across muscles. The common drive can be observed through simple observation of common fluctuating motor units, or in more detail by measuring the cross-correlation of motor unit firings with essentially zero time shift. The common drive has been reported in antagonist muscle groups (De Luca & Mambrito 1987), synergist muscle groups (De Luca & Erim 2002), hand dominance (Kamen et al. 1992; Adam et al. 1998), exercise training (Beck et al. 2011) and in ageing (Erim et al. 1999). The investigation into the effects of ageing on motor unit control by Erim et al. (1999) presented an interesting finding with the differences between young subjects and elderly subjects. The most striking finding was that the elderly subjects demonstrated a decreased common drive, less commonality in motor unit firings, compared to the young subjects. The diminished commonality suggests that the ageing process significantly alters the control of the motor unit pool, presenting the first evidence that the control of a muscle can be dysfunction or inefficient compared to a healthy individual. The applicability of this method coupled with surface EMG decomposition techniques could offer significant insight into the control of a muscle in PFP subjects.

### 2.2.5 Vastus Medialis Function

Since the seminal work of Lieb and Perry (1968) with the investigation into Quadriceps function there has been a dogmatic and popularized view that the Vastus Medialis muscle is two distinguishable muscles, the Vastus Medialis Longus (VML) and Vastus Medialis Obliquus (VMO). Lieb and Perry's (1968) investigations were comprised of applying tension to the individual components of the Quadriceps, using external weights, on cadaver specimens in an attempt to determine their individual contributions and function. The authors determinate for Quadriceps function being open-chain knee extension in cadaver specimens. They found that when applying tension to the proximal area of the VM it was able to both individually, and as part of the Quadriceps group, perform knee extension. However, when applying tension to the distal area of the VM it was unable to individually produce knee extension and the only movement occurring was a medial shift of the patella. The authors inferred from these observations that the VM should be considered in two anatomically and functionally differing portions, namely the VML and VMO, which lay unchallenged and accepted for decades.

This debate, now spanning over four decades, has yet to reach an empirically led consensus. Various arguments have been proposed for the existence of two distinct portions of VM with the main topic areas concerning physiological and morphological differences, including: fibre orientation, fascial planes and nerve innervation.

#### 2.2.5.1 Fibre Orientation

Anatomists have documented the observation, through dissection, that the Vastus Medialis has distinct differences in fibre orientation, decreasing in the obliquity from the most distal portion to the most proximal portion of the VM as highlighted in a systematic review (Smith et al. 2009). It was found that there large variations in the reported orientation of the VM portions with 40° to 77° and 11.5° to 35° for the distal and proximal portions respectively. However, no study has found any correlation or suggestion that fibre orientation is associated with PFP or degeneration, therefore the lack of clinical relevance to these findings should be considered and emphasized.

#### 2.2.5.2 Fascial Planes

As with fibre orientation, anatomists have explored cadaver specimens for the presence of differing facial planes, potentially separating the Vastus Medialis muscle into two distinct

portions. The investigations have simply been made by observation and whether there was a separate fascial plane present or not. Conflicting evidence for this has been presented with Galtier et al. (1995) reporting no definitive separation of muscle portions of 44 cadaver specimens, yet Javadpour et al. (1991) reported all 15 specimens had clear fascial separation. The heterogeneous findings around the existence of VM fascial planes is further confounded by the lack of evidence for its involvement in patellofemoral conditions.

#### 2.2.5.3 Nerve Innervation

In addition to the aforementioned anatomical investigations, authors have investigated the innervation characteristics of the VM. Smith et al. (2009) found that nerve innervation in the VM had been investigated in 11 studies, summarising that 194 knees or 59% of the cohort found a single nerve trunk and 135 or 41% found two nerve trunks. These mixed observations were found in cadaver knees which were seemingly non-symptomatic with no observable patellofemoral joint conditions. Galiter et al. (1995) also reported similar heterogeneous observations within pathological specimens with 45% presenting with a single nerve branch and 55% with two nerve branches. However, upon further exploration Galiter et al. (1995) found a correlation between the degree of patellofemoral joint cartilaginous damage and the presence of either one or two nerve branches, one nerve branch indicating the higher severity of degeneration.

It could be concluded that the anatomical and morphological evidence is far from arriving at a consensus as to whether we should consider the VM being two distinct portions, but perhaps more worryingly is the lack of relevance or consideration to function and clinical application. An important aspect that has yet to be addressed, is whether there is an actual functional difference between the proximal and distal portions of the muscle. The neurophysiological approach would suggest that muscle fibres are distributed evenly throughout the muscle (Basmajian & De Luca 1985), and consequently so are the motor units, thus a single muscle could be seen as one functional unit. However, there is currently no literature that has adequately addressed the suggestion that the Vastus Medialis has different neuromuscular control mechanisms for different areas of the muscle as has been previously inferred from anatomical studies. The current investigations have however highlighted the importance of understanding the disparity in its findings which has, and does, consequently affect clinical understanding and reasoning for patellofemoral pain and similar conditions.

## 2.3 Pathomechanics

The anatomical and morphological characteristics of the tibiofemoral and patellofemoral osseous and soft tissue structures are comprehensively documented in a plethora of texts, which would far excel any attempts made in this thesis. Therefore this chapter shall instead focus on presenting the pathological background and current understanding of PFP.

### 2.3.1 Background

There exists a remarkably delicate and yet beautiful evolutionary relationship between the flat triangular patella bone, the femoral condyles and the surrounding soft tissue structures that combined form the Patellofemoral Joint (PFJ), having key responsibilities in the knee and lower limb functionality. The PFJ has been reported to be responsible for quadriceps efficiency, centralising quadriceps forces, transmitting femoral forces, functioning as a bony shield, and even providing a cosmetic appearance to the knee (Aglietti & Menchetti 1995). However, for numerous purported reasons these responsibilities and relationships seemingly become dysfunctional and individuals experience pain in and around the patella.

### 2.3.2 Patella Mechanics

There is a deep and extensive literature base for the purported role of the patella, which has been likened to the mechanical components of a lever with a balance beam, fulcrum, load and effort (Richards 2008). In the first attempt of understanding the contact zones of the patella, Wiberg (1941) demonstrated that as the knee moved from extension to flexion the band of contact moved proximally from the pole towards the base of the patella, which was also later shown by Fulkerson and Shea (1990). The effect and importance of the contact zone moving has shown that at knee flexion angles of less than 60 degrees the quadriceps lever arm holds a mechanical advantage, yet at angles greater than 60 degrees it works at a mechanical disadvantage (Nissel & Ekholm 1985; Gill & O'Connor 1996). This phenomenon was also demonstrated in healthy individuals during a step descent, where at 61 degrees there was a dramatic loss of eccentric control (Selfe 2000), also later shown in PFP subjects at 58% (Selfe et al. 2001), which demonstrates that the symptomatic individuals may have a more dysfunctional Patellofemoral control mechanism.

### 2.3.3 Patella Tracking

The long standing and relatively unchallenged theory for the main contributor to PFP is the abnormal tracking of the patella within the trochlear groove (Fulkerson & Shea 1990; Fulkerson 2004), including static and dynamic components. Grelsamer (2005) describes the abnormal positioning of the patella in any plane as ‘patella malalignment’, and an abnormally positioned patella at one or more points in the flexion-extension cycle as ‘patella maltracking’. The dynamic pathway of the patella within the trochlear groove comprises of a delicate articulation between the medial and lateral facets of the patella and the medial and lateral condyles of the femur. The articulation being far from a simple flexion-extension pathway involves spin, tilt and glide within a multi-degrees of freedom movement of the patella, thus becomes difficult to objectively measure, and even more challenging to measure clinically. Evidence for patella malalignment first surfaced 40 years ago with Merchant et al. (1974), who did not actually study PFP patients, this was then followed up with similar findings from Laurin et al. (1978) and Agiletti et al. (1983) who all used various static radiographic methods in an attempt to substantiate differences in patella malalignment between non-symptomatic and symptomatic subjects. The use of radiographic has since been shown to be an insensitive and unreliable method in investigating patella alignment (Muhle et al. 1999); instead more recent works have explored patella alignment using MRI. McNally et al. (2000) demonstrated that more subjects in the non-symptomatic group (63%) presented with lateral patella displacement compared to the symptomatic group (57%), thus suggesting that these measures, even during non-stability challenging or non-clinically relevant tasks, are unable to distinguish non-symptomatics and symptomatics individuals. An evolution of imaging, explicitly dynamic MRI, has shown to be sensitive when measuring change in the position of the patella with the application of the McConnell taping technique (Derasari et al. 2010); suggesting that the patella is shifted inferiorly in response to tape. However, limitations remain with the fact that these techniques are difficult to access, operate and interpret the results requiring both opportunity and significant expense. But perhaps more importantly and often not explicitly stated is the lack of functional relevance with the low loading and open kinetic chain activities performed and thus the context of the findings should be considered as to their clinical relevance.

#### 2.3.4 Tibiofemoral Mechanics and Control

A well-established avenue to investigate has been the study of 3-dimensional tibiofemoral kinematic and kinetic joint mechanics in symptomatic subjects (Salsich et al. 2002; Richards et al. 2008; Selfe et al. 2008; Paoloni et al. 2010; Selfe et al. 2011) through the use of optoelectronic stereophotogrammetric technology; commonly referred to as motion capture (Cappozzo et al. 2005). Numerous investigators have explored the knee joint kinematics and kinetics in a PFP population, which have often reported conflicting evidence. Nadeau et al. (1997) demonstrated that in just 5 symptomatic subjects there was a significant reduction in knee flexion angle compared to the 5 non-symptomatic subjects whilst walking down a 9 metre walkway, measured using a video camera sampling at 30 Hz. These results were then reported to demonstrate a strategy to avoid quadriceps contraction, even though no muscle measurements were made. The small sample size, limited technology and discrete results from the sagittal plane question the applicability of this work. Similar work and methods were in agreement that the knee flexion angle was differing in symptomatic subjects (Dillon et al. 1983). However, in opposition to these findings it has been reported that there are no changes in knee flexion angle in symptomatic individuals during gait (Heino & Powers 2002; Powers et al. 1999). . However, investigating the sagittal plane knee mechanics during step ascent and descent in symptomatic individuals has been able to exhibit some significant changes (Crossley et al. 2004; Brechter & Powers 2002; Aminaka et al. 2011; Salsich et al. 2001) reporting lower knee flexion angles and moments. The reported reduced knee flexion is often described as an altered strategy or a load re-distribution amongst symptomatic subjects; as such are presenting with a different control mechanism or response. However, these studies did not compliment the joint biomechanics measurements with EMG and therefore the justification of such conclusions are questionable. Regardless of the evidence presented about the knee flexion angle during gait the results should be placed in context to the condition under investigation, PFP, which has been reported for many years being exacerbated under more significant loads such through activities such as stair ascent and descent or running. It is thought that the load exerted by walking upon the PFJ is not sufficient enough to reveal consistent biomechanical changes, which may explain the aforementioned conflicting work. Researchers within the field face the problem as to how define the activities that may be functionally relevant to PFP patients and at the same time sufficiently challenge the dynamic stability of the joint. To add further frustration and difficulty with this goal the activities should avoid inducing pathological overload with consequent risk of injury. Instead it is suggested that stair ascent and descent

will serve as more appropriate means of eliciting changes since the activity loads the PFJ to a greater degree (Costigan et al. 2002). In the past decade there has been an increase in the investigations that are exploring the variables associated with eccentric control during step descent (Crossley et al. 2002; Crossley et al. 2004; Nijs et al. 2006; Gilleard et al. 1998; Salsich et al. 2001; Selfe et al. 2001; Selfe 2000; Selfe et al. 2008; Richards & Selfe 2011). The eccentric control required during a step descent provides an additional challenge compared to step ascent and significantly difference to low load activities such as gait. During stair descent the centre of mass is carried forwards and then gravity is resisted during the controlled lowering phase, this is achieved through eccentric muscular contraction controlling the rate of lowering of the centre of mass. In the absence of strong eccentric muscle activity around the knee and other structures, the centre of mass would accelerate due to gravity. In addition during the controlled lowering phase the knee joint starts from a relatively stable extended position and flexes, towards an increasingly unstable position (Selfe et al. 2008). The increased joint flexion causes a progressive increase in the external flexion moment which is matched by progressively increasing eccentric muscle contraction, in order to prevent medial collapse that is seen as detrimental to the optimal patella contact zones due to the cam shape of the femoral condyles. This causes the patella tendon lever arm to lengthen and the quadriceps lever to shorten. The effect of the moving contact zone is significant; at angles of less than 60 degrees knee flexion the quadriceps lever arm works with a mechanical advantage, however, at angles of greater than 60 degrees knee flexion the quadriceps work at a mechanical disadvantage (Nissel & Ekholm 1985; Gill & O'Connor 1996). Achieving this level of knee flexion in gait is not possible and therefore the use of gait to investigate the control of the knee joint and specifically within PFP research may not be an appropriate task or measure to take. In conclusion, measuring the sagittal plane the authors infer that the knee is a simple flexion-extension mechanism and seemingly not considering the other planes of motion at the knee, the coronal and transverse planes, for their importance and contribution to the control of the knee.

Several researchers have however highlighted the importance of studying the coronal and transverse planes of motion when investigating the knee joint mechanics (Kowalk et al. 1996; Selfe et al. 2008; Karamanidis & Arampatzis 2009; Paoloni et al. 2010; Selfe et al. 2011). Kowalk et al. (1996) were the first to propose the importance of investigating the abduction-adduction knee moments, reporting that although the sagittal plane moment are important for propulsion the coronal plane plays a vital role in the medio-lateral stability of the knee. Following on from this Selfe et al. (2008) eloquently presented that not only was the coronal

plane demonstrating a significant role in the control of the knee during a slow step descent, but the transverse plane was also significantly involved. An equally important finding from this work was that it was shown that clinical interventions, neutral taping and a soft brace, could offer clinically meaningful alterations to the coronal and transverse planes. Selfe et al. (2008) reported significant reductions in the maximum coronal plane knee angle from 10.7 degrees to 8.1 degrees in the neutral taping condition and further reductions in the soft brace to 5 degrees, these changes were also mimicked in the reduction in coronal plane knee moment from 0.39 Nm/kg to 0.36 Nm/kg in the taping condition and 0.24 Nm/kg with the soft brace condition. Similar changes were also later demonstrated in a Patellofemoral Pain population (Selfe et al. 2011). These findings demonstrated that common clinical interventions, tape and bracing, can offer significant and clinically important changes in control. However, it should be noted that although changes were statistically significant there were large standard deviations in both knee angle and moment, which could indicate that some subjects present with a different response or strategy. Movement control changes in the coronal and transverse plane have also been observed in the work of Paoloni et al. (2010) where PFP subjects displayed significantly higher knee abductor and external knee rotator moments in gait loading response compared to non-symptomatic individuals. It was suggested, although not measured, that this was due to a dysfunction between the Vastus Medialis and Vastus Lateralis and/or a delayed Vastus Medialis activation. In knee osteoarthritis similar differences can be seen in the coronal and transverse planes between elderly and young subjects (Karamanidis & Arampatzis 2009) during stair ambulation, with elderly subjects demonstrating significantly higher adduction and internal rotation at the knee joint. These findings were reported to present a re-distribution of the mechanical load in the elderly subjects and seemingly offer different strategies in negotiating a stability challenging task compared to younger subjects.

In addition, and complimentary, to exploring the step tasks there have been a wealth of research using squatting exercises to challenge the motor control system and investigate the mechanical and muscular changes that occur between patient groups. The squat exercise, in all of its variations, is an integral part to the majority of strength and conditioning programs for its ability to strengthen multiple large muscle groups. Equally as important is the application of this exercise within rehabilitation as can be reflected by the volume and variety of investigations exploring its use (Lutz et al. 1993; Ohkoshi et al. 1991; Shelbourn & Nitz 1990; Stuart et al. 1996; Yack et al. 1993; Richards et al. 2008; Mostamand et al. 2011; Clément et al. 2014; Noehren et al. 2012; Wilson et al. 2009). Squatting activities replicate daily function

tasks such as; sit-to-stand, kneeling, stair ascent/descent etc., and offer a stability challenge to the patient so is often a preferred exercise for measurement and quantification as well as the rehabilitation protocol itself. The biomechanics of a squat is a complex combination of multiple joints, muscles and tendons all which interact in an attempt at producing a smooth generation of force and maintain the body in a stable and aligned position. To manipulate the contribution of the muscles, joints and tendons many different variants of squatting are employed; double limb, single limb, body weight, barbell weighted, inclined squats, declined squats, mini squats, deep squats, wide stance squats and even more to create an exhaustive variant list. However, for the application within PFP research there has been a focus on the use of the single limb (Richards et al. 2008) or quasi-static squats (Clément et al. 2014) which provide a stability challenging task involving the lower limb and specifically the knee and its surrounding structures. The basic principle of a squat is that as the knee angle increases the ground reaction force becomes distanced from the knee joint, moving the centre of pressure in the posterior direction, and thus an increased knee extensor joint moment and consequently an increase in the knee extensor muscles and patellofemoral joint reaction forces (Richards 2008). Within clinical practice therapists either increase the load at the knee joint in order to stimulate a quadriceps dominant exercise or decrease the load of the knee joint and consequent Quadriceps loads. It has been shown this can be altered by performing the squat on a decline, whereby the increase in decline angle increased the knee joint moment whilst decreasing the ankle joint (Richards et al. 2008). As previously highlighted the flexion movements may not be the clinically relevant measure to extract for the PFP population, where there has been a focus on the ‘control’ element by studying the medio-lateral and rotational movements. However, to the authors knowledge there is no literature focussing on these movement variables during squatting tasks, Clément et al. (2014) designed an appropriate study using 3-dimensional kinematic analysis and investigating the differences between a quasi-static and fast single limb squat however only studied the flexion angles, velocities and vertical ground reaction force thus not describing suggestively useful information about the medio-lateral and rotational control.

Control and stability, measured by studying discrete and subtle coronal and transverse plane joint mechanics, has been shown to be different amongst different subject groups and their response to a clinically orientated intervention. However, these findings can only speculate on the underlying mechanisms as they lack the investigation of seemingly important sensory-motor control process such as the neuromuscular and psychosocial factors.

## 2.4 Psychosocial Involvement

Historically, movement control and related disorders have been questioned through mechanical and neuromuscular measurements with less consideration to the psychosocial features. However, it has been shown that psychosocial elements, in-particular pain and fear of pain, can have distinct and significant influences on motor control (Lethem et al. 1983).

### 2.4.1 Pain and Movement Control

Despite the extensive history in exploring the mechanisms and understanding of pain, dated back to the early systemic work of Descartes (1662), a comprehensive understanding continues to elude researchers. As defined by the International Association for the Study of Pain (IASP) pain can be described as:

*“An unpleasant sensory and emotional experience associated with the actual or potential tissues damage, or described in terms of such damage”* (Merskey & Bogduk 1994).

The generality in the very definition of pain is mimicked by the disparity and vagueness of pain reported clinically with PFP subjects, most likely due to the subjective nature of pain. The patella maltracking theory suggests that the abnormal tracking of the patella changes the contact zones and thus causes a noxious stimulus (Fulkerson 2004), which is then subjectively and individualistically inferred as pain by the patient. Various classification tools have been used by researchers and clinicians in the study of PFP to determine the level of pain patients experience and the response from a clinical intervention (Crossley et al. 2004; Van Tiggelen et al. 2009; Tucker & Hodges 2010; Kaya et al. 2010; Salsich et al. 2012; Papadopoulos et al. 2014; Ferrari et al. 2014). Smart et al. (Smart et al. 2012) interestingly demonstrated that symptomatic features rather than clinical signs were more useful for identifying nociceptive pain, which indicates that subjectively orientated tools, as used in the previous PFP research, are sensitive and useful at determining the pain experienced. This is in agreement with Stinson et al. (2006) and Pagé et al. (2012) who demonstrated the validity of using the Numerical Rating Scale (NRS) as a measure of pain intensity and unpleasantness.

It was first proposed by Melzack and Wall (1965) that pain experience was jointly determined by physiological, motivational, cognitive and emotional responses. The process arguably revolutionised pain research with a multi-dimensional concept, which has consequently been furthered by Melzack (1999 and 2001). The premise that pain and movement are inter-related

is now a well-established phenomenon, yet remarkably poorly understood or misinterpreted, which is evident by the various theories of pain and the body's response and adaptation to pain. The Vicious Cycle theory (Roland 1986) proposes that all muscles stereotypically will increase their activity in response to pain or pain within the region, which is in complete opposition to the later proposed Pain Adaptation theory (Lund et al. 1991). The pain adaptation theory instead suggests that the activity of the muscle that is painful or produces a painful voluntary contraction is stereotypically inhibited. However, two of the major limitations are that the majority of the experimental and clinical findings are inconsistent with the proposed theories and secondly that the evidence between the theory and rehabilitation is weak (Hodges 2011). In opposition to the theories propositions, Holroyd et al. (1984) stated that clinical improvements were reported but with no evidence of associated change in muscle activity, therefore perhaps suggesting that cognitive processes may be involved in the presentation and rehabilitation. Hodges and Tucker (2011) propose a new theory in attempt to explain the adaptation to pain, arguing that pain is distributed within and between muscles rather than a stereotypical inhibitory or excitatory response from the muscles. This theory has recently been complimented with empirical evidence (Hodges et al. 2013) demonstrating that in most individuals' acute lower back pain leads to an increased spinal stability and that patterns of muscle activity are not stereotypical, but instead present with individualistic responses.

#### 2.4.2 Conscious Processing

Lethem et al. (1983) had previously proposed that pain and 'fear of pain' may generate, in some individuals, a strategy to either avoid or confront a painful situation thus suggesting conscious aspects of movement may influence a musculoskeletal pain response. Masters and Maxwell (2008) proposed the theory of re-investment, furthering developing the concept of conscious involvement of movement. The theory of re-investment suggests that individuals present conscious aspects in the execution and control of a movement, which may be altered in certain populations and disrupt optimal performance or execution. Selfe et al. (2014) in a cross-sectional study of pain free and self-reported knee pain subjects found that symptomatic subjects had a higher conscious motor processing score on the Movement Specific Reinvestment Scale (MSRS) (Masters & Maxwell 2008) compared with people who are pain free. For the first time this showed that subjects with self-reported knee pain have a propensity to consciously control their movements, meaning they were more likely to be concerned with the execution and control of their movements. These findings may suggest that there could be

a disruption in the effective automatic control processes (Masters & Maxwell 2008), which has also been seen with a higher falls incidence in the elderly (Wong et al. 2008) and movement impairments in stroke subjects (Orrell et al. 2009). These findings are similar to the previous propositions that individuals may display different psychological traits and responses to pain or the fear of pain, with extreme examples described as being 'confrontation' and 'avoidance', although likely a mixture of the two (Lethem et al. 1983).

The conscious motor processing and experience of pain have been shown to play important roles, although perhaps not causative factors in developing or worsening symptoms, in PFP and should perhaps be a point of consideration and reflection during investigations of the complex sensory-motor processes.

## 2.5 Therapeutic Interventions

Since the landmark paper by McConnell (McConnell 1986) there has been an exponential rise and popularity in the application of patellar taping for the treatment and management of PFP. McConnell (McConnell 1986) described the application of rigid tape across the patella with various alterations of the position of the patella in the process, including; patella tilt, patella spin and patella glide. It was originally proposed that the tape application, particularly the medial glide aspect, may adjust the tracking of the patella within the femoral groove and the Vastus Medialis resumes its responsibility acting as a medial stabiliser (McConnell 1986). These postulates have been explored through radiographic investigations, demonstrating that there may be some evidence of an altered patella position with the application of tape (Bockrath et al. 1993; Larsen et al. 1995; Somes et al. 1997). However, the radiographic findings do not directly confirm the original thought of a mechanical shift, as the shift in the patella position could be due to various other mechanisms; such as a change in Vasti muscle activity distribution and control. Opposing evidence for the mechanical effect of patellar taping can be found in the work of Selfe et al. (2008 and 2011). It was found that adhesive tape placed over the patella, with no stretch or patella glide, could significantly reduce the mediolateral and rotational joint moment. These findings suggest that the application of a neutral tape can significantly improve the stability of the knee joint in both healthy and PFP subject, suggesting that tape may offer a proprioceptive effect. It has previously been demonstrated that subjects with poor proprioceptive ability, as measured by active and passive ankle reproduction, can benefit from the application of tape with an enhanced proprioceptive status (Callaghan et al. 2002). The detailed review of Crossley et al. (2000) suggests that tape demonstrates sporadic yet unexplainable clinical success in reducing pain and improving function in PFP subjects, concluding that more studies should explore the Vasti motor control system in functional tasks.

Complimentary to the observed changes in joint mechanics and angle reproduction with the application of tape, significant changes have been demonstrated with brain activity in response to clinical interventions (Thijs et al. 2010; Callaghan et al. 2012). Thijs et al. (2010) using functional magnetic resonance imaging (fMRI) investigated levels and areas of brain activation with a knee brace, knee sleeve and without any application. It was found that higher levels of cortical activation were present with the application of the two interventions. Similar findings were later found by Callaghan et al. (2012) with a taping intervention, where significant increase in blood oxygenation level-dependent (BOLD) were found in the taped condition.

Both of these studies present evidence suggesting that a peripheral proprioceptive intervention, such as tape or knee braces, influence brain activity in areas of the brain thought to be responsible for proprioception. These findings coupled with previous work investigating the changes with joint mechanics, gross muscular changes and conscious motor processing involvement suggest that tape and other proprioceptive orientated interventions are capable of modifying the sensory-motor processes but still lacks information on the mechanisms of force and control.

## 2.6 Somatosensory Input

The somatosensory system, a complex scheme of sensory receptors and neurons, provides crucial information about the external environment and our bodies interactions with it; including information on position and movement (proprioceptors), skin stimuli (cutaneous receptors) and pain (nociceptors). The sensory receptors and neurons reside within the periphery such as the skin, muscle, tendons and joints with deeper neurons within the central nervous system, and both the central and peripheral systems being delicately entwined and majestically controlled. The eminent neurophysiologist, Sir Charles Sherrington, was the first to introduce the concept and term 'The Proprioceptive System' in 1906 describing it as being a group of varied sensory receptors to give the body the ability to sense position of self and movement (Burke 2007).

Therapists often aim to enhance the patients' movement and reduce pain through manipulating the somatosensory inputs in a wide range of musculoskeletal and neurophysiological conditions. The method of the sensory manipulation has been addressed in various ways (joint mobilisations, movement re-education, medication, injection therapy etc.) but with no direct measurement of the sensor receptor activity feasible then therapists and researchers alike rely on indirect measures such as joint position sense, clinical questionnaires and scores, patient perceived benefit, measures of movement control or muscle behaviour. Taping of the joint has been used across many clinical populations as a way of supporting and enhancing the movement control in patients and specifically in Patellofemoral Pain patients, as discussed in section 2.5, for which proprioception has been inferred to be the mechanism behind the observed changes. There have been a plethora of studies demonstrating significant changes with the application of tape to the ankle on ankle proprioception (Karlsson & Andreasson 1992; Robbins et al. 1995; Heit et al. 1996; Simoneau et al. 1997) showing enhanced movement control and recovery. This is similar to the work described in section 2.5 for PFP patients showing the effects of joint taping or similar proprioceptive orientated interventions (Tubigrip, soft braces, non-adhesive bandages etc.), which have been suggested to provide a proprioceptive enhancement and perhaps through cutaneous stimulation. Murray & Husk (2001) describes tape causing an increase in proprioception through increased stimulation to cutaneous receptors, although measured indirectly. Grigg (1994) suggests that applying pressure to, and stretching the skin can stimulate cutaneous receptors, and that the sense of stretching is thought to possibly signal information of joint movement or joint position. Furthermore, it has been stated that cutaneous receptors might play a role in detecting joint

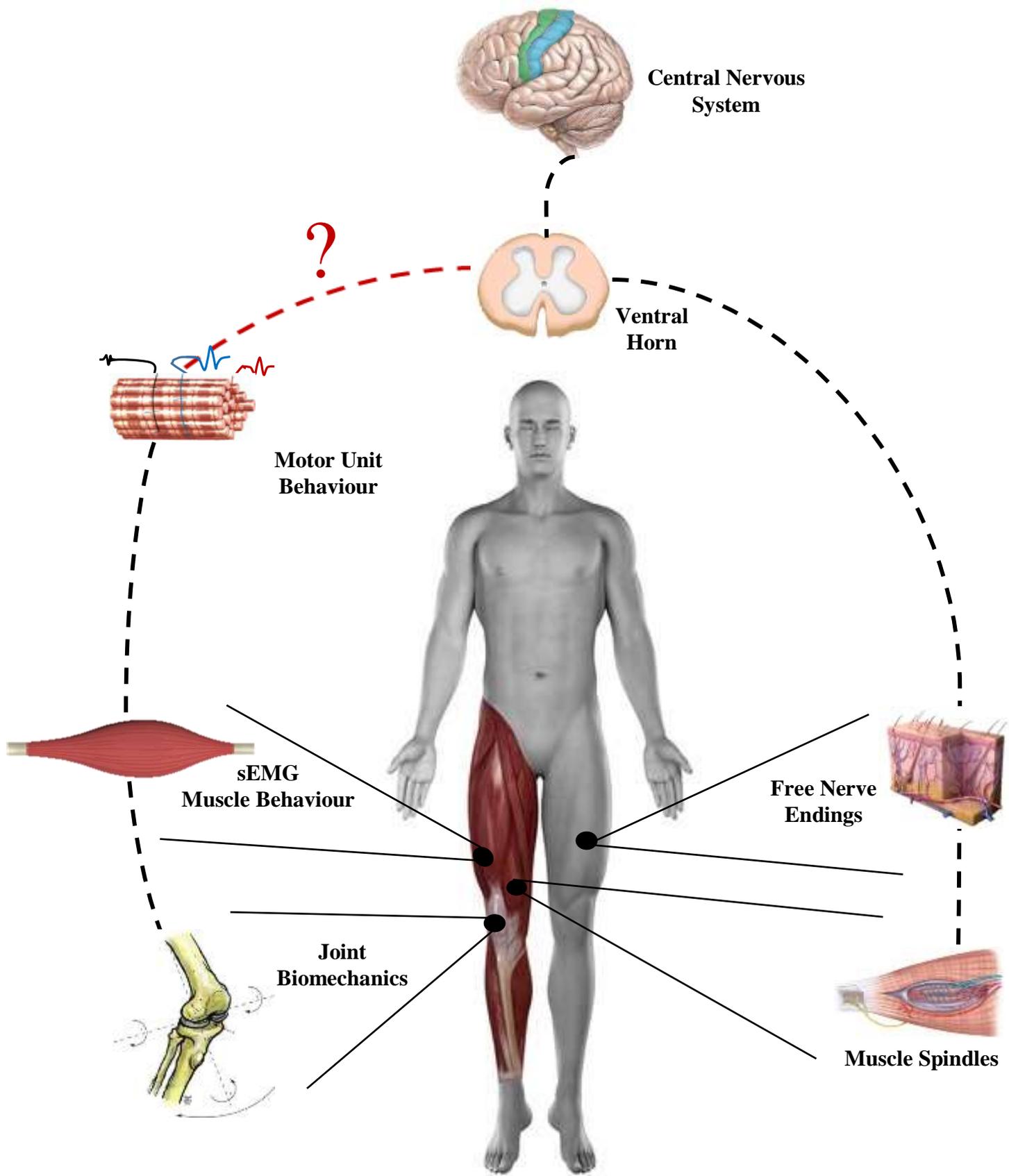
movement and position resulting from the stretching of skin at extremes of motion, much like joint mechanoreceptors (Riemann & Lephart 2002). While the exact role of cutaneous receptors is still under discussion, it has become evident they may signal joint movement and to some extent joint position (Simoneau et al. 1997).

The changes in joint position and control through varying proprioceptive orientated interventions come about due to the muscle behaviour controlling the kinematic adjustments, so investigations into the muscle activity have been explored to try and understand the effects of proprioception. Selkowitz et al. (2007) found decreased upper trapezius activity and increased lower trapezius activity in people with suspected shoulder impingement with tape applied to the shoulder joint. In opposition to these findings Alexander et al. (2003), using a scapular taping technique on healthy individuals, found a decreased amplitude of the lower trapezius H-reflex, and suggesting an inhibitory influence of taping. But again in opposition to previous work Cools et al. (2002) found no significant differences between scapular taping and no taping for the upper, middle, and lower trapezius, and the serratus anterior. These previous works have investigated 'gross' muscle activity through simply investigating the amplitude of the signal, which arguably may not offer enough sensitivity or with enough confidence the changes in the muscle behaviour. Macgregor et al. (2005) explored the motor unit firing rate, using invasive EMG methods, to establish the effect of a taping intervention on the Vasti muscles. The authors used three different applications of tape by varying the direction of stretch across the patella and recording the motor unit firing rate, documenting that although there was not a net increase in the firing rate the majority of the motor units in the Vastus Medialis increased their firing rate during the lateral stretch with no change in the Vastus Lateralis. The effect between a cutaneous afferent stimulation has also been seen previously (McNulty et al. 1999) whom demonstrated that firing of a single cutaneous afferent influences muscle activity in the hand. Interestingly not just the firing rate of the motor units have demonstrated a change to a cutaneous stimulation as Garnett and Stephens (1981) found a change in the order of the motor unit recruitment in the dorsal interosseous muscle during cutaneous stimulation of the hand. The underlying mechanism for the apparent modification are unable to be expressed definitively, however it has been deduced that the application of the tape could be presenting a form of feedback to the muscle, most likely the through the muscle spindles (De Luca et al. 2009), which both the central and peripheral nervous systems alter the motor unit pool by adjusting the force and its control within the muscle that may consequently adjust the joint mechanics.

These works have demonstrated that there exists some significant changes in the muscle behaviour with proprioceptive orientated interventions, excitingly suggesting that taping may adjust muscle activity via proprioceptive feedback, a sensory modality allowing a person to identify the position of a limb in space and perceive limb motion. However there is still a lack of consistent and clear understanding on the responses and/or a fuller description on other involved changes such as the joint mechanics and psychosocial elements.

## 2.7 Summary

Previous investigations have found significant and clinically important changes in the joint biomechanics, psychosocial factors, brain activity and gross neuromuscular activity yet there is a lack of conclusive understanding on the motor unit behaviour within a Patellofemoral Pain population and the efficacy of a tape intervention (Figure 2-3). A contributory limiting factor may also be that most investigations have studied these sensory-motor processes in isolation opposed to a complex yet desirable inter-disciplinary approach. This study aims to provide a unique and multifaceted investigation into the motor unit control, biomechanical, neuromuscular and psychosocial factors in understanding the movement control of Patellofemoral Pain subjects and the response to a common clinical intervention.



**Figure 2-3 Graphical representation of motor control systems**

## 2.8 Study Aims and Objectives

### 2.8.1 Aim of MPhil

To investigate the neuromuscular and biomechanical control of the knee joint and the response of a taping intervention within a non-symptomatic population.

### 2.8.2 Objectives of MPhil

2.8.2.1 To develop methods in order to capture a host of neuromuscular and biomechanical measures that are appropriate and relevant for Patellofemoral Pain.

2.8.2.2 To determine the mechanical control of the knee joint during a stability challenging task and the response of a taping intervention.

2.8.2.3 To explore the motor unit behaviour using new and existing methods of non-invasive surface electromyography and the response of a taping intervention.

2.8.2.4 To measure the muscular control of the knee joint during isometric and stability challenging tasks and the response of a taping intervention.

### 2.8.3 Aim of PhD

To investigate the neuromuscular, biomechanical and clinical changes associated with control of the knee joint on Patellofemoral Pain patients and the response of a taping intervention.

### 2.8.4 Objectives of PhD

2.8.4.1 To determine the mechanical control of the knee joint during a stability challenging task with patellofemoral pain patients and the response of a taping intervention.

2.8.4.2 To determine the muscular control of the knee joint during a stability challenging task with patellofemoral pain patients and the response of a taping intervention.

2.8.4.3 To determine the clinical, neuromuscular and biomechanical effects of a taping intervention on patellofemoral pain patients.

2.8.4.4 Explore the differences in the control between the non-symptomatic participants and patellofemoral pain patients.

2.8.4.5 Explore the relationships between clinical outcomes, neuromuscular and biomechanical control with a taping intervention applied.

### 3. General Methods

#### 3.1 Introduction

To measure and explore the detailed yet discrete control mechanisms of the neuromuscular and biomechanical system a battery of objective measures associated with PFP were required. The study design consequently employed the use of four separate measurement tools: kinematics, kinetics, surface EMG and surface EMG decomposition. This required a combination of integration and synchronisation techniques, all presenting technical challenges due to the variety of data types, connection options, synchronisation delays and sampling frequencies. The following section provides a technical summary of the equipment and the techniques used throughout the thesis.

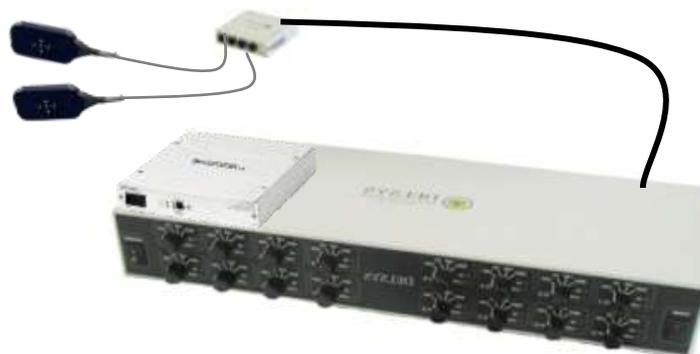
#### Chapter Outline

- Stating the type of equipment employed (3.2)
- Describing and justifying the sampling frequencies of the equipment (3.3)
- Pertinent information relating to the surface EMG setup (3.4)
- Pertinent information relating to the kinetic and kinematics setup (3.5)
- Pertinent information relating to the surface EMG decomposition setup (3.6)
- Integration and synchronisation methods (3.7)

#### 3.2 Equipment Used

##### 3.2.1 Surface EMG Decomposition System

The Delsys Surface EMG Decomposition system (dEMG, Delsys Inc., Boston, MA) (Figure 3-1) is a surface EMG decomposition system that uses 5-pin array sensor collecting 4 channels of single differential surface EMG data.



**Figure 3-1 The Delsys dEMG system**

### 3.2.2 Surface EMG System

The Delsys Trigno Lab system (Delsys Inc., Boston, MA) (Figure 3-2) is a wireless EMG system that uses a single differential electrode configuration to detect the electrical signals from the surface of a given muscle.



**Figure 3-2 The Delsys Trigno EMG system (left) and the Delsys Trigno EMG sensor (right)**

### 3.2.3 Motion Capture System

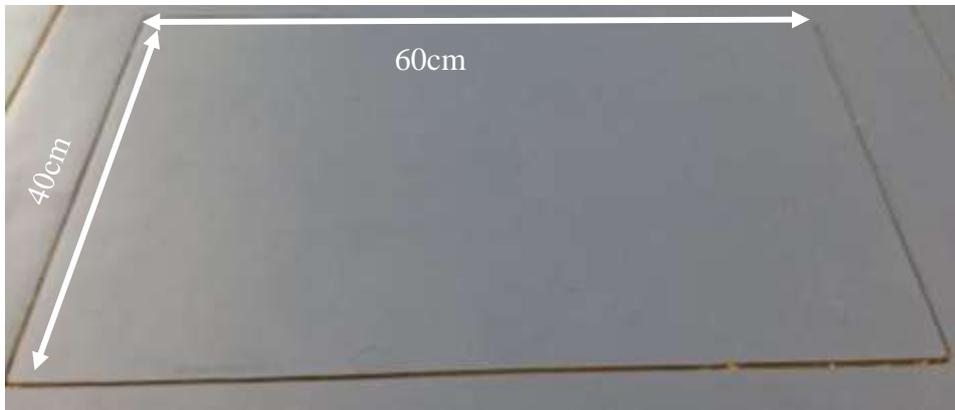
The Qualisys passive motion capture system (Qualisys Medical AB, Gothenburg) (Figure 3-3) uses high quality two dimensional (2-D) digital cameras, which emit short infrared pulses. The infrared pulses are reflected back into the camera after hitting retro-reflective markers, which are placed upon a subject.



**Figure 3-3 The Qualisys Oqus 310 camera series**

### 3.2.4 Force Platform

The AMTI BP400600 (Figure 3-4) (Advanced Mechanical Technology Inc., Boston, MA) force platforms are strain gauge platforms utilising the principle of strain, a ratio of changes between original dimensions and the deformed dimensions (Richards 2008).



**Figure 3-4 AMTI BP400600 Force Platform imbedded in the laboratory floor**

### 3.3 Sampling Frequencies

In contemporary analyses and applications of many physiological and biomechanical signals, such as sEMG or motion capture data, computers and their algorithms are required. The algorithms necessitate that the signals are expressed in numerical sequences. The process of converting the detected analog signals into the numerical sequences is called analog-to-digital (A/D) conversion, generating a sequence of numbers where each number represents the amplitude of an analog signal at a specific time point. The consequent number sequence is then called a digital signal, the analog signal is then said to be ‘sampled’. The process of digitising a signal is defined by the concept of the sampling frequency, which plays a critical role in providing an accurate and reproducible representation of the sampled signal.

Selecting the sampling frequency is dependent on various factors, two of the main factors being; Nyquist Theorem and the type of activity being measured. Nyquist Theorem (Shannon 1948) states that the sampling frequency should be at least twice the highest frequency component being measured in order to accurately reconstruct the signal. Therefore it is important to consider the type of activities being captured to establish the highest frequency component and the consequent minimum frequency. Throughout this thesis the tasks performed are comprised of low frequency sagittal plane movements, which are coupled with higher frequency coronal and transverse plane movements. Although the movements are only semi-dynamic the sampling frequencies need to reflect all the discrete components of the movements.

#### 3.3.1 dEMG Sampling Frequency

In order to decompose the sEMG signal into its constituent MUAPs the sampling rate is required to be significantly higher than traditional sEMG data collection, as MU shapes discrimination needs a high volume of data points, therefore a sampling frequency of 20,000 Hz is recommended (Nawab et al. 2004).

#### 3.3.2 sEMG Sampling Frequency

Frequency content of sEMG signals can be up to 400 Hz (Basmajian & De Luca 1985). Therefore to abide by Nyquist Theorem, sampling at no less than twice its frequency, the sEMG signal should be sampled at a minimum of 900 Hz to avoid aliasing of the signals. The sEMG

was sampled at 2000 Hz, the same frequency as the kinetic data as both systems were integrated into the same A/D board.

### 3.3.3 Kinematic Sampling Frequency

Selfe et al. (2008 & 2011) whom were investigating the discrete coronal and transverse plane movements in slow controlled sagittal plane movements utilised a 100 Hz sampling frequency for kinematics. Therefore a sampling frequency of 200 Hz will provide a highly accurate representation of the desired kinematic data.

### 3.3.4 Kinetic Sampling Frequency

Selfe et al. (2008 & 2011) investigating similar activities sampled kinetic data at 200 Hz. However, in this current work the force platforms and sEMG system were being sampled through the same (A/D) board. Therefore both sampling frequencies had to be the same with the kinetic data up-sampled to compliment the sEMG sampling. Therefore a sampling frequency of 2000 Hz was used to collect the kinetic data.

### 3.4 EMG Data Fidelity

The quality of the detected signals determines the usefulness and accurate interpretation of the muscle activity, these include the intrinsic and extrinsic factors. Intrinsic factors, as classified by De Luca (1997), refer to anatomical, physiological and electrical properties that are not controllable by the user. Extrinsic factors fortunately can be controlled by the user and the sensor manufacturer, these include: sensor location, electrode configuration, EMG bandwidth, skin preparation and noise sources.

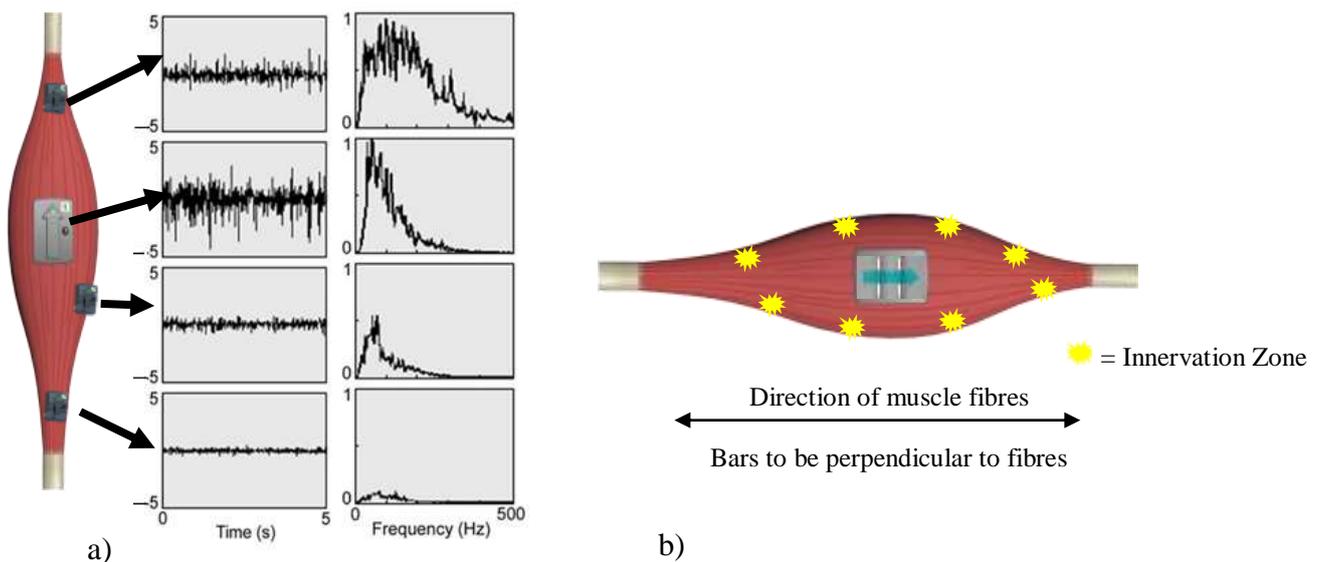
#### 3.4.1 EMG Sensor Location

##### 3.4.1.1 Surface EMG Sensor

The location and positioning of EMG sensors is a much discussed topic with various recommendations either based upon surveys (SENIAM Recommendations) (Hermens et al., 2000) or through empirical evidence (Roy et al., 1986). It has been shown that the location of the sensor is one of the most important factors in obtaining a high fidelity EMG signal, with differing locations rendering dramatically different EMG characteristics (De Luca 1997). Sensor placement has also been shown that it may have a considerable effect on the temporal relationship of the vasti muscles (Wong & Ng, 2006), which has been a commonly investigated variable within the study of PFP (Wong, 2009). Roy et al. (1986) demonstrated the effects of positioning the sEMG sensor across varying areas of the muscle with respect to sEMG signal characteristics. It was found that with the electrode being positioned in proximity to the tendonous insertion of the muscle and the innervation zones was detrimental to signal fidelity. The differing placements and consequent differing signal characteristics are represented in Figure 3-5a. Placement of sEMG sensors has therefore been recommended to avoid innervation zones, which often reside near the edge of the muscles, tendonous origin and insertions with the optimal placement being the middle of the muscle belly (De Luca 1997). Positioning of the sEMG sensors during data collection was conducted with the sensors being placed in the middle of the muscle belly and with the bar electrodes perpendicular to the muscle fibre orientation as shown in Figure 3-5b.

As discussed throughout section 2.2 there are a host of lower limb muscles that have been used when investigating PFP and lower limb control, but mainly focussing locally around the knee joint. In order to gain a fuller understanding of the lower limb muscle behaviour sEMG sensors were placed on the Medial Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus

Medius. Selecting these muscles allows information to be extracted about the ankle, knee and hip musculature, which have all been shown to have an important role in the control of the lower limb (section 2.2). The investigation of these muscles allows a better understanding of the control of the lower limb, response to the taping intervention and any between group differences as per the project objectives (section 2.8).



**Figure 3-5 Surface EMG optimal sensor location on a muscle a) Amplitude and Frequency characteristics of different placements b) Sensor placement avoiding innervation zone and perpendicular to muscle fibres**

### 3.4.1.2 Surface EMG Decomposition Sensor

The placement of the surface EMG decomposition (dEMG) sensors, whose design is considerably different to traditional surface EMG sensors (section 3.4.2), have not had the same extensive review of standard sEMG sensor placements. As part of the development of the methods (section 5.2) the optimal location of the dEMG sensors was investigated with regards to the motor unit behavioural differences. It was found that placement of the dEMG sensor can be placed either proximally or distally to the innervation zone and still provide representative behaviour of the whole muscle. However, a study by Zaheer et al. (2012) did describe a marginally greater motor unit yield when the dEMG sensors were placed proximal

to the middle of the muscle belly. Therefore, the dEMG sensors were placed slightly proximal to the middle of the muscle belly on both the Vastus Lateralis and Vastus Medialis muscles, an example of the placement can be seen in Figure 3-6.



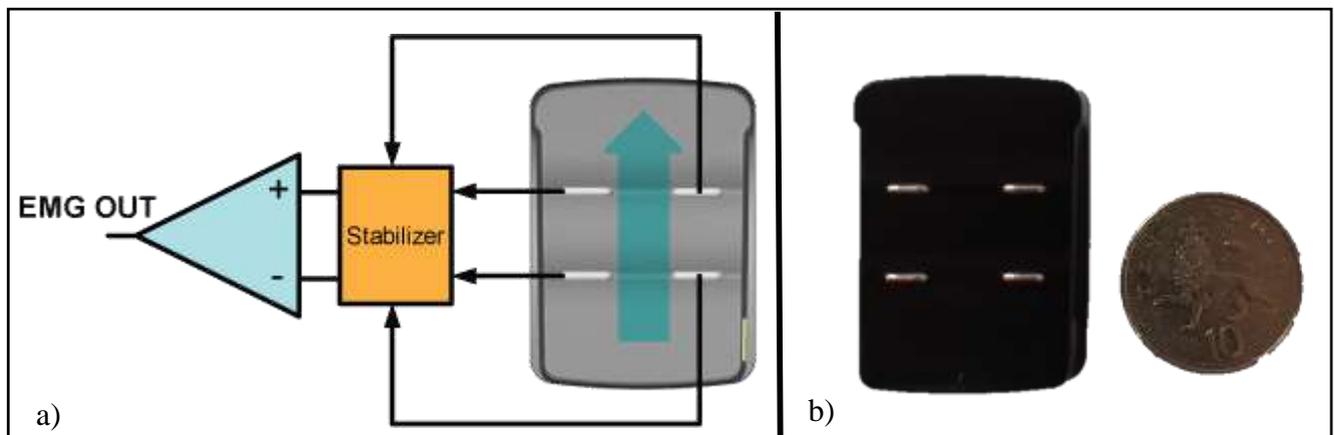
**Figure 3-6 An example of the dEMG sensor location on the right Vastus Medialis and Vastus Lateralis**

### 3.4.2 EMG Electrode Configuration

#### 3.4.2.1 Surface EMG Electrode

Typical sEMG sensors employ a single differential electrode configuration, where the voltage at each electrode is measured with respect to a third reference electrode and then subtracted using a differential pre-amplifier. Thus any voltage that is common to the two electrode contacts such as line interference, movement artefact and muscle crosstalk are subtracted to zero. The Delsys sEMG electrode contacts are designed in a parallel bar configuration opposed

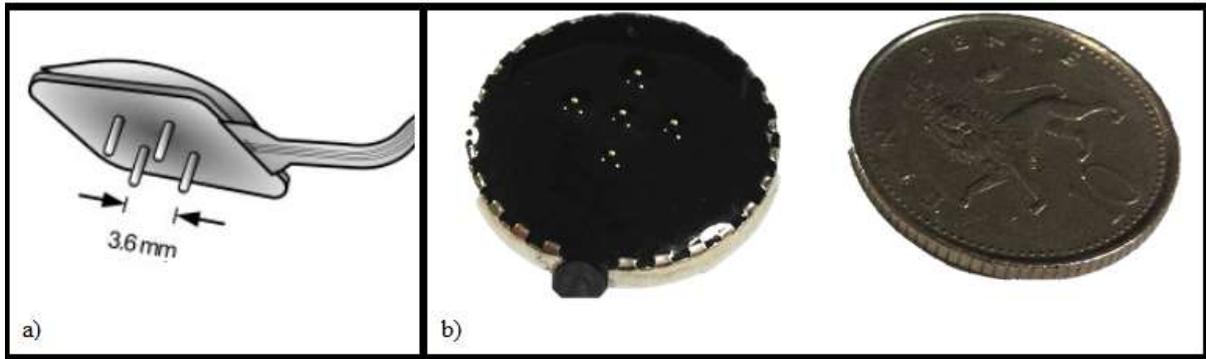
to other sEMG systems that use a disc electrode configuration. The parallel bar configuration allows a repeatable and consistent 10mm inter-electrode distance, thus significantly reducing the likelihood of muscle crosstalk and inter-intra subject reliability issues (De Luca et al. 2012). The Delsys Trigno EMG sensor (Figure 3-7) employs a single differential configuration with two EMG electrode contacts and two stabilising reference contacts.



**Figure 3-7 a) Graphical representation of the Delsys Trigno EMG sensor b) Actual Delsys Trigno EMG sensor**

#### 3.4.2.2 Surface EMG Decomposition Electrode

dEMG signals were collected using a 5-pin surface sensor, which consists of five cylindrical pins (0.5 mm diameter each) with blunted ends that protrude from the sensor housing to enhance the skin-electrode interface without puncturing the skin (Figure 3-8). Four pins are placed at the corners of a 5x5 mm square with the fifth pin placed in the centre of the four pins having an inter-electrode distance of 3.6mm. Pair-wise subtraction of voltages from the five pins is used to create four channels of single differential EMG signal. The four channels thus create a multi-channel sEMG system allowing the decomposition algorithm to discriminate the MUAP shapes (LeFever & De Luca, 1982). In addition, a dermatode reference electrode was placed over the dorsal aspect of the hand.



**Figure 3-8 a) Graphical representation of the Delsys dEMG sensor b) Actual Delsys dEMG sensor.**

### 3.4.3 EMG Bandwidth

The frequency content of the sEMG signal typically ranges from 0-400 Hz and can be affected by various factors including: electrode spacing, the amount of fatty tissue between the skin and the muscle, the shapes of the action potentials and the muscle type (Basmajian & De Luca 1985). The low-pass bandwidth employed, responsible for attenuating high frequency components, is often in the range of 400-450 Hz as this is typically the point at which noise components exceed the sEMG signal (De Luca et al. 2010), with most sEMG commercial components following this reasoning.

The high-pass filter is responsible for removing low frequency noise components from the signal, such as movement artefact. However, the high-pass frequency cut-offs do not have the same consensus as the low-pass filter cut-offs, with various standards and recommendations being proposed and followed (Winter et al. 1980; Merletti 1999; Hermens et al. 2000). The difficulty with selecting an appropriate high-pass filter lies within the low frequency noise contamination being expressed from various sources. De Luca et al. (2010) provided empirical evidence for the selection of a 20 Hz high-pass filter as this offers the best compromise in retaining the desired sEMG content and removal of low frequency noise sources. Therefore both the EMG systems used for data collection had an analog Butterworth bandwidth filter of  $20 \pm 5$  Hz –  $450 \pm 50$  Hz, consequently attenuating any frequency below 20 Hz and above 450 Hz.

#### 3.4.4 EMG Skin Preparation

A key factor in collecting a high fidelity sEMG signal is through an effective preparation of the skin-electrode interface. Skin preparation is often satisfied through removing skin debris with the application of a 70% Isopropyl pad across the application site. Signal fidelity was inspected following skin preparation and sensor placement, which involved inspection of the baseline noise component, Signal-to-Noise Ratio (SNR) and 50 Hz signal contamination. If the signal fidelity was contaminated with 50 Hz noise, a large baseline noise or poor SNR component then the skin preparation procedure was repeated and the sensor re-applied to the middle of the muscle belly. This procedure was performed prior to all data collection sessions.

The electrode pins and the inter-electrode distance of the dEMG sensors are critical design features but, by their nature, generate more skin-electrode noise than more traditional sEMG sensors. Consequently the signal quality procedure is paramount to a high MU yielding and accurate firing data set. The optimal skin preparation procedures were investigated (see section 5.4) and found that the following steps (Figure 3-9) were required to be performed with each subject prior to data collection to ensure a high fidelity signal.



**Figure 3-9. Process of skin preparation before applying the dEMG sensor.**

Three steps were taken to inspect the signal fidelity following the skin and sensor preparation: Baseline noise inspection, Signal-to-Noise Ratio (SNR) and line interference.

##### 3.4.4.1 Baseline Noise

The baseline noise is the sum of the inherent sensor electronic noise and the skin-electrode interface, the lower the baseline noise component allows enhanced discrimination of the small motor units. With the subject in a fully extended and relaxed position magnification of the baseline noise within the acquisition software (EMGworks, Delsys Inc., Boston, MA) was performed. Baseline noise was deemed acceptable with values of  $<4.8 \mu\text{V RMS}$ , as per manufactures guidelines. If the baseline noise component exceeded  $<4.8 \mu\text{V RMS}$  then the skin preparation procedure was repeated until it the value fitted within the given parameters.

#### 3.4.4.2 Signal-to-Noise Ratio

The SNR can be defined by the following equation:

$$\text{SNR} = \frac{\text{sEMG Signal Amplitude (RMS)}}{\text{Baseline Signal Amplitude (RMS)}}$$

Manual inspection of the SNR can provide information for the suitability of the signal fidelity. If the SNR was poor but the baseline noise component acceptable the sensor location was relocated and procedures repeated until the SNR was acceptable.

#### 3.4.4.3 Line Interference

Interference from power lines and other sources can adversely affect the motor unit yield and accuracy, as the frequency of the line noise is typically found at 50 Hz and therefore is within the same frequency bandwidth as EMG signals. Expanding the time series of the signal plotting exposes any cyclical 50 Hz line interference. An inspection was conducted prior to data collection, if there was a significant 50 Hz component then the skin preparation procedure was repeated to ensure this was due to skin-electrode interface, as opposed to mains line noise entering the system as discussed in section 5.4.

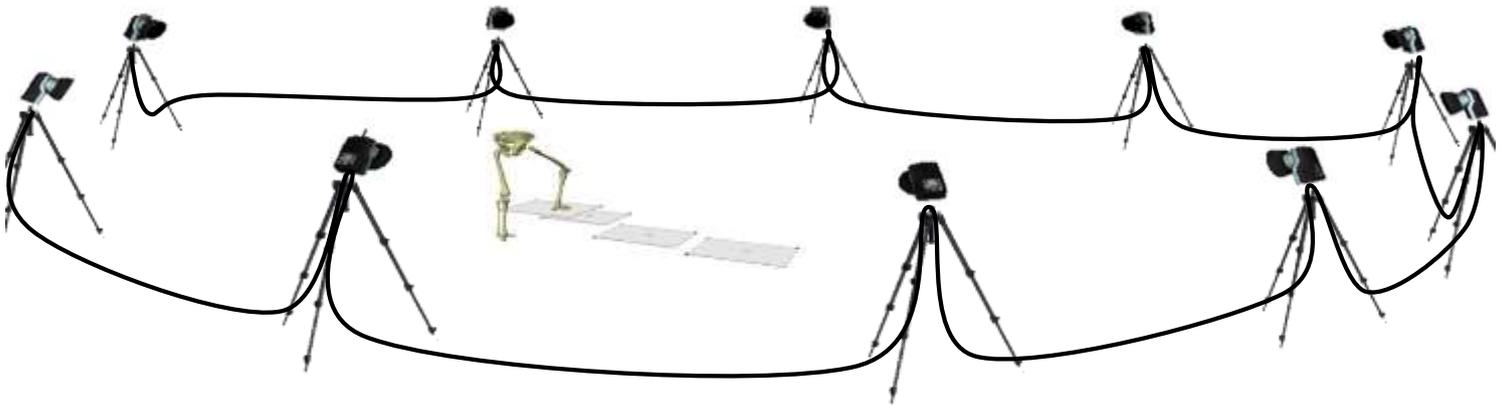
#### 3.4.5 Data Fidelity Validation

The above factors were all taken into consideration during data collection ensuring that each session abided by the strict parameters. The data did not always fit within the stated parameters at first attempt. The baseline noise parameter was violated in approximately 20% of the subjects, therefore the skin preparation procedure was repeated in these cases to ensure it did not exceed <4.8  $\mu\text{V}$  RMS. If the SNR was poor but the baseline noise component acceptable the sensor was location was slightly adjusted and skin preparation procedures repeated until the SNR was acceptable, this rule was violated in approximately 10% of subjects. No evidence of 50 Hz line interference was found during any data collection periods.

### 3.5 Kinematics and Kinetics Setup

#### 3.5.1 Camera Positioning

Ten cameras were placed upon tripods, elevated to 2.1 metres and spaced approximately 2 metres apart, which were arranged to focus on the data measurement area. See Figure 3-10 below for a graphical representation of the camera arrangement around the data measurement area.

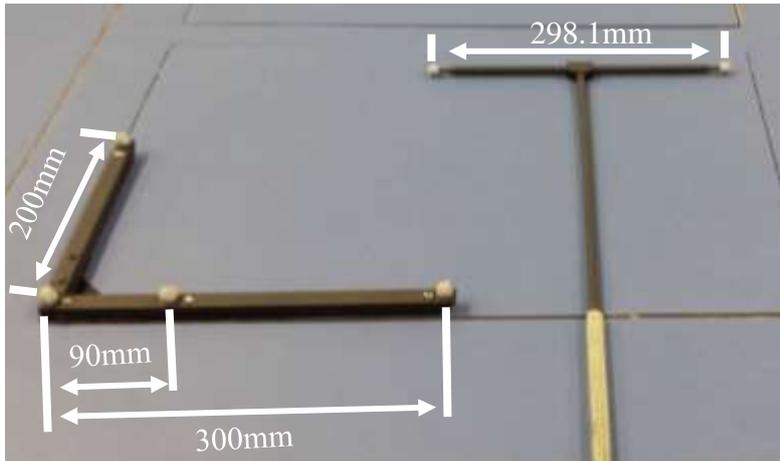


**Figure 3-10 A graphical representation of the camera positioning**

#### 3.5.2 Kinematic Calibration

In order to resolve the two dimensional (2D) data into three dimensional (3D) data the Qualisys software, Qualisys Track Manager (QTM), requires information about the orientation and position of each camera. To gather this information a static and dynamic calibration procedure was performed prior to each data collection session, defining the global coordinate system and the scaling of the axes. The calibration procedure is directly related to the accuracy of the data, thus robust methods were adhered to.

To define the global coordinate system a static L-shaped reference structure (Wand 300 Calibration Kit, Qualisys Medical AB, Gothenburg, Sweden) as seen in Figure 3-11 was placed in the data measurement area, comprising of an aluminium frame and 4 retro-reflective markers. The L-shaped structure provides positional information with respect to a known frame of reference (Richards 2008).



**Figure 3-11. L-Shaped reference structure (Left) placed in data measurement area and the calibration wand (Right).**

In addition to the static reference a calibration wand (Figure 3-11), with 2 retro-reflective markers spaced 298.1mm apart, was moved within the measurement volume in all three planes ensuring that all axes were properly scaled. The information on the camera positioning and orientation from the calibration procedure is used by the calibration algorithm within QTM. The system was calibrated for 30 seconds with the manufactures default sampling frequency of 100 Hz.

### 3.5.3 Kinematic Calibration Quality

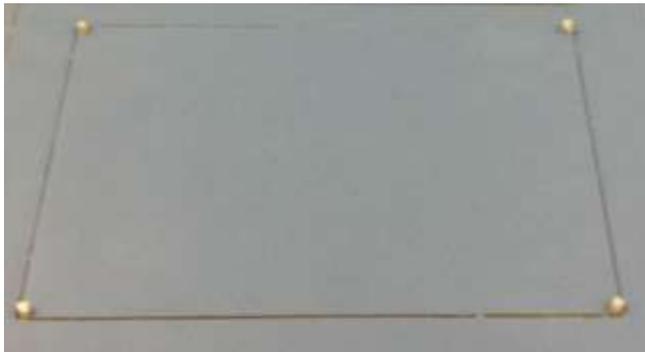
The average residuals of the retro-reflective markers identified by each camera were populated following the calibration procedure. These residual values are the average of errors (in mm) from the distance between the 2D marker ray and its corresponding 3D point. A value below 1.0mm for each camera is deemed acceptable following the manufactures guidelines and previous publication (Richards 1999). Calibration values did not exceed 1.0mm within all data collection sessions. An example of a successful calibration and each cameras' residual values can be seen in Figure 3-12



**Figure 3-12 Example of calibration results**

### 3.5.4 Force Platform Calibration

In order to provide positional information about the imbedded force platform retro-reflective markers were placed in each corner of the force platform (Figure 3-13), followed by a 2-second data collection period using QTM. The marker positional information allowed the software to resolve both the location and position of the force platform.



**Figure 3-13 Retro-reflective markers positioned for positional calibration**

### 3.5.5 Marker Set and Anatomical Model

In order to model the bony segments of the subjects, retro-reflective markers (Figure 3-14) were placed on specific anatomical landmarks, providing an anatomical frame. The placement of the anatomical markers on the externally palpable landmarks is critical. Palpation of the external landmarks was approached with due care during the preparation of each subject.



**Figure 3-14 9mm Spherical Retro-Reflective Markers**

Technical frame marker clusters (Figure 3-15), consisting of at least three non-colinear markers, were placed in relatively arbitrary positions on body segments and respective of the sEMG sensor placements. The model used throughout the thesis was the Calibrated Anatomical System Technique (CAST), first proposed by Cappozzo et al. (1995).

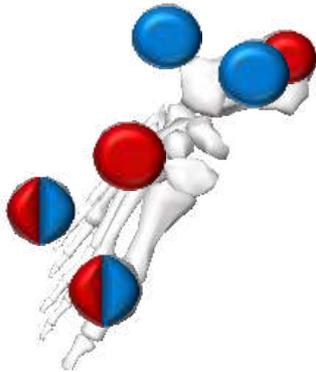


**Figure 3-15 Rigid technical frame marker clusters applied to the thigh and shank segments**

Specific details on the modelling of each segment can be found below:

#### 3.5.5.1 Foot Segment Marker Set

The foot segment coordinate system was defined with markers placed upon the heads of the 1<sup>st</sup> and 5<sup>th</sup> metatarsals, medial aspect of malleolus and lateral aspect of the malleolus. The technical frame markers, used for segment tracking, were placed on the heads of the 1<sup>st</sup> and 5<sup>th</sup> metatarsals, mid-foot marker and the posterior surface of the calcaneus. Figure 3-16 below shows the location of the markers used to model and track the single segment foot.

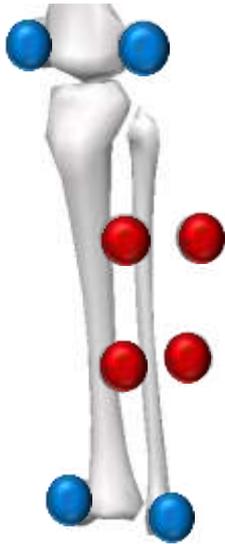


**Figure 3-16. Model marker set used for the foot segment.**

**(Blue = Anatomical Markers, Red = Technical Frame Markers, Blue/Red = Anatomical and Technical Frame Markers)**

#### 3.5.5.2 Shank Segment Marker Set

The shank segment coordinate system was defined by proximal markers placed upon the medial and lateral femoral epicondyles and the distal end was defined by markers placed upon the medial and lateral aspects of the malleoli. The four technical frame markers were fixed on a rigid cluster and attached to the shank. The location of the anatomical and technical frame markers can be seen in Figure 3-17.



**Figure 3-17. Model marker set used for the shank segment**

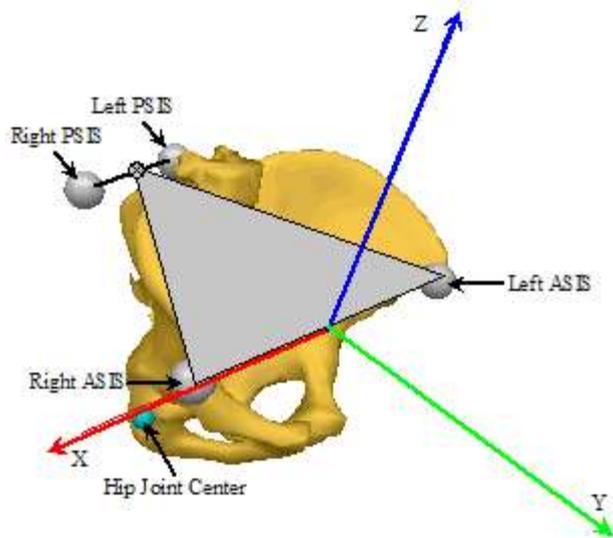
**(Blue = Anatomical Markers, Red = Technical Frame Markers, Blue/Red = Anatomical and Technical Frame Tracking)**

### 3.5.5.3 Thigh Segment Marker Set

The thigh segment coordinate system was defined with distal markers placed on the medial and lateral femoral epicondyles and the proximal end with a marker placed on the external projection of the greater trochanter. The proximal marker placement was used in calculating the hip joint centre, derived from the Bell method (Bell et al. 1990). The hip joint centre calculation used is described below in Table 3-1 and represented in Figure 3-18:

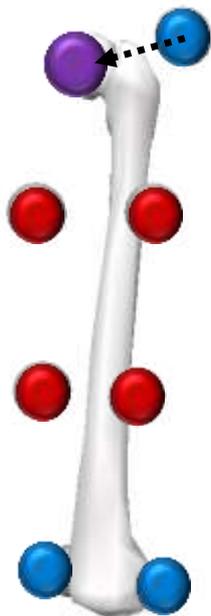
**Table 3-1 Hip Joint Centre (HJC) calculation values and respective planes of motion**

Right Hip Joint Centre	$0.36 * \text{ASIS\_Distance}$ (X Axis – Sagittal)	$-0.19 * \text{ASIS\_Distance}$ (Y Axis – Coronal)	$-0.3 * \text{ASIS\_Distance}$ (Z Axis – Transverse)
Left Hip Joint Centre	$-0.36 * \text{ASIS\_Distance}$ (X Axis – Sagittal)	$-0.19 * \text{ASIS\_Distance}$ (Y Axis – Coronal)	$-0.3 * \text{ASIS\_Distance}$ (Z Axis – Transverse)



**Figure 3-18** Coordinate system of the pelvis segment and calculation of the hip joint centre

The four technical frame markers were fixed on a rigid cluster and attached to the thigh, which can be seen in Figure 3-19.



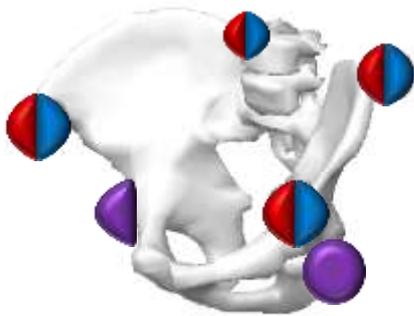
**Figure 3-19** Model marker set used for the thigh segment

(Blue = Anatomical Markers, Red = Technical Frame Markers, Blue/Red = Anatomical and Technical Frame, Purple = Calculated Hip Joint Centre)

#### 3.5.5.4 Pelvis Segment Marker Set

The pelvis segment was defined with markers being placed on the left and right Anterior Superior Iliac Spine (ASIS) and the left and right Posterior Superior Iliac Spine (PSIS).

The origin of the pelvis segment coordinate system was defined as the mid-point between the ASIS markers. The ASIS and PSIS markers were also used as the technical frame markers, thus tracking the pelvis segment. The location of the markers for the pelvis segment can be seen in Figure 3-20.

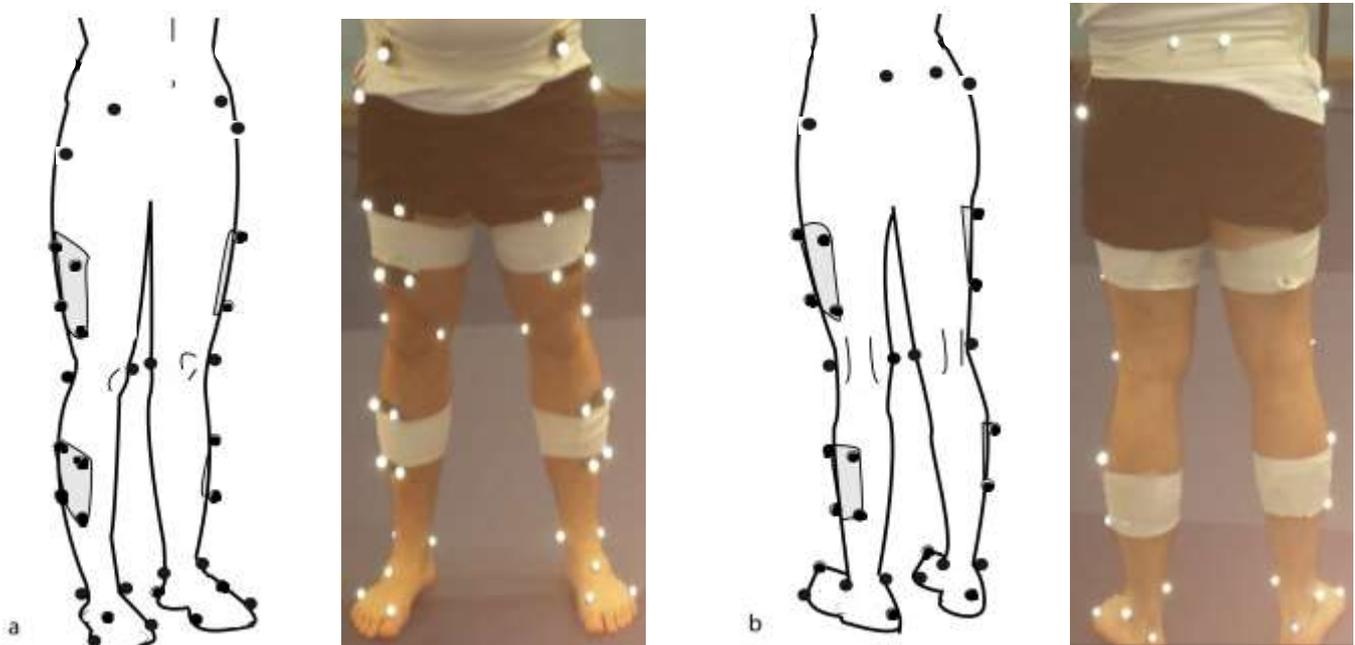


**Figure 3-20 Model marker set used for the pelvis segment**

**(Blue = Anatomical Markers, Red = Technical Frame Markers, Blue/Red = Anatomical and Technical Markers, Purple = Calculated Hip Joint Centre)**

#### 3.5.5.5 Complete Marker Set

An example of the full marker set, 38 retro-reflective markers, can be seen on the anatomical figure and an example subject in Figure 3-21.

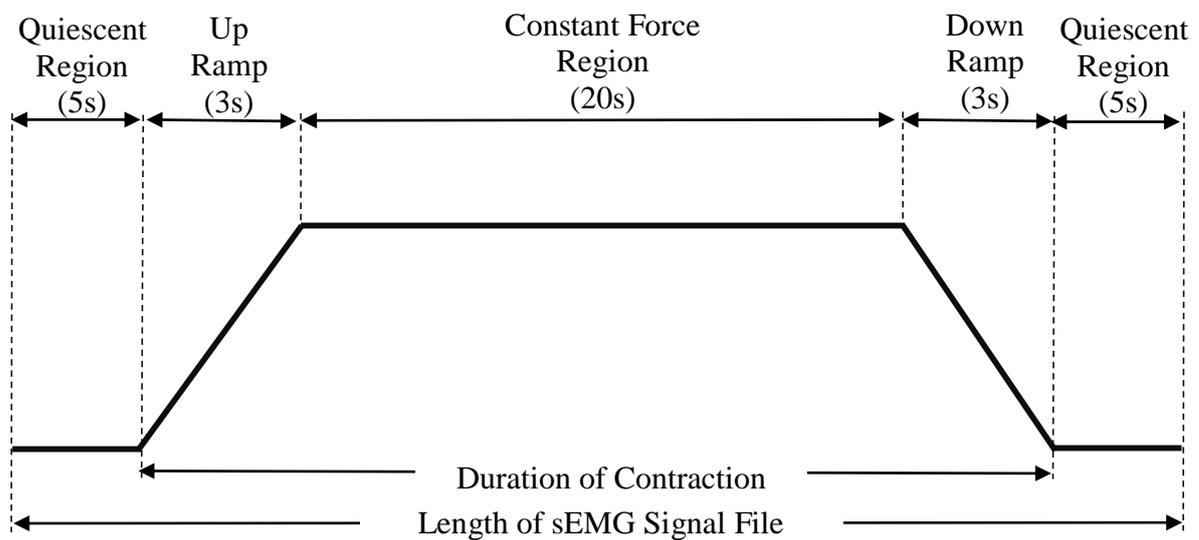


**Figure 3-21 Example of full marker set on anatomical figure (a) and subject (b)**

### 3.6 dEMG Setup

#### 3.6.1 Tracking Paradigm

The decomposition algorithm was designed to decompose sEMG signals from isometric contractions, following specific contraction guidelines (Nawab et al. 2010). A quiescent region must be present at the beginning and the end of the contraction, allowing the algorithm to establish the baseline noise and the recruitment and de-recruitment of the MUs. A progressive increase and decrease of a contraction allows the algorithm to accurately monitor the recruitment and de-recruitment of motor units, a contraction with a rapid increase or decrease would result in a complex superposition of motor units for the algorithm to resolve. A contraction period of at least 10 seconds was required, as this provided the algorithm sufficient information on the identity of MUAP shapes. Figure 3-22 shows the tracking paradigm which the contraction followed however, subjects were not provided this as visual feedback but instead received instructions from the operator (see section 6.5).



**Figure 3-22 Decomposition Tracking Paradigm**

### 3.7 Integration and Synchronisation

In order to collect the neuromuscular and mechanical variables under investigation in this thesis a collection of specialised measurement tools were required. Considerable exploration and investigation was required to ensure the previously mentioned issues were addressed, Figure 3-24 shows an overview of the equipment used and the method of integration and synchronisation. Details of the connections and relevant details can be found below.

#### 3.7.1 Surface EMG Decomposition

The Delsys dEMG system (Figure 3-23, item 4) was managed and recorded separately to the rest of the data acquisition systems. The analog EMG data was amplified and then output via a Small Computer System Interface (SCSI) cable (NI SH68-68-EPM) to an A/D device (NI USB 6251) (Figure 3-23, item 7). The converted digital data was then output from the A/D device, via a USB cable, to a laptop computer and controlled via Delsys EMGworks Acquisition software (Figure 3-23, item 8).

#### 3.7.2 Surface EMG

The Delsys Trigno EMG system (Figure 3-23, item 3) was also integrated via its analog connection. The SCSI cable (NI SH68-68-EPM) formed a data connection between the Delsys Trigno EMG system and the BNC interface (NI BNC 2090A). BNC cables then connected the BNC interface to the A/D board (Figure 3-23, item 6) allowing the raw analog data to be streamed into Qualisys Track Manager (QTM) (Figure 3-23, item 5). The Delsys Trigno EMG system had a fixed 48ms delay, which was offset within QTM, and the synchronisation was managed by the same method as the kinetics, via the synchronisation cable from the master camera of the Qualisys motion capture system.

#### 3.7.3 Kinematics

The Qualisys motion capture system (Figure 3-23, item 1) was connected from a LEMO-to-ethernet cable exiting the master camera and entering the computer (Figure 3-23, item 5), creating a direct digital connection into QTM.

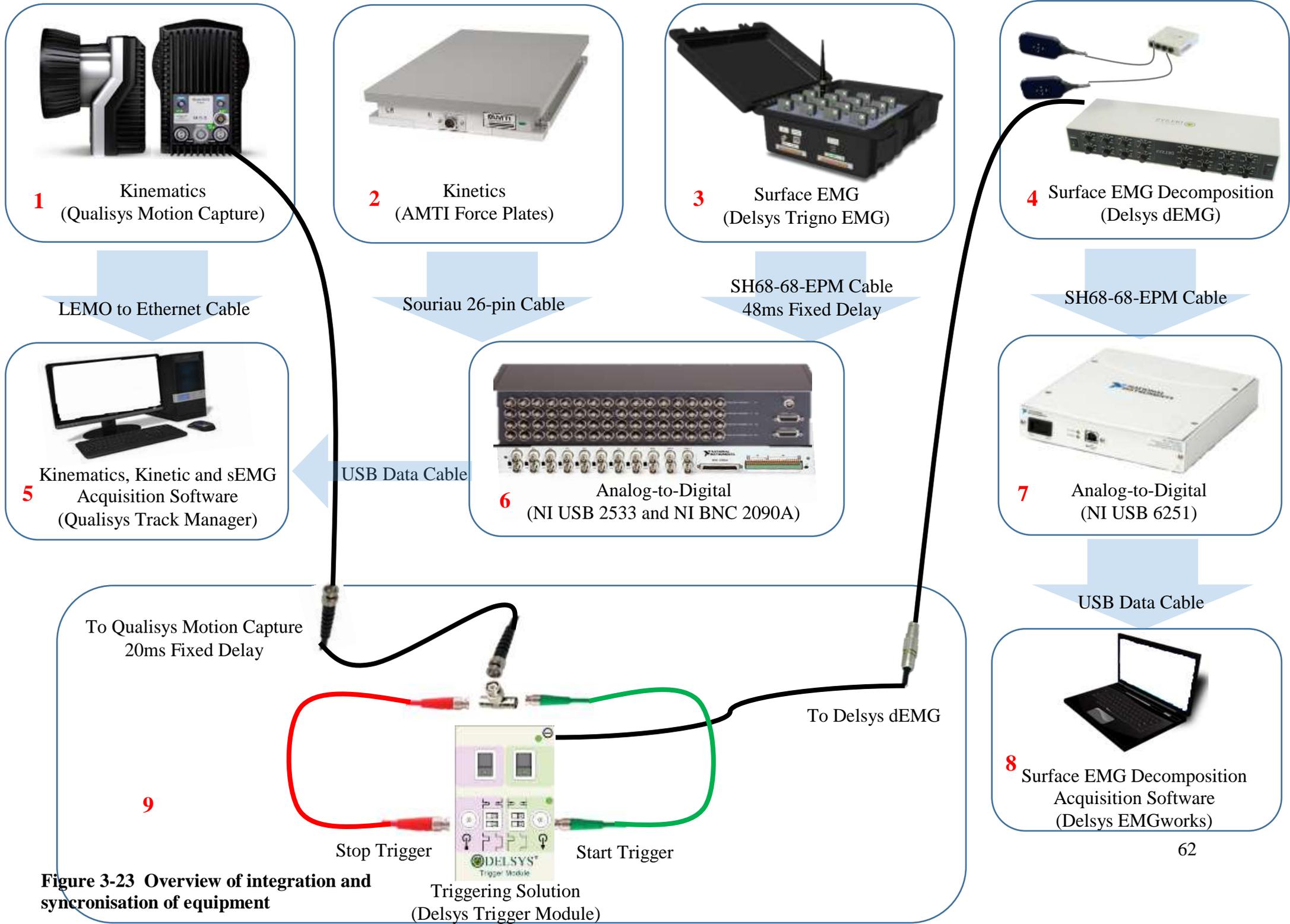
#### 3.7.4 Kinetics

The AMTI force plates (Figure 3-23, item 2) were integrated via analog connections. The Souriau 26-pin cable was input into the amplifier and the signals fed into the (A/D) board (NI USB 2533) via BNC cables. The A/D board (Figure 3-23, item 6) delivered the data into QTM via USB, where it was managed and captured (Figure 3-23, item 5). The force plates were synchronised with the Qualisys motion capture system via the ‘Synchronisation In’ connector on the master camera, thus ensuring time synchronisation. To ensure synchronisation between this and the other systems a triggering solution was required.

#### 3.7.5 Triggering Solution

The Delsys Trigger Module was used to create a hardware synchronisation between the Surface EMG Decomposition system and the other three measurement systems. The trigger module was connected to the Delsys dEMG system via its LEMO connector, so when a trigger command was sent from the trigger module it would start and stop data acquisition, therefore the Delsys dEMG was a slave/secondary device in this setup scenario.

BNC cables were connected from both the ‘start output’ and the ‘stop output’ BNC connections on the trigger module, which were input into a BNC Tee connector. The third BNC connection, from the BNC Tee connector, housed a single BNC cable which was connected to the ‘Trigger In’ connection on the master camera of the Qualisys motion capture system. The Kinetics, Kinematics and Surface EMG systems were then also configured to be slave/secondary devices to the trigger module. When using an external trigger with QTM there is a 20ms fixed delay, which was accounted for in post-processing of the data. The trigger module was configured to be an independent trigger, being the master/primary device to all connected devices. Upon pressing the start or stop button all the connected systems would respond accordingly. The connected systems were configured to start and stop data acquisition on a +/- 5V Transistor-Transistor Logic (TTL) pulse with a negative pulse polarity. This triggering setup ensured all devices were all time synchronised and also allowed simpler data acquisition protocols.



**Figure 3-23 Overview of integration and synchronisation of equipment**

## **4. Data Processing Methods**

### **4.1 Introduction**

Employing multiple data acquisition methods provides the much needed wealth of data to provide insights into the complexities of the motor control system. In order to provide meaningful and appropriate quantification of these complexities the data set, comprising of approximately 500,000 data points per subject, requires specific and targeted data processing techniques. Some of these data processing methods are well-established techniques whilst others are newly introduced, regardless all are described in detail in the following chapter demonstrating the process from raw data to final data extraction for the targeted analysis exhibited throughout this thesis.

#### **Chapter Outline**

- Outline of the surface EMG decomposition algorithm utilised (4.2)
- Details pertaining to the accuracy of the surface EMG decomposition algorithms accuracy and application to this work (4.3)
- Pertinent information relating to the processing of the surface EMG decomposition variables (4.4, 4.5 and 4.6)
- Pertinent information relating to the surface EMG processing (4.7)
- Pertinent information relating to the kinematic and kinetic processing (4.8)
- Details of the taping intervention application methods (4.9)

## 4.2 Decomposition Algorithm

The Delsys decomposition algorithm is based upon artificial intelligence and utilises advanced signal processing techniques, using the Integrated Processing and Understanding of Signals (IPUS) concept (Lesser et al. 1995) followed by the Iterative Generate and Test (IGAT) stages. A detailed description of the algorithm and its processes are beyond the scope of this work, descriptions of the algorithms processes and complexities are detailed by De Luca et al. (2006) and Nawab et al. (2010). However, a brief overview of the steps involved in the decomposition algorithm can be found below.

### 4.2.1 IPUS Stage

#### 4.2.1.1 MUAP Template Creation

The algorithm begins by identifying as many templates for the various uncontaminated MUAP shapes as possible from the EMG data. When a sufficient number of similar shapes are identified they are averaged and designated a MUAP template (De Luca et al. 2006).

#### 4.2.1.2 MUAP Template Matching

The matching of MUAP templates against the remaining sEMG signal takes place through a Maximum A-posteriori Probability Classifier (LeFever & De Luca 1982), using the action potential amplitude and the residual EMG signal.

#### 4.2.1.3 MUAP Template Updating

MUAP templates are updated through a recursive weighting process whenever the matching procedure detects a new instance of a previously detected MUAP (Nawab et al. 2002).

### 4.2.2 IGAT Stage

This stage of the algorithm identifies any template whose presence is objectively indicated in any of the complex superpositions in the EMG signal.

#### 4.2.2.1 Template Matching

A template-matching procedure is performed on the EMG signal to identify locations where the shape of the EMG signal and the shape of an identified MUAP template exhibits a correlation of at least 20% (Nawab et al. 2004).

#### 4.2.2.2 Discrimination Analysis

A discrimination analysis is performed, at each of the aforementioned location, to determine which of the multiple matching templates has contributed (Nawab et al. 2004).

#### 4.2.3 Decomposition Process

Previous attempts at sEMG decomposition involved operator editing in order to resolve signal complexities and to improve the accuracy. The Delsys dEMG algorithm was designed so that users did not require extensive signal processing understanding, instead the algorithm was designed to be an automatic process. The EMG data is processed within EMGworks Analysis (Delsys Inc., Boston, MA) where the EMG channels and feedback channel are used alongside the MVC and offset values. The algorithm then automatically begins to decompose the EMG data.

### 4.3 Decomposition Accuracy

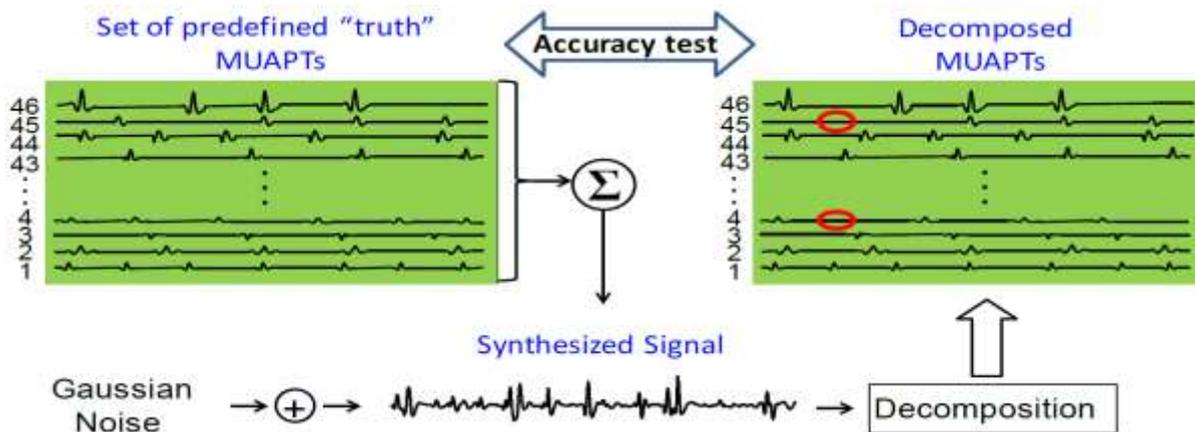
#### 4.3.1 Introduction

In order to have confidence in the outcome variables from a measurement system it is vital that the technology has been validated appropriately and it can demonstrate the outputs are not masked by measurement error. The surface EMG decomposition (dEMG, Delsys Inc.) has been challenged considerably and consequently validated, as discussed in section 2.2.3 demonstrating that the technology has the ability to provide robust and accurate information on the motor unit properties. Equally important is to be able to validate each decomposed file and the individual motor unit firing properties as the motor unit accuracy is of paramount importance to have confidence in the consequent measured behavioural characteristics of the motor units, without such vigilance differentiating between errors and true physiological events becomes an impossible task. The term ‘accuracy’ in this context is the testing of the decomposition algorithms ability to successfully resolve the complex EMG signal into its constituent motor unit action potential firings from each recorded signal, thus being specific to the users testing. This accuracy testing provides a percentage output to describe the amount of common firings it has found after ‘re-decomposing’ the signal, and therefore an understanding on the success of the algorithm and the level of confidence we can place in the individual motor units for each contraction.

In an ideal world all motor unit firings would be resolved with 100% accuracy, however the inherent complexities of decomposing a sEMG signal into its constituent components requires an exponentially increasing set of operations, therefore the Delsys decomposition algorithm limits the combinatorial calculations and accepts a small (typically <5%) error (De Luca et al. 2006; Nawab et al. 2010; De Luca & Nawab 2011). The process for verification of the decomposition accuracy, termed Decompose-Synthesize-Decompose-Compare (DSDC) test, was first proposed by Nawab et al. (2010) and has since been included in the commercial software package from Delsys (Delsys Inc., Boston, MA). The DSDC process is outlined below, a more detailed description and validation of the process can be found in Nawab et al. (2010) and the appendix of De Luca & Contessa (2012).

### 4.3.2 Software Processes

The Delsys Decomposition Accuracy program automatically determined the accuracy characteristics of a decomposed data set. The program background process used a previously decomposed data file that contains the ‘truth’ signal, consisting of a set of MUAPT for which the firing instances and MUAP shapes are known. Gaussian noise was then added to the ‘truth’ signal, simulating the normally occurring noise in the EMG signal, creating a new synthesised file. The synthesised file was then decomposed and compared to the original decomposed signal, an overview of the process can be seen in Figure 4-1.



**Figure 4-1** A graphical representation of the Decompose-Synthesise-Decompose-Compare (DSDC) process.

The Delsys Decomposition Accuracy software produced a plot comparing the original ‘truth’ firing instances and the synthesised firing instances, an example of this output can be seen in Figure 4-2. Each blue bar represents a firing instance of the original MUAPT, the black ‘X’ above a blue bar represents agreement between the original and synthesised signal, true positive. A red ‘O’ above the firing instance represents a false negative with the decomposed synthesised signal missing the firing instance. The red ‘+’ is indicative of an erroneously detected firing from the synthesised signal, a false positive. The plot provided an accuracy value (percentage) and number of error/s for each MUAPT either for the whole contraction length or a selectable range, as shown in Figure 4-2.



**Table 4-1 Motor unit selection criteria**

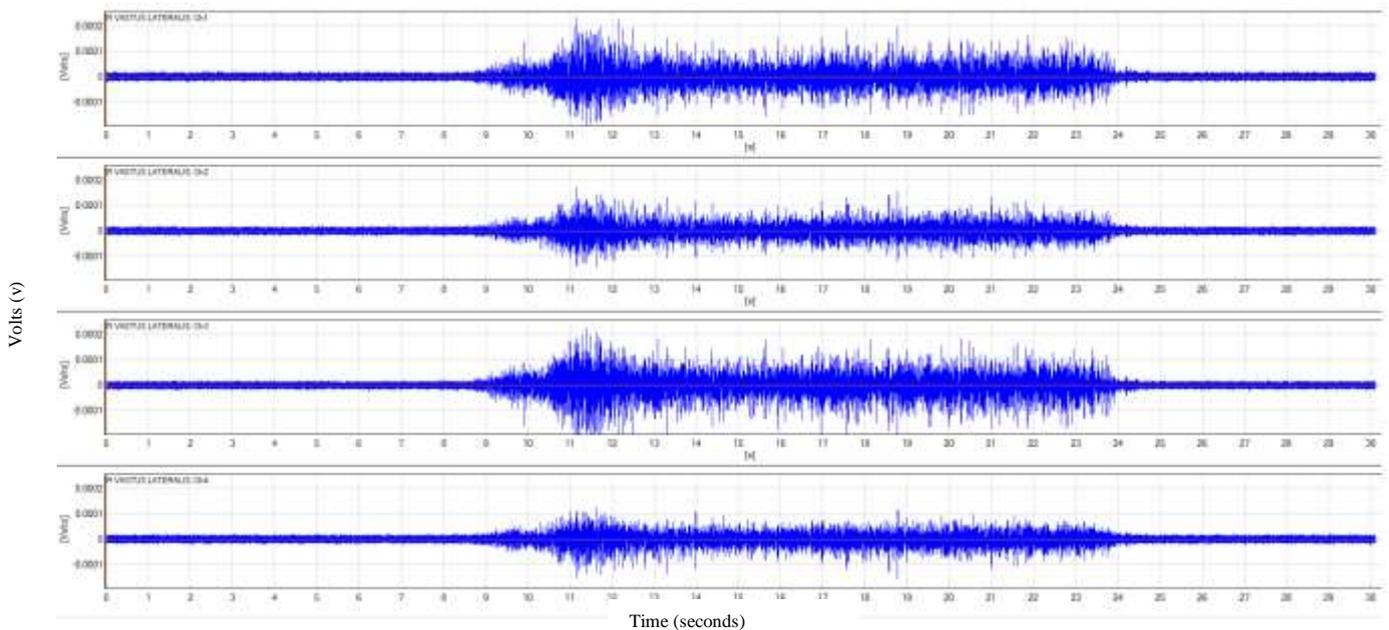
Calculation Output	Motor Unit Selection Criteria (%)
Mean Firing Rate	$\leq 90\%$
Recruitment Threshold	$\leq 90\%$
Cross-Correlation	$\leq 95\%$

Motor units with a percentage level  $<90\%$  were discarded and not included in any further analyses. All contractions were processed using the Delsys Decomposition Accuracy software (Delsys Inc., Boston, MA) and was calculated for both the whole contraction length and a 5-second period in the constant force region.

## 4.4 Mean Firing Rate Processing

### 4.4.1 Stage 1 - Raw EMG

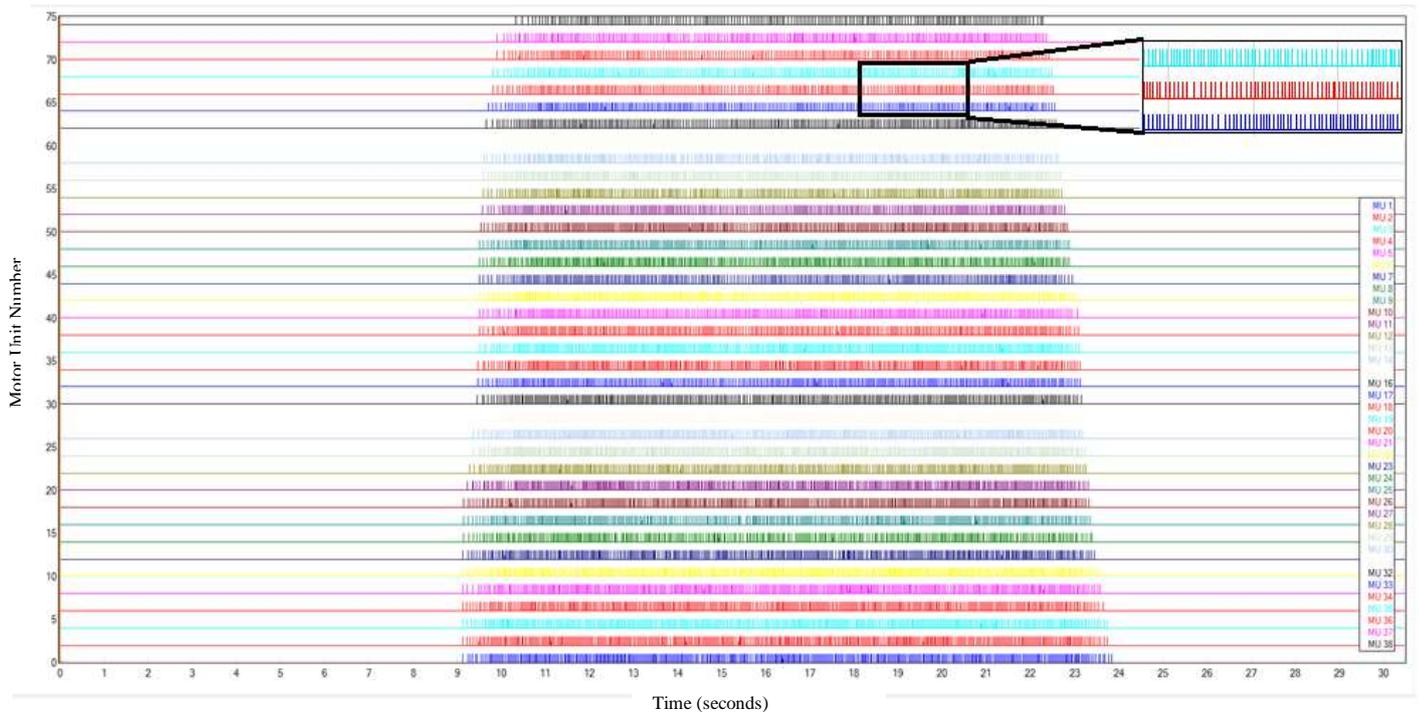
Four channels of sEMG simultaneously collected from a single muscle, Vastus Lateralis in this example, were imported into EMGworks Analysis (Delsys Inc., Boston, MA) (Figure 4-3). The raw sEMG data was then input into the decomposition algorithm (Version 42).



**Figure 4-3 Example of raw EMG from Vastus Lateralis collected from the dEMG sensor**

### 4.4.2 Stage 2 - Firing Rates

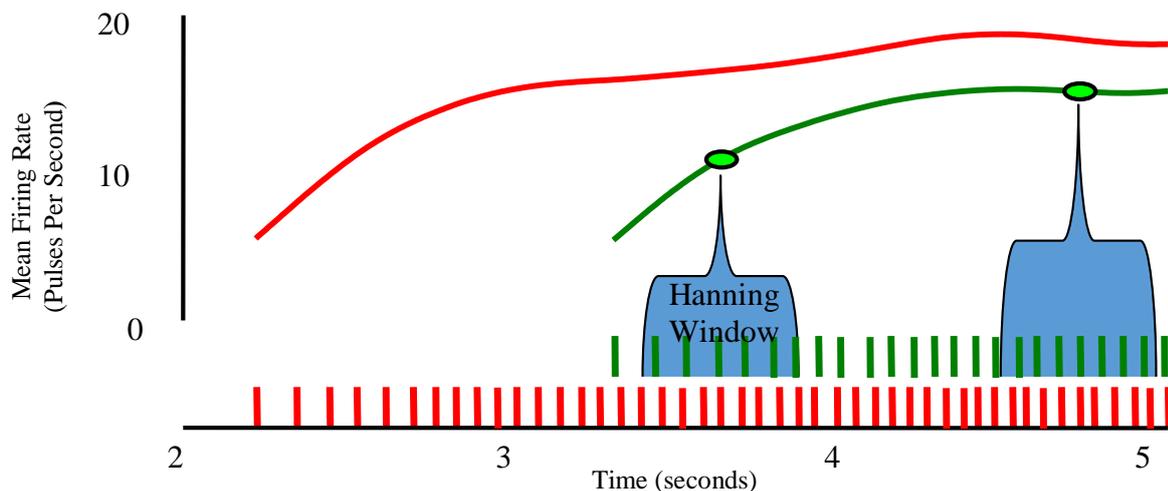
The decomposition algorithm provided firing characteristics of individual MUAP firings, which were then automatically allocated to a MUAPT. MUAP firings and their allocation to a MUAPT can be seen for all the identified MUs in Figure 4-4, each line representing a single firing instance of a given MU. This example contraction presents 38 motor units, with an accuracy <90%, from the Vastus Lateralis.



**Figure 4-4 Example motor unit firing from Vastus Lateralis**

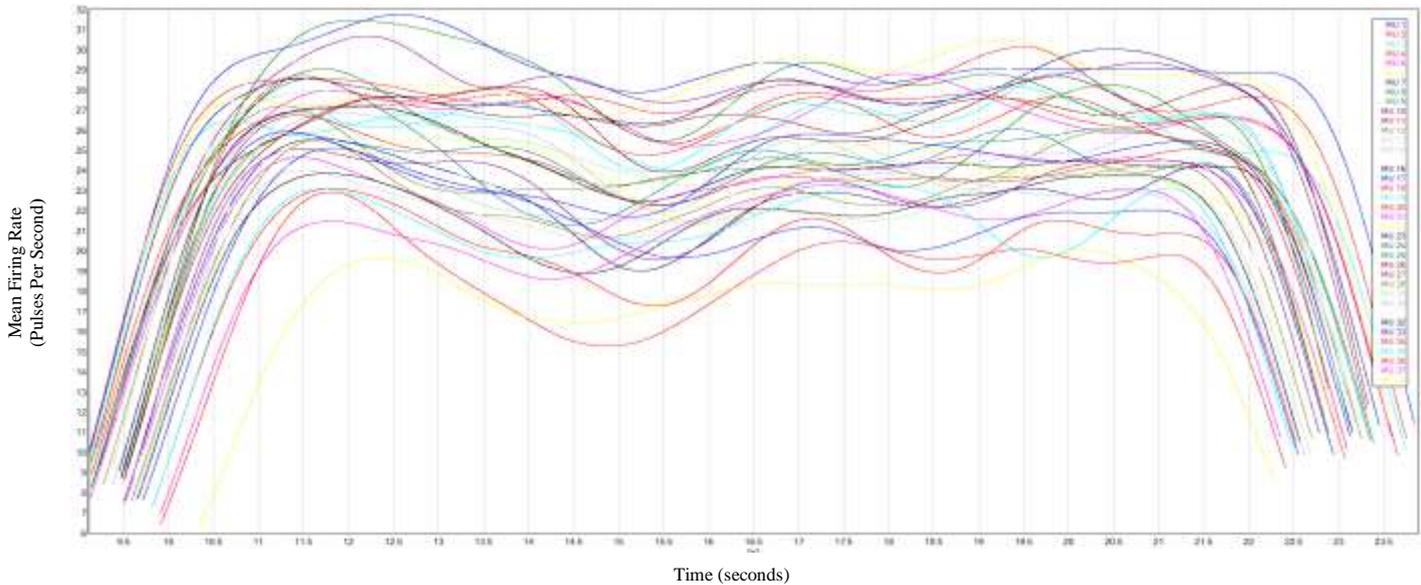
#### 4.4.3 Stage 3 - Mean Firing Rate

To extract additional parameters from the individual MUAPTs, the firing instances can be calculated as the number of pulses per unit of time, commonly expressed as pulses per second (PPS). This parameter is extrapolated by calculating the firing rate of an individual motor unit over a moving time window, thus providing a mean firing rate (MFR). Figure 4-5 provides an illustration of the calculation of the mean firing rate. A Hanning averaging filter was passed over the MUAPT and the number of pulses counted. The length of the Hanning window can be modified to adjust the smoothness of the firing rate trajectories. For additional details on the filtering procedure see De Luca et al. (1982).



**Figure 4-5 Graphical representation of the mean firing rate calculation using a Hanning filter**

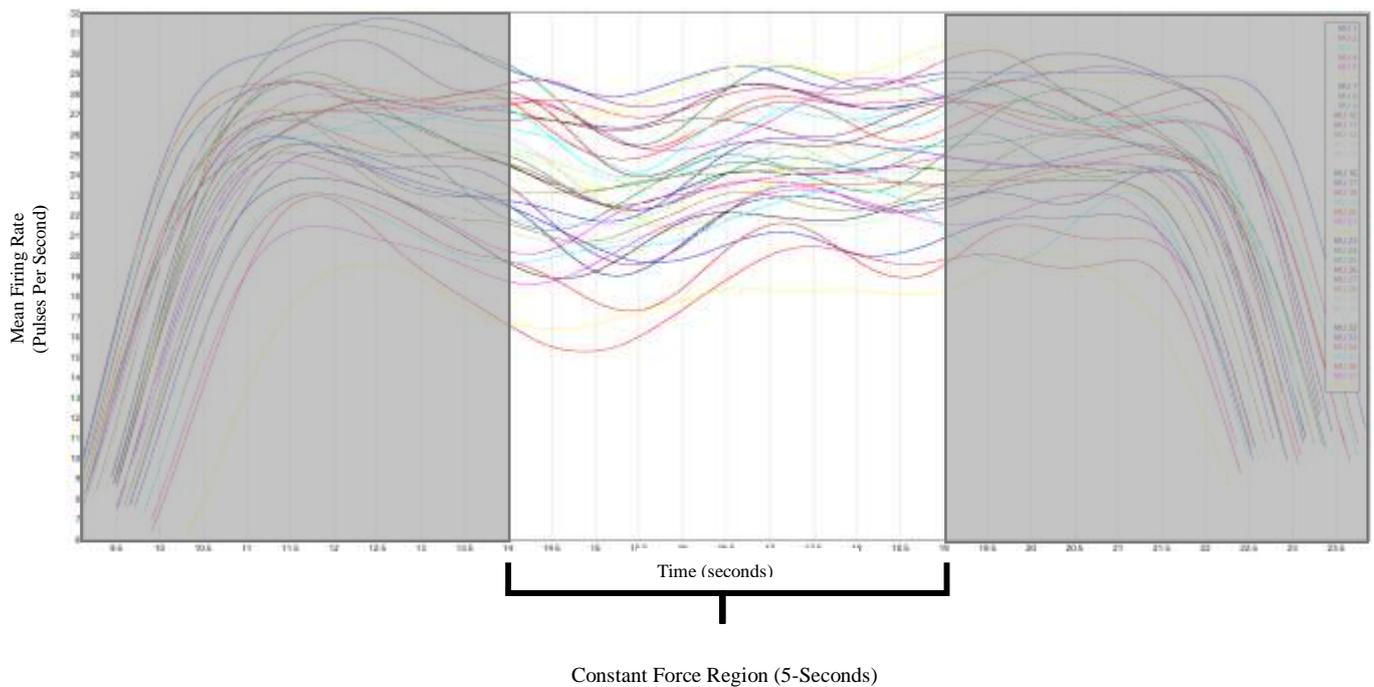
The same example contraction from previous illustrations was then computed with a 3-second Hanning window to exhibit the MFR of all 38 identified MUs. Each line represents the mean firing rate of an individual motor unit. The 3-second window was chosen as it smooths the firing rate trajectories sufficiently whilst maintaining an accurate representation of the firing rate behaviour.



**Figure 4-6 Example mean firing rate plot from the Vastus Lateralis after a 3-second Hanning window**

#### 4.4.4 Stage 4 - Constant Force Region Extraction

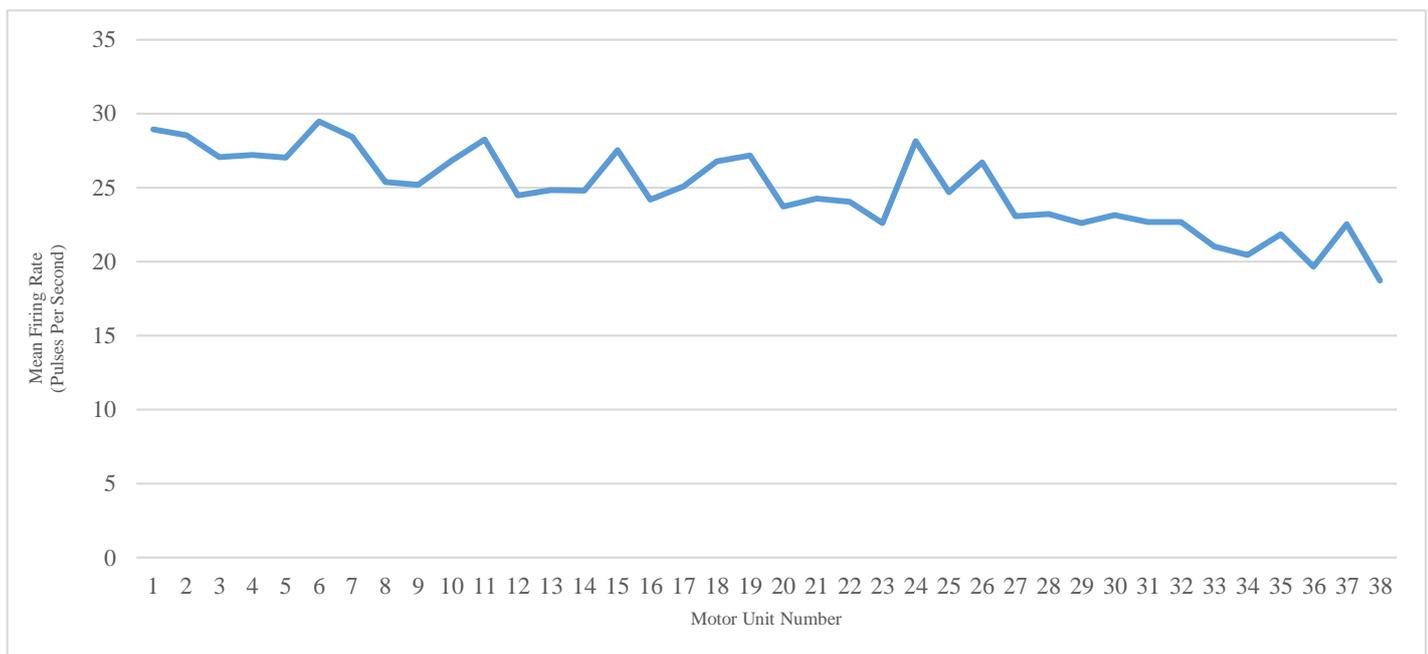
In order to better understand the behaviour of the motor units during the given task the recruitment and de-recruitment phases of the contraction were ignored for this analysis. A 5-second period within the constant force region, an area where no new motor units were recruited or excessive firing fluctuations occurred, was selected for further analysis.



**Figure 4-7 Selected 5-second constant force region of the mean firing rate**

4.4.5 Stage 5 – Average MFR

The mean firing rate (MFR) of all the motor units for the 5-second constant force region were extracted. The average firing of each motor unit MFR was then computed, as can be seen in Figure 4-8.



**Figure 4-8 Example of the average MFR from a Vastus Lateralis contraction**

#### 4.4.6 Stage 6 – Data Extraction

The mean firing rate from all subjects were exported from EMGworks Analysis (Delsys Inc.) into Microsoft Excel where the minimum, maximum, mean and standard deviation values were computed for each muscle and condition for each subject. The motor unit firing behaviour is structured, described as the “Onion Skin Phenomenon” (De Luca & Hostage 2010), therefore the mean firing rate output is normally distributed. Consequently the mean and standard deviation was an appropriate measure to extract. The mean MFR values were then entered into SPSS for inferential analyses. Table 4-2 provides example statistics of the MFR variables extracted for each individual.

**Table 4-2 Example statistics of the MFR variables extracted; Minimum, Maximum, Mean and Standard Deviation**

Mean Firing Rate (pps)	Minimum	Maximum	Mean (SD)
Vastus Lateralis	12.7	30.8	24.1 (3.6)

## 4.5 Cross Correlation Processing

### 4.5.1 Stage 1 - Raw EMG

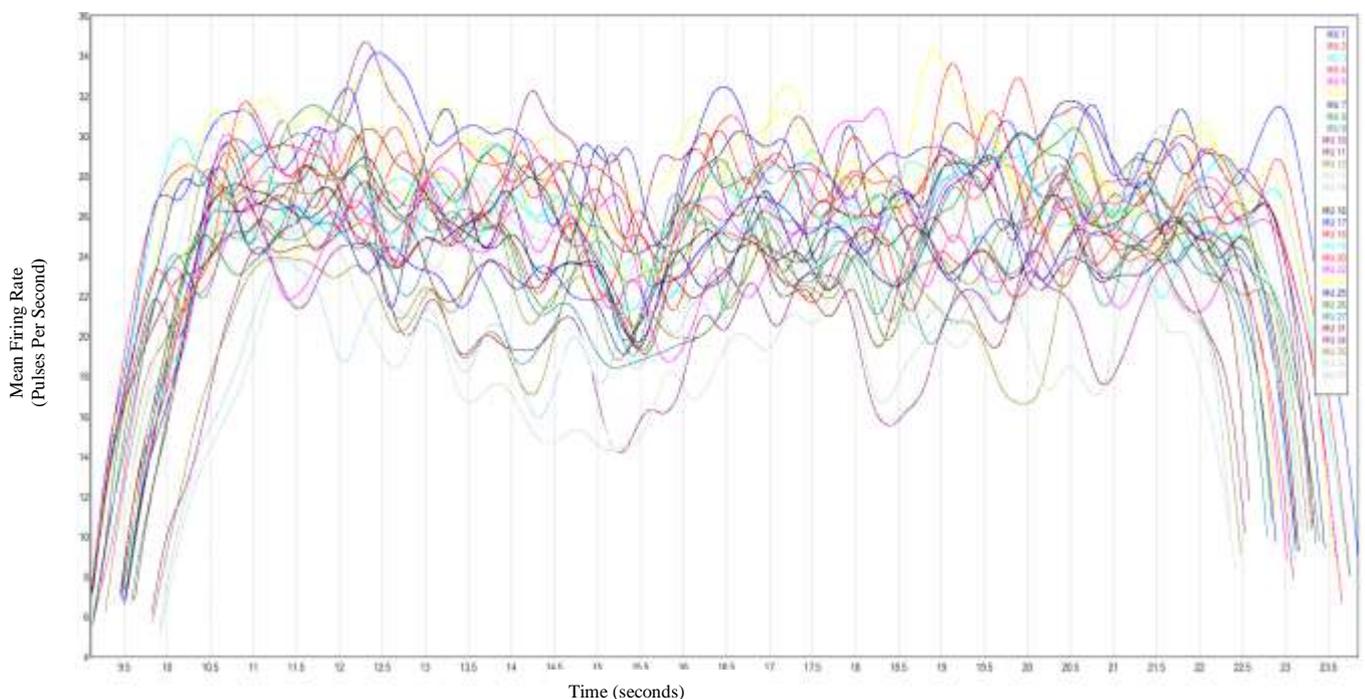
Four channels of single differential sEMG were simultaneously collected from a single muscle, Vastus Lateralis. The raw sEMG data was inputted into the decomposition algorithm (Version 42), details of which can be found in section 4.4.1.

### 4.5.2 Stage 2 - Firing Rates

MUAP firings were automatically allocated to a MUAPT for all of the identified motor units, as can be seen in (Figure 4-4) with each line representing a single firing instance of a given motor unit. In this example contraction 26 motor units from the Vastus Lateralis, with an accuracy <95%, were identified.

### 4.5.3 Stage 3 - Mean Firing Rate

As described in section 4.4.3 the mean firing rate (MFR) is a useful variable to extract from the individual MUAPTs, it's also an important step and requirement in exploring the common drive through a cross-correlation calculation. As before a Hanning window is passed over the MUAPT, however a narrower window is required in order to examine the small fluctuations between motor units. To investigate the common drive through cross-correlation calculations

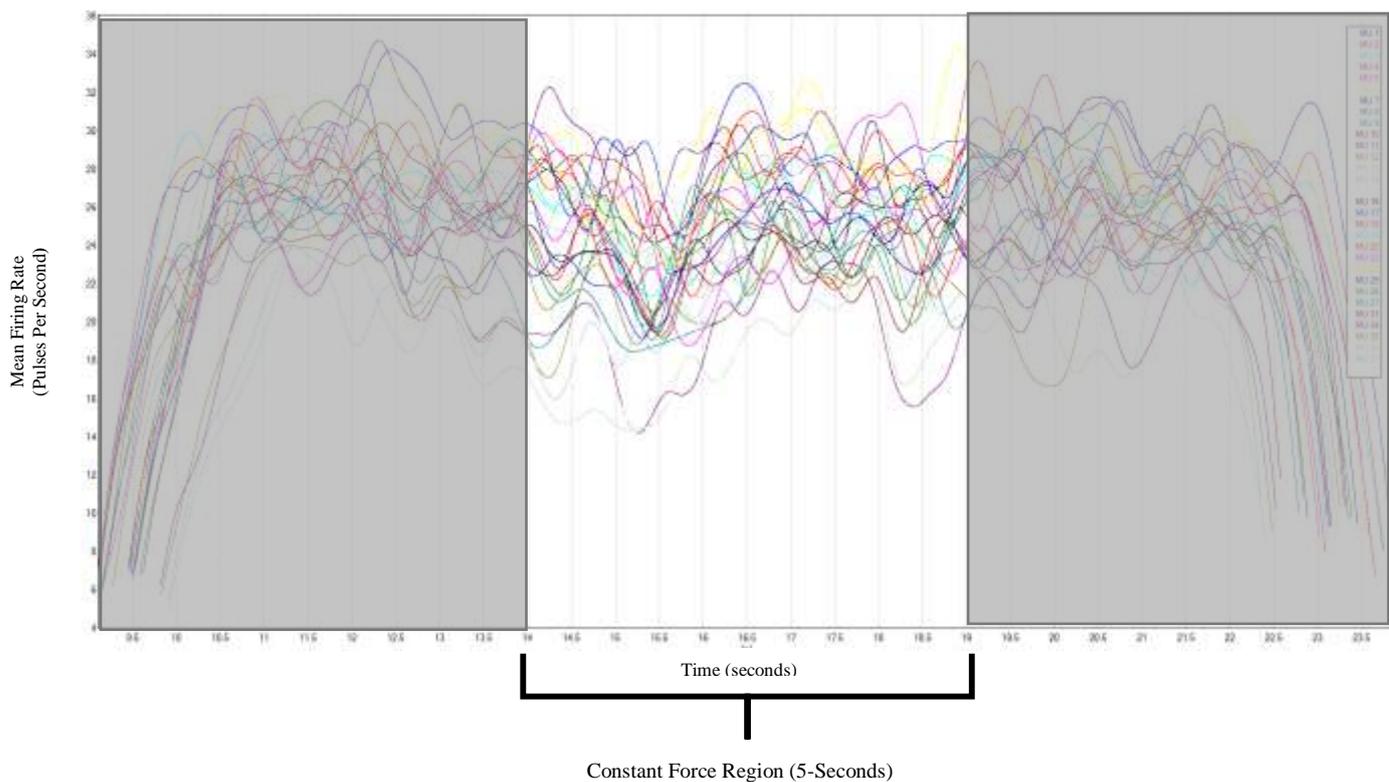


**Figure 4-9 Mean Firing Rate of the Vastus Lateralis with a 800ms Hanning window filter**

a 800ms Hanning window was passed over the MUAPTs, Figure 4-9 shows the resultant mean firing rate of each motor unit, the Vastus Lateralis in this example.

#### 4.5.4 Stage 4 – Constant Force Region Extraction

In order to examine the firing rate fluctuations and whether they were firing in unison a constant force region was required, thus the recruitment and de-recruitment phases of the contraction were ignored for this aspect of the analysis. A 5-second period within the constant force region, an area where no new motor units were recruited or excessive firing fluctuations occurred, was selected for further analysis.

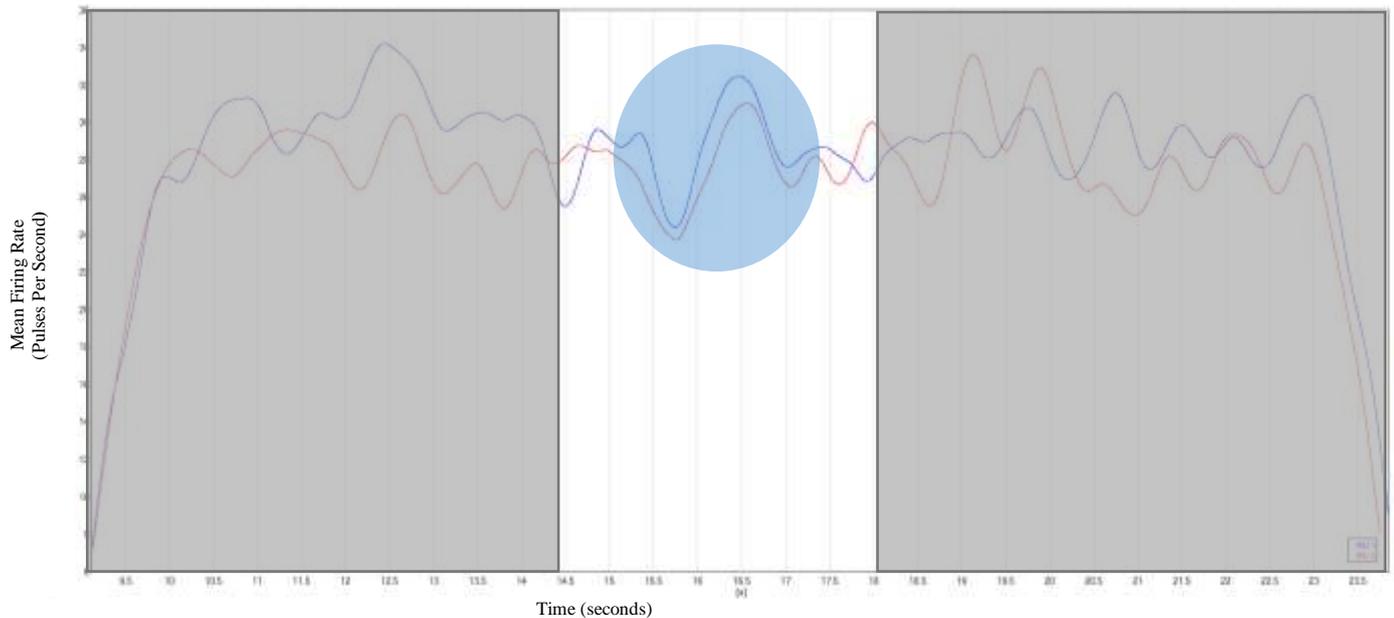


**Figure 4-10 Selected 5-second constant force region of the mean firing rate**

#### 4.5.5 Stage 5 – Cross-Correlation

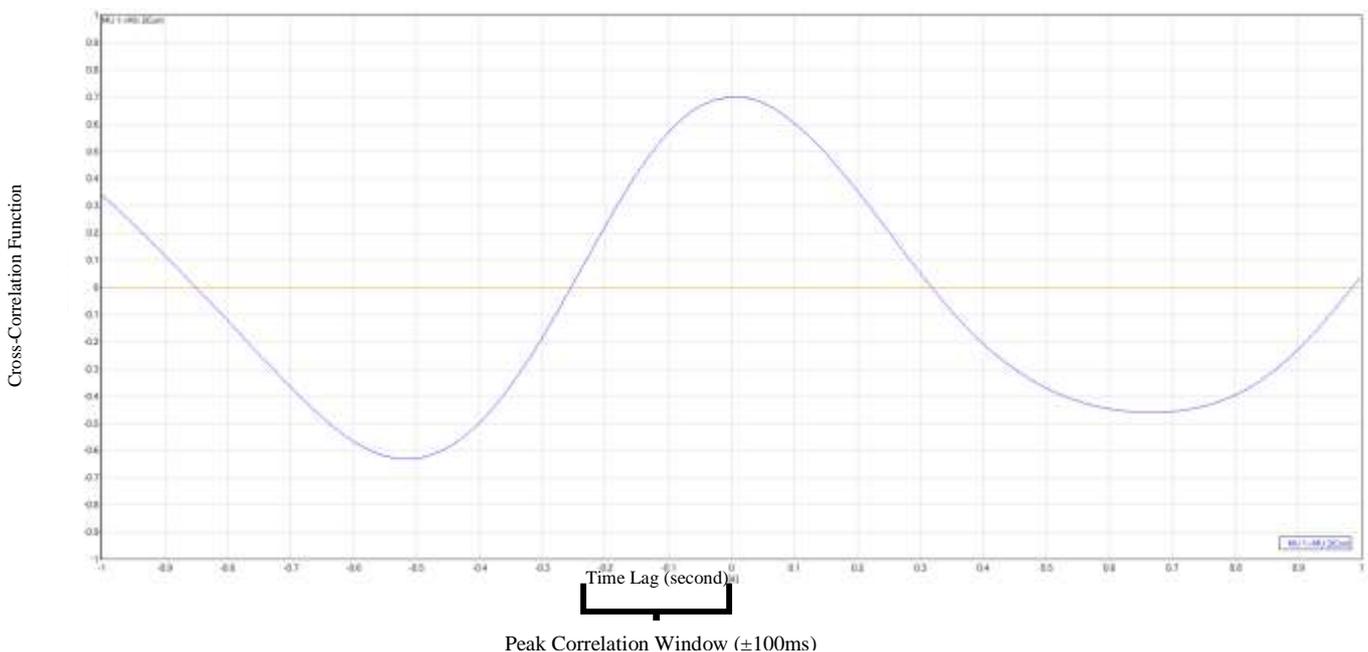
In order to attain the degree of correlation between the mean firing rate fluctuations of pairs of concurrently active motor units the mathematical operation of cross-correlation was used. The cross-correlation calculation was directed to the 5-second constant force region. The cross-correlation calculation searches for the highest value of cross-correlation function in pairs of motor units within a  $\pm 100$ ms window. If there was no cross correlation function within that

window then the motor unit pairing was not included in the output. Figure 4-11 shows two motor units mean firing rate (800ms Hanning window) and the highlighted area (blue) exhibits an example of the common fluctuations in motor unit firing.



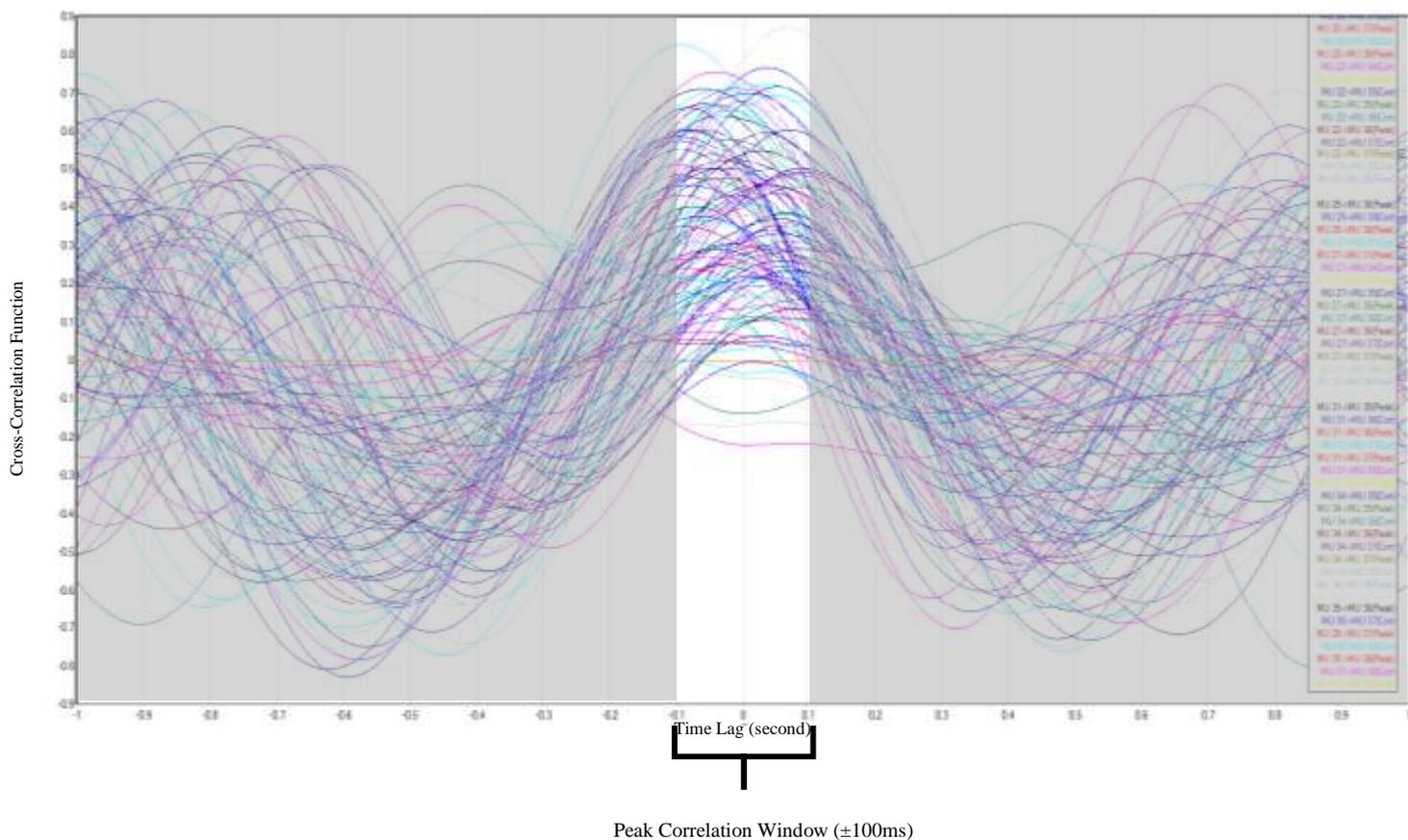
**Figure 4-11 Example of two motor unit mean firing rate showing common fluctuation**

The same motor units from the previous figure (Figure 4-11) were cross-correlated, i.e. the calculation searched for a common fluctuation in MFR between MU 1 and MU 2 in a  $\pm 100\text{ms}$  window. The figure below (Figure 4-12) shows that there was a cross-correlation and to what degree, in this case the peak cross-correlation function was 0.7.



**Figure 4-12 Example of cross-correlated motor unit pairing**

The cross-correlation calculation was repeated on all motor units for each muscle, for each repetition, for each condition and for all subjects. Figure 4-13 below is a plot of all the pairs of cross-correlated motor units within a Vastus Lateralis contraction from one subject, the peak cross correlations occurring within the  $\pm 100\text{ms}$  window. This example clearly shows evidence for common drive in the Vastus Lateralis with 139 motor unit pairs being cross-correlated and their degree of correlation.



**Figure 4-13 Example of cross-correlation on a single contraction from the Vastus Lateralis**

#### 4.5.6 Stage 6 – Data Extraction

Peak cross-correlations for all motor unit pairings within a muscle for all repetitions were combined. The peak cross-correlation data was not normally distributed amongst some subjects, therefore the median and inter-quartile range (IQRs) values were extracted for both muscles and in each condition. An example of peak cross-correlation results with the median and IQR values for a subject can be seen in Table 4-3.

**Table 4-3 An example of the cross-correlation data extraction reporting the median and inter-quartile (IQR) 25th and 75th percentile range**

<b>Cross-Correlation</b>	<b>Vastus Lateralis</b>
MEDIAN	0.40
IQR	0.24-0.56

In order to explore the level of cross-correlation in more detail the peak cross-correlation values were sorted and counted within levels of cross-correlation from 0.0-0.1 up to 0.9-1.0, as can be seen below in Table 4.4-2. Each level of cross-correlation has the number of pairs of cross-correlated motor units for each muscle and each condition.

**Table 4-4 Representative example of peak cross-correlation values for a subject within the different cross-correlation values**

<b>Level of Cross-Correlation</b>	<b>Vastus Lateralis</b>
0-0.1	4
0.1-0.2	20
0.2-0.3	24
0.3-0.4	18
0.4-0.5	18
0.5-0.6	23
0.6-0.7	17
0.7-0.8	5
0.8-0.9	1
0.9-1.0	0
<b>Total MU Pairs</b>	<b>131</b>

#### 4.5.7 Stage 7 – Cross-Correlation Normalisation

As can be seen from Table 4-4 there are different totals of cross-correlated motor unit pairs, which if plotted and analysed would bias the results. This is due to different numbers of MUs being identified for each muscle, subject, condition and also different amounts of those MUs were found to be cross-correlated; therefore a normalisation procedure was required. Previous

work (De Luca et al. 1993; De Luca & Erim 1994; Erim et al. 1999) using cross-correlation to investigate common drive used intramuscular EMG and therefore a low MU yield and consequent small amount of MU pairings being cross-correlated and so normalisation was not previously required. As this data set is unique, in particular with the large number of pairs of cross-correlated MUs, then there are no previous publications proposing or guiding such a procedure to normalise the data. After personal communications with Dr Carlo De Luca and Dr Paola Contessa (August 2013) and numerous explorations an appropriate method was established.

Cross-correlation data was normalised by the number of paired cross-correlated MUs, for each level of cross-correlation, against the total number of paired cross-correlated MUs. The example below shows the calculation for Vastus Medialis - No Tape (NT), at level 0.0-0.1, as highlighted in Figure 4-14 and Table 2-1.

<b>Level 0.0 – 0.1</b>	<b>4</b> (Number of paired motor units cross-correlated for 0.0 - 0.1)
	<hr style="width: 50%; margin: auto;"/>
	<b>131</b> (Total number of paired MUs)
	Multiply by <b>x100</b> Level of cross-correlation (Normalised) = <b>3 %</b>

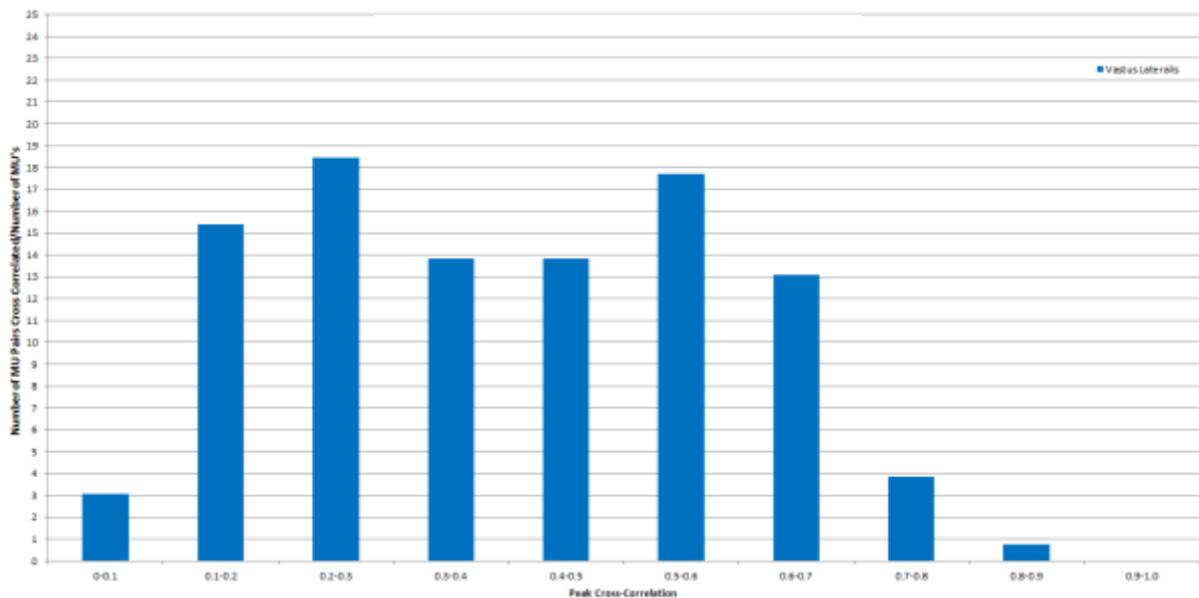
**Figure 4-14 Calculation used to normalise cross-correlation data**

**Table 4-5 Example data from normalised cross-correlation calculations**

Level of Cross-Correlation	Vastus Lateralis
0-0.1	3
0.1-0.2	15
0.2-0.3	18
0.3-0.4	14
0.4-0.5	14
0.5-0.6	18
0.6-0.7	13
0.7-0.8	4
0.8-0.9	1
0.9-1.0	0
<b>Total Percentage</b>	<b>100</b>

4.5.8 Stage 8 – Data Presentation

The normalised cross-correlation data was presented in a bar plot where each bar represents the cross-correlation percentage for each cross-correlation level. Figure 4-15 presents the data from a representative Vastus Lateralis contraction.



**Figure 4-15 Example of the normalised peak cross-correlation result presenting the Vastus Lateralis common drive**

## 4.6 Recruitment Threshold Processing

### 4.6.1 Stage 1 - Raw EMG

Four channels of single differential sEMG were simultaneously collected from a single muscle, Vastus Lateralis. The raw sEMG data was inputted into the decomposition algorithm (Version 42)

### 4.6.2 Stage 2 - Firing Rates

MUAP firings and their allocation to a MUAPT can be seen for all the identified motor units (Figure 4-4), each line representing a single firing instance of a given motor unit. In this example contraction 38 motor units from the Vastus Lateralis were identified, with an accuracy <90%.

### 4.6.3 Stage 3 - Mean Firing Rate

The firing rates were passed through a 3-second Hanning window to exhibit the mean firing rates of all 38 identified MUs. Each line represents the mean firing rate of an individual motor unit, with the mean firing rate increasing through the recruitment phase, remaining stable during the constant force region, then decreasing through the de-recruitment phase. The 3-second window was chosen as it smooth's the firing rate trajectories sufficiently whilst maintaining an accurate representation of the firing rate behaviour.

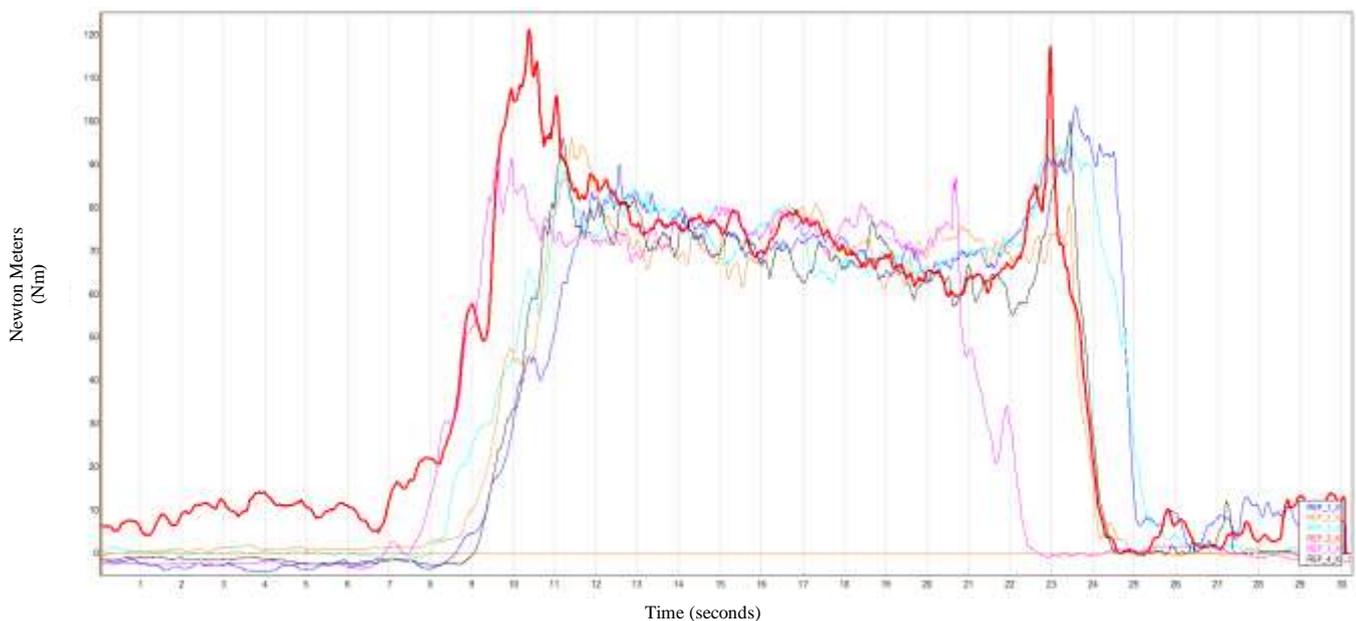
### 4.6.4 Stage 4 - Average MFR

The mean firing rate (MFR) of all the motor units for the 5-second constant force region were extracted (see Figure 4-10). The average firing of each motor unit MFR was then computed, as previously described in 4.4.5.

### 4.6.5 Stage 5 – Peak Knee Moment

The force acting around the knee was represented by the sagittal plane knee moment and provided a recruitment threshold percentage, which required a normalisation procedure thus a peak knee moment was needed. All repetitions for an individual's knee moment were plotted together to find the peak knee moment.

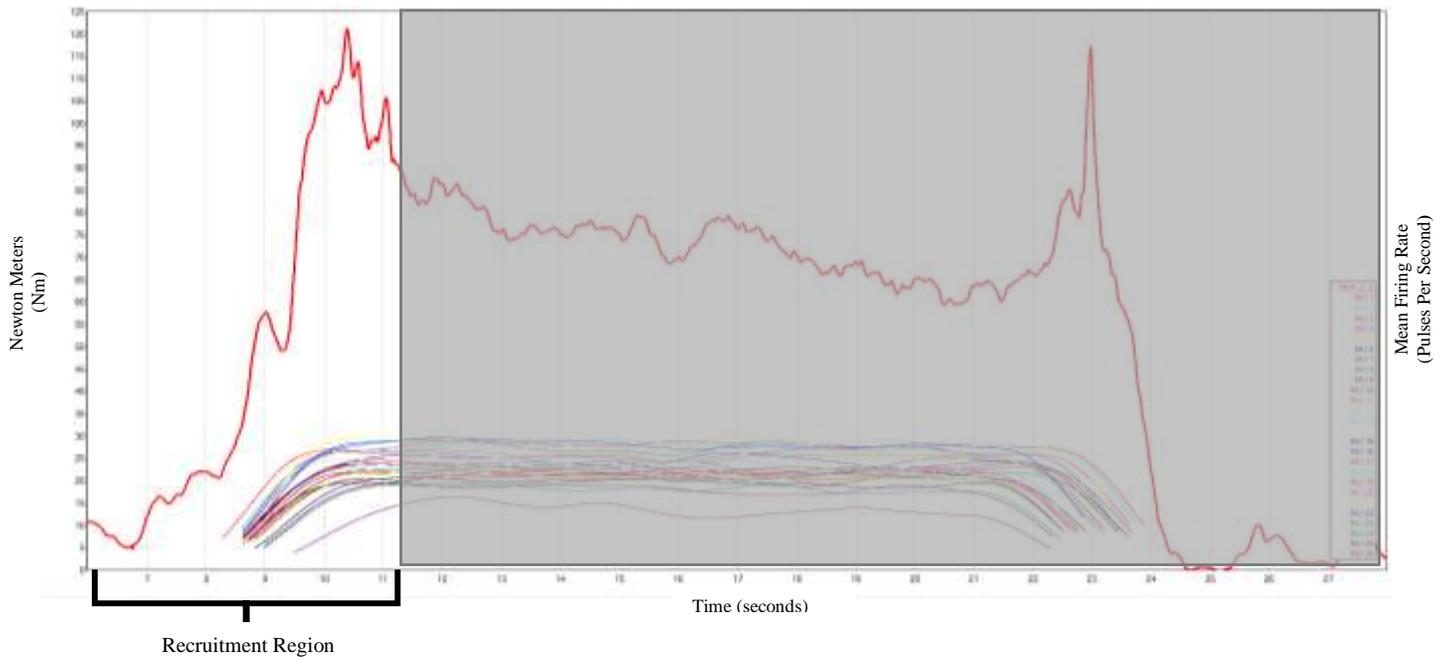
Figure 4-16 shows 6 repetitions of an individual's sagittal knee moment during the given task, it can be seen that the highlighted red plot exhibited the highest knee moment thus was used as the peak observed knee moment in the following calculations



**Figure 4-16 Representative example of a participants sagittal knee moment. Red line being the highest knee moment used for normalisation.**

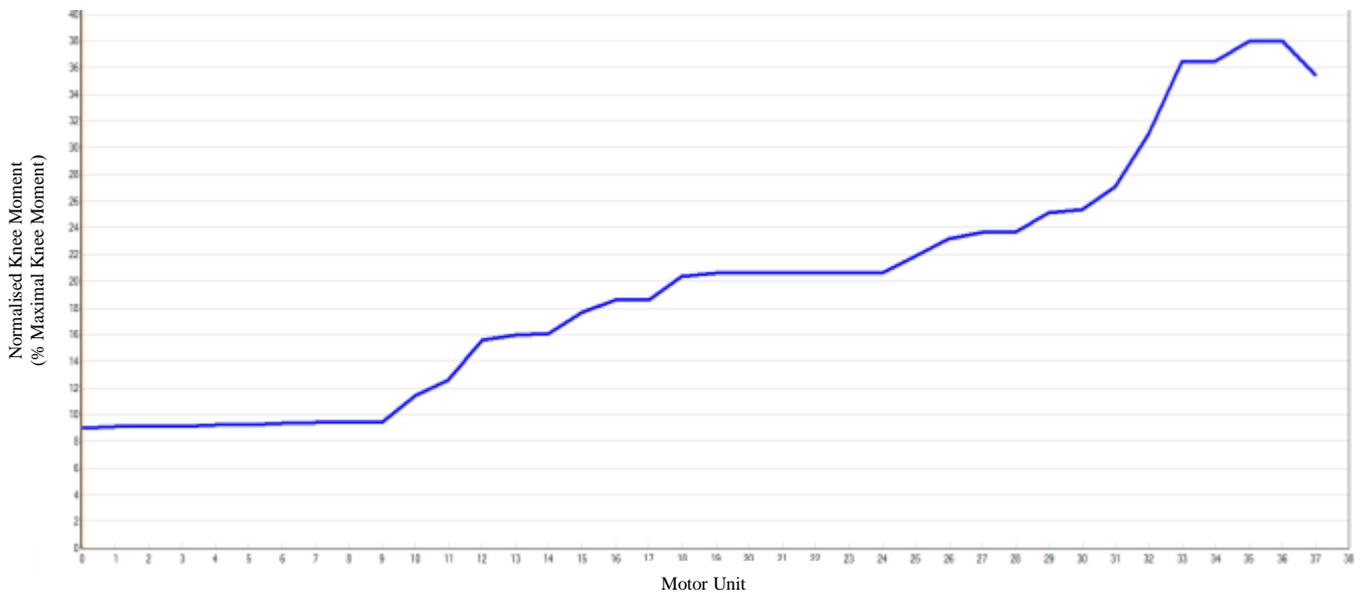
#### 4.6.6 Stage 6 – Recruitment Threshold Calculation

The recruitment threshold calculation used the sagittal plane knee moment, normalised against the previously created peak knee moment, to determine at what percentage level the individual MUs were recruited. The calculation allows any offset to be compensated in case the individual moves prior to the main movement. Figure 4-17 below shows an example Vastus Lateralis contraction with the corresponding sagittal plane knee moment (red line).



**Figure 4-17 Example of sagittal plane knee moment (red line) and the associated Vastus Lateralis motor unit MFR with the recruitment phase highlighted.**

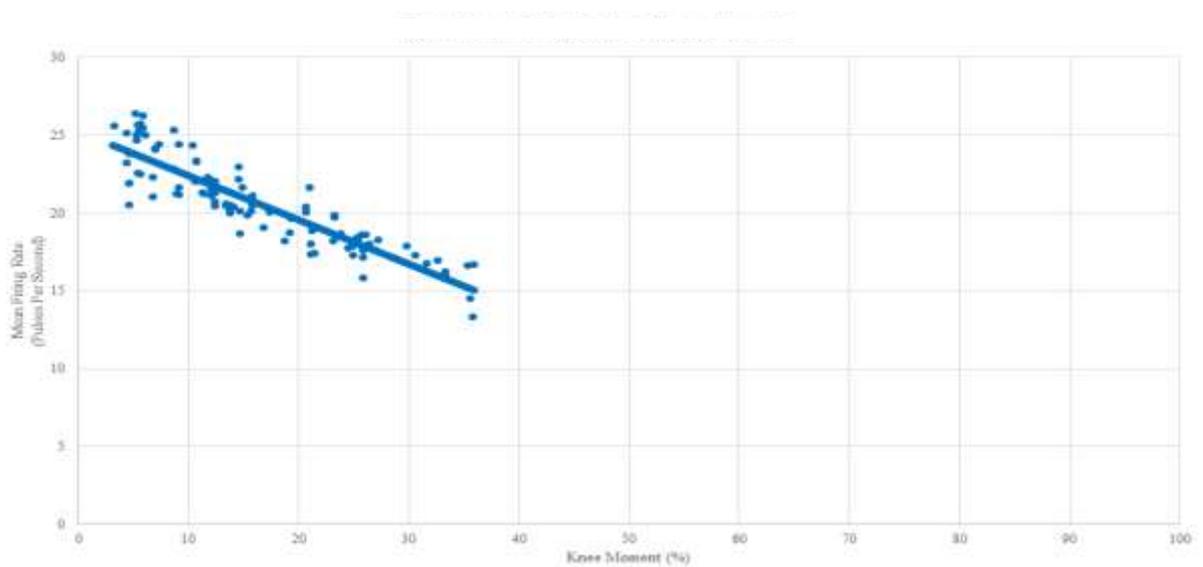
Figure 4-18 shows at which percentage level of the peak knee moment the MUs were recruited. In this example the first 9 motor units were recruited at approximately 9% peak knee moment with the remainder of the motor units being recruited in response to the increase in load.



**Figure 4-18 Resultant recruitment threshold from Vastus Lateralis showing the recruitment of 39 motor units normalised against sagittal plane knee moment**

#### 4.6.7 Stage 7 – Recruitment Threshold and Average MFR

The recruitment threshold of each motor unit and the motor unit mean firing rate were extracted from EMGworks Analysis and a linear regression analysis was performed within SPSS with the recruitment threshold being the independent variable and mean firing rate as the dependent variable. The linear regression will provide information on the recruitment strategy of the muscle and its response to the taping intervention. Once regressed and plotted, the negative linear relationship between these two variables becomes evident in this example, as shown in Figure 4-19.



**Figure 4-19 Regression plot of average motor unit MFR and the recruitment of the motor units**

#### 4.6.7.1 Recruitment Threshold

The intercept and slope values were calculated for Vastus Medialis and Vastus Lateralis in the two conditions, the two regression lines for each muscle were then compared to provide the intercept and slope difference values and p-values. Table 4-6 below provides an example of the statistical data extracted for the two muscles when the no tape and tape conditions are compared.

**Table 4-6 A example of the extracted data from the recruitment threshold calculation**

Vastus Lateralis			
Intercept		Slope	
Value	p-Value	Value	p-Value
3.78	<0.001	-0.04	<0.05

#### 4.6.7.2 Recruitment Operating Point

The recruitment operating point was defined as being the point at which the first identified motor unit was recruited. The first motor unit identified indicated the start of the contraction, and was extracted from EMGworks Analysis (Delsys Inc.) into Microsoft Excel. The recruitment operating points from the 3 contractions were averaged to provide excitation point for the Vastus Medialis and Vastus Lateralis in both the no tape and tape conditions. The mean difference between the two conditions was calculated to provide a measure for change in the recruitment operating point. Table 4-7 provides an example of the recruitment operating point data extracted from an individual for the Vastus Medialis and Vastus Lateralis in the tape and no tape condition.

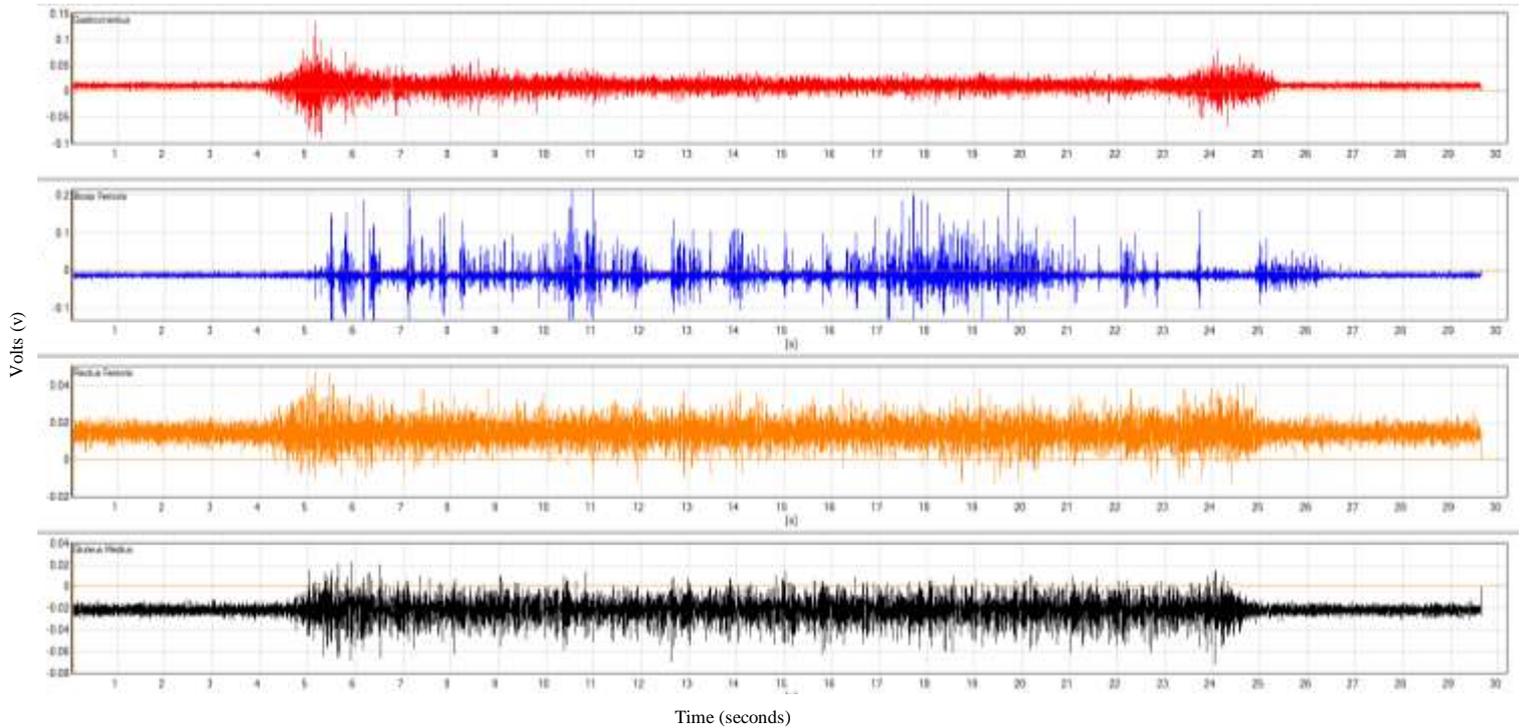
**Table 4-7 A example of the extracted data from the recruitment operating point calculation**

Recruitment Operating Point	Vastus Medialis
	Operating Point (%)
No Tape	16.17
Tape	5.83
Mean Difference	-10.34

## 4.7 Surface EMG Processing

### 4.7.1 Stage 1 – Raw Data

Raw sEMG from four muscles (Gastrocnemius, Bicep Femoris, Rectus Femoris and Gluteus Medius) were imported into EMGworks Analysis (Delsys Inc., Boston, MA).



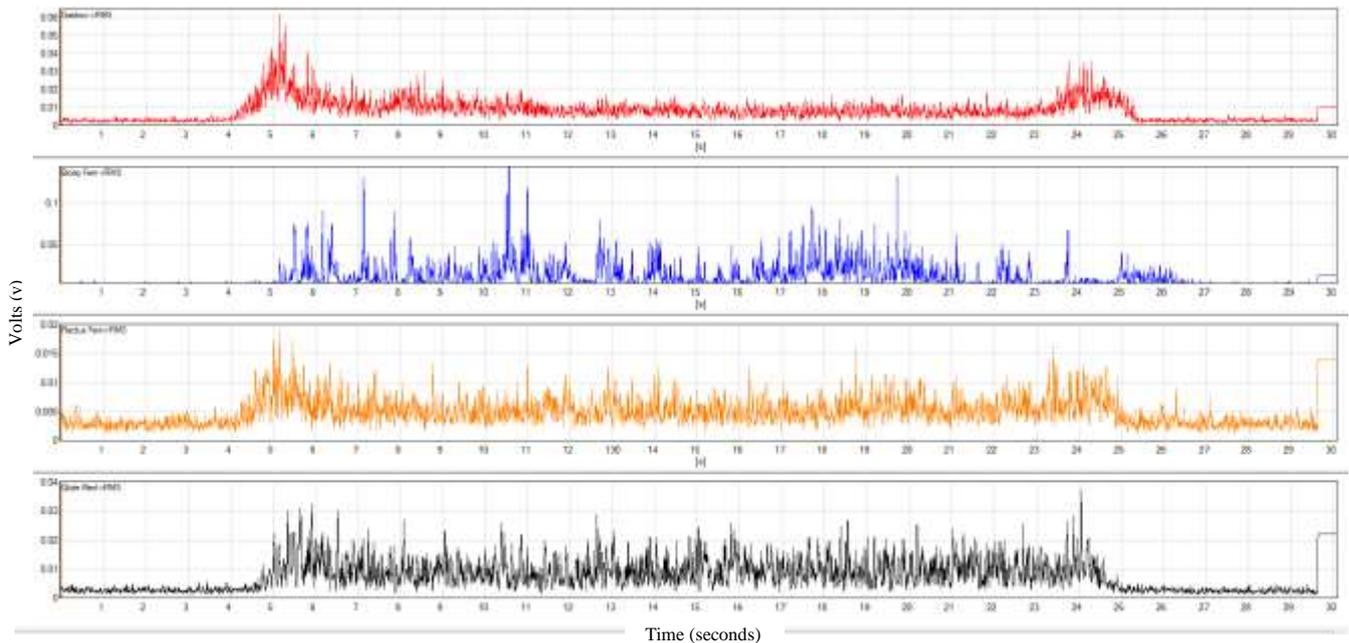
**Figure 4-20 Plot of raw EMG data from Gastrocnemius, Bicep Femoris, Rectus Femoris and Gluteus Medius**

### 4.7.2 Stage 2 – sEMG Filtering

As raw sEMG data is variable, by its stochastic nature, filtering is commonly applied to the signals in order to smooth the data and provide a representative behaviour of the muscle. The root-mean-squared (RMS) calculation was used on the raw sEMG data, which consists of three steps:

- 1) Square all of the values in the specified window
- 2) Determine the mean of the resultant values
- 3) Take the square root of the result

The window length selected was 0.125 seconds with a window overlap period of 0.0625 seconds, these parameters offered sufficient filtering of the data whilst not masking the behaviour of the muscles during the task. The calculation also removed the DC offset, consisting of subtracting the mean value from the raw data.



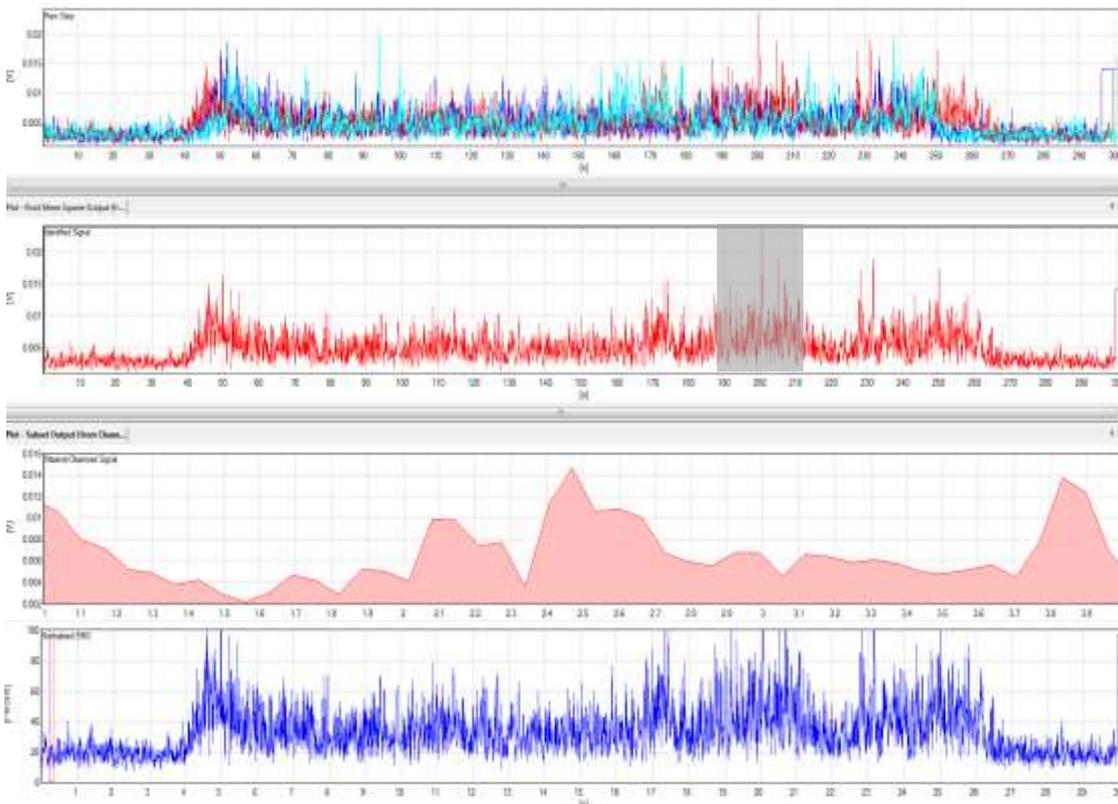
**Figure 4-21 Filtered EMG data from Gastrocnemius, Bicep Femoris, Rectus Femoris and Gluteus Medius**

#### 4.7.3 Stage 3 – EMG Normalisation

In order to compare across muscles, conditions and subjects the sEMG data is required to be normalised to a reference EMG signal. By normalising to a reference contraction the plethora of factors that affect an EMG signal are referenced to the same point and therefore you are able to obtain a valid relative measure of muscle activity. The most commonly applied method of normalising an EMG signal is to a Maximal Voluntary Contraction (MVC), however as highlighted by Burden (2010) and others, there is no consensus on the ‘best’ method of normalising an EMG signal with numerous techniques and variations for normalisation being task, condition and subject dependent (Halaki & Ginn 2012). As highlighted the most cited method is the MVC, whereby subjects are encourage to perform a maximal isometric contraction often for a period of 3-seconds and repeated 3 times with the researcher desiring the maximal neural activation of the muscle in question. However, one of the main limitations

of this method is using this with a patient group and explicitly those whom experience pain during movement, such as PFP patients. To ask a PFP patient to perform a maximal contraction, specifically the knee extensors, would firstly be unethical as it would most likely cause pain to the subject knowingly. Secondly, the patient group would likely either be unable or unwilling to perform such a contraction and therefore the MVC technique would be redundant or unreliable. A technique that is used commonly within the literature and clinical practice is the Maximal Observed Signal, which is method of normalising the EMG data to the maximum activation obtained during the task under investigation. The Maximal Observed Signal has been shown to decrease variability between individuals (Chapman et al. 2010) and between trials (Albertus-Kajee et al. 2011). The Maximal Observed Signal method is comprised of selecting the maximal EMG signal within the given activity and for each muscle, often from 3-5 repetitions, and using this signal to divide against the task EMG signal.

This study used the Maximal Observed Signal to normalise the EMG activity from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medias. For each subject all repetitions of a muscle were plotted and the maximal observed EMG signal was identified. Following the identification of the maximal EMG signal within the activity a 3-second period was subset to create a reference signal.



Step 1.  
Raw EMG Data for individual muscle, all contractions.

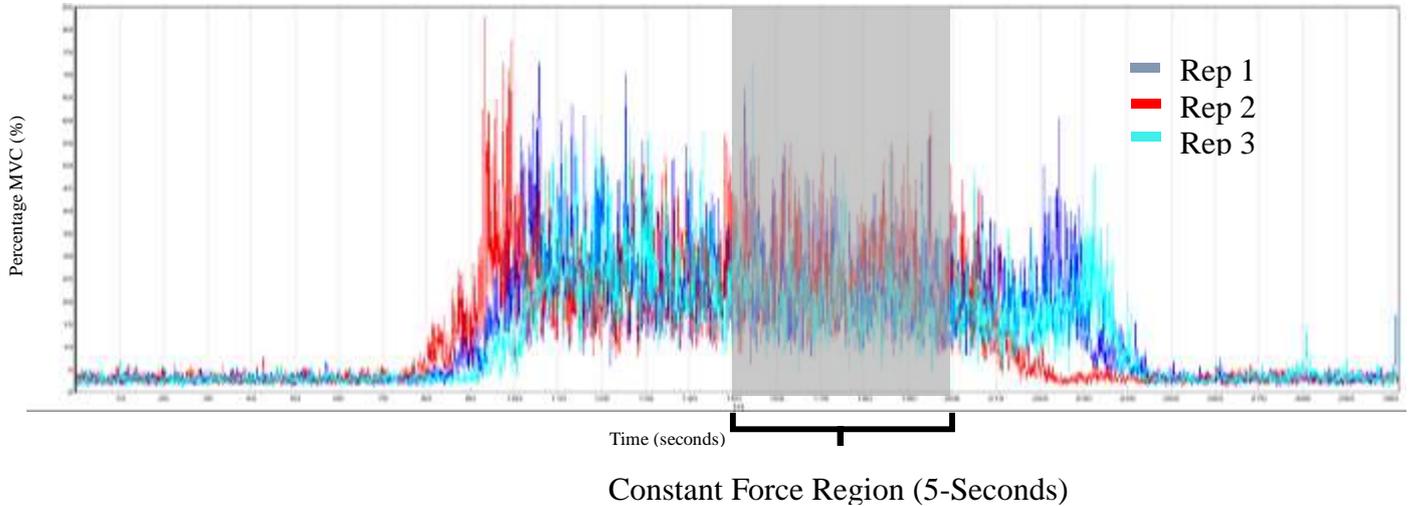
Step 2.  
Selected maximal observed signal in contraction, subset maximal signal

Step 3.  
Create data file with selected maximal signal

Step 4.  
Normalise the EMG data file to the maximal observed signal.

#### 4.7.4 Stage 4 – Data Extraction

All muscles were processed following the previous documented stages. Data was then exported to extract pertinent variables associated with muscle amplitudes. Data was subset to analyse a 5-second period in the constant force region as with processing of the EMG decomposition data set, which can be seen in Figure 4-23 below.



**Figure 4-23 Selection of 5-second period from constant force region for data extraction**

Average normalised amplitudes were taken for each muscle and each repetition within the 5-second constant force region, repetitions for each muscle in each condition were then averaged. This provided two values for each muscle, in the tape and no tape condition, describing the average muscle amplitude during the constant force region. An example of the data output can be seen in Table 4-8 below.

**Table 4-8 Example of average normalised EMG for the Rectus Femoris**

Muscle	Condition	Rep	Average Amplitude (%)	Rec Fem Average (%)
Rectus Femoris	No Tape	1	23.99	23.95
		2	26.10	
		3	21.74	

## 4.8 Kinematic and Kinetic Processing Methods

Kinematic and Kinetic data captured from the motion capture system (3.2.3) and force plates (3.2.4) respectively were exported, in Coordinate-3D (C3D) file format, from Qualisys Track Manager. Data were imported into Visual 3D (Version 5.01.11, C-Motion Inc., USA) for processing. Motion files were assigned to an anatomical model file (see section 3.5.5 for details) and files tagged under the appropriate condition, tape or no tape.

### 4.8.1 Filtering

In order to attenuate high frequency components residing in the kinematic and kinetic signal, introduced through various sources such as soft-tissue artefact or improper retro-reflective marker digitization, filtering the data was necessary (Winter et al. 1974). Kinematic data was filtered using a low-pass zero-lag Butterworth 4<sup>th</sup> order filter at 6 Hz (Winter et al. 1974). Kinetic data was also subjected to a low-pass zero-lag Butterworth 4<sup>th</sup> order filter but with a 25 Hz cut-off frequency (Antonsson & Mann 1985). The filter cut-off frequencies for both the kinematic and kinetic data were the same as used in study's with similar protocols (Selfe et al. 2008; Selfe et al. 2011).

### 4.8.2 Cardan Sequence

The kinematic data was calculated based upon the Cardan sequence of XYZ following recommendations from Grood and Suntay (1983). The joint coordinate systems were defined as below (Table 4-9).

**Table 4-9 Joint coordinate system and axes, planes of motion and respective movements**

<b>Axes</b>	<b>Planes of Motion</b>	<b>Movement</b>
X Axis	Sagittal Plane	Flexion/Extension
Y Axis	Coronal Plane	Adduction/Abduction
Z Axis	Transverse Plane	Internal/External Rotation

### 4.8.3 Joint Moment Calculations

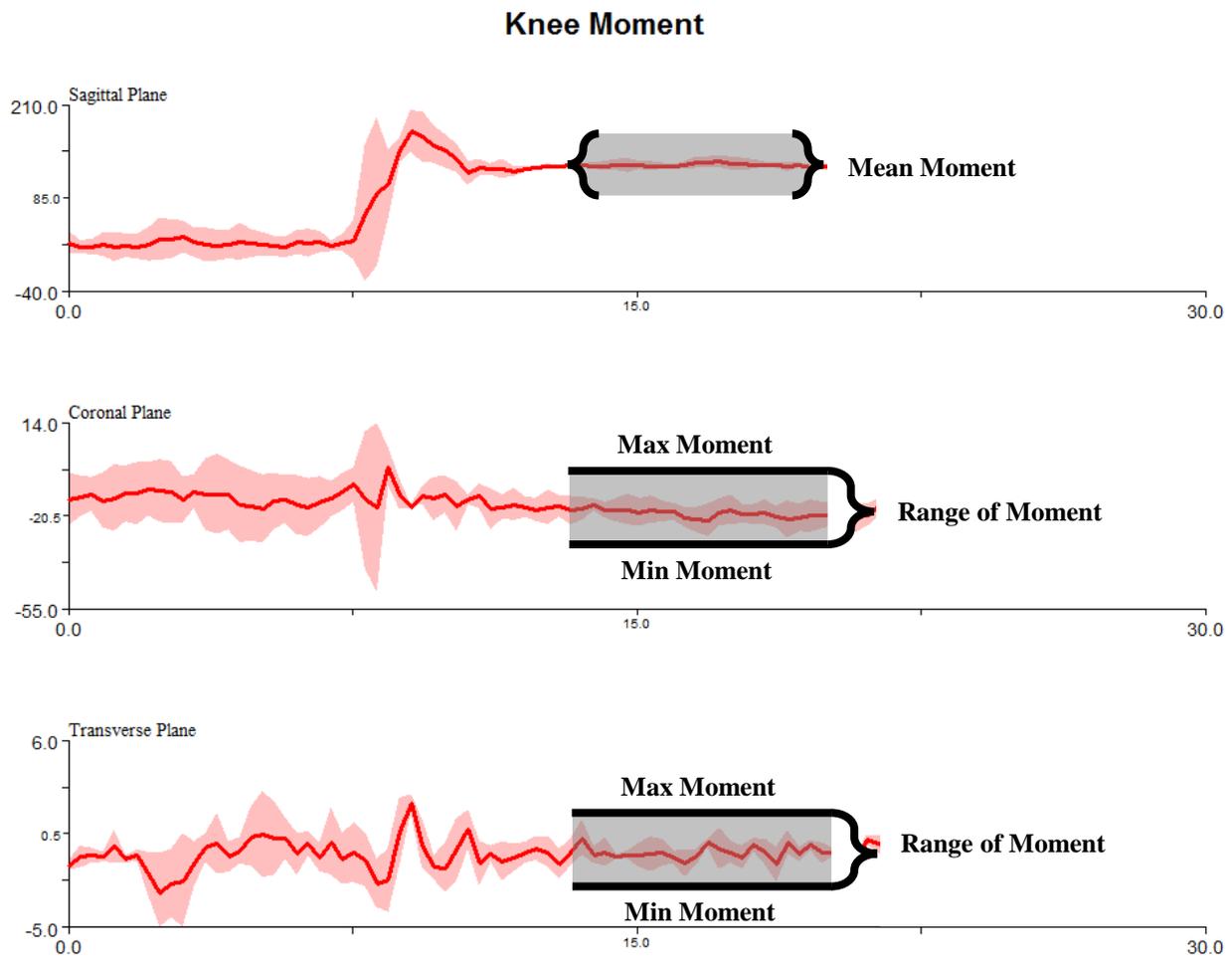
The knee joint moments were calculated relative to the shank coordinate system within Visual 3D. Force platform height was raised by 20cm in order to compensate for the step height and thus adjust the joint moment calculation. Joint moments were normalised to subjects' body weight.

#### 4.8.3.1 Sagittal Plane Knee Moment

The mean knee moment from the constant force region were calculated from the three repetitions for each subject (Figure 4-24).

#### 4.8.3.2 Coronal and Transverse Plane Knee Moment

The minimum and maximum knee moments from the constant force region were calculated, thus providing a range of moment. The range of moments from the three repetitions in each condition were averaged, consequently giving a mean range of moment for each subject. As discussed in section 2.3.4 these measures were used following previous publications that studied the knee joint biomechanics control in PFP patients and found that this measurement provided key clinically important information on the control of PFP patients and measuring the response to a proprioceptive intervention. The mean knee moment was also calculated for each subject. These calculations were performed on the Coronal and Transverse planes (Figure 4-24).



**Figure 4-24 Joint Moment calculations and extracted information**

#### 4.8.4 Joint Angle Calculations

The knee joint angles were calculated relative to the shank coordinate system within Visual 3D

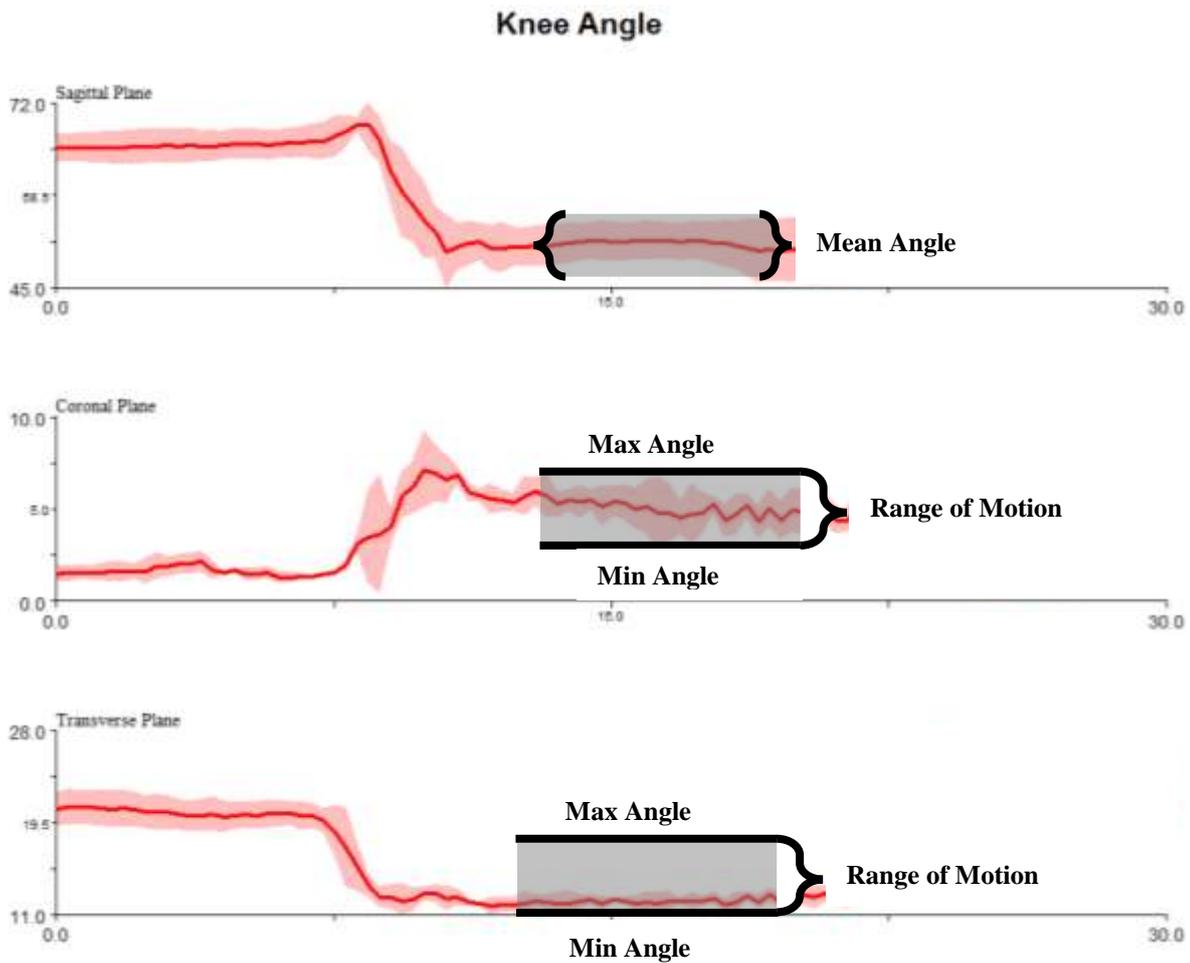
##### 4.8.4.1 Sagittal Plane Knee Angle

The mean knee angle from the constant force region were calculated from the three repetitions for each subject (Figure 4-25).

##### 4.8.4.2 Coronal and Transverse Knee Angle

The minimum and maximum knee angles from the constant force region were calculated, thus providing a range of motion. The range of motion from the three repetitions in each condition were averaged, consequently giving a mean range of angle for each subject. Similar to the knee joint range of moment and discussed in section 2.3.4 these measures were used following

previous publication studying the knee joint biomechanics control in PFP patients and found that this measurement provided key clinically important information on the control of PFP patients and measuring the response to a proprioceptive intervention. The mean knee angle was also calculated for each subject. This calculation was performed on the Coronal and Transverse planes (Figure 4-25).



**Figure 4-25 Joint Angle calculations and extracted information**

#### 4.9 Taping Intervention

A medial patella glide taping technique, which forms part of the McConnell technique (McConnell 1986), was used throughout the thesis for symptomatic and non-symptomatic subjects alike. Subjects were asked to lay supine with the leg in full extension so the tape could be applied without any resistance from quadriceps contraction (McConnell 1986). Two 5cm width pieces of self-adhesive polyester tape (Hypafix, Smith & Nephew, London, UK) were measured as half the knee circumference and placed, with no stretch or pull, over the knee from the lateral to the medial epicondyles covering the entire patella (Figure 4-26, step 1). This tape was primarily used in order to protect the skin from the application of the rigid tape, however it also served as a good fixation surface for the application of the rigid tape. Two 2cm width pieces of Zinc Oxide high-tensile rigid tape (Leukotape, BSN Medical, Hull, UK) were measured 2cm shorter than the polyester tape. Starting from the lateral aspect the tape was anchored (Figure 4-26, step 2) with no stretch or pull, the patella was then glided medially and held whilst the rigid tape was pulled medially over the patella and fixed to the medial aspect. The rigid tape application was repeated with the second piece of tape overlapping the first application (Figure 4-26, step 3). Finally, with the therapist holding the four corners of the tape the subject was asked to fully flex and extend the knee 3 times in order to ensure good adhesion of the tape to the skin. Subjects were given 1 minute to familiarise themselves with the application and the feel of the tape. The application of the tape was conducted by the researcher, whom is a trained therapist, with each subject to ensure reliability across subjects.



2) Application of Hypafix tape across the knee.



3) Anchoring rigid tape and medial glide of Patella.



4) Maintaining medial glide of Patella whilst pulling rigid tape medially and fixing to medial side.



1) Completed application of taping intervention.

**Figure 4-26 Example application of taping intervention**

## **5. Development of Methods**

### **5.1 Introduction**

In order to address the various methodological concerns four different pilot studies were designed and executed, from which the respective findings could be applied in the design of the main study protocol. These questions were raised in order to satisfy the study's first MPhil objective (see section 2.8.2). The main questions asked and explored were as follows:

5.1.1.1 Do the Vastus Medialis Obliquus and Vastus Medialis Longus present any functional differences?

5.1.1.2 What is the optimal task which will provide a stability challenge and be functionally appropriate whilst being applicable for use with surface EMG decomposition technology?

5.1.1.3 What are the best methods for attaining a high fidelity EMG signal for surface EMG decomposition?

5.1.1.4 Are there neurophysiological differences between open and closed kinetic chain tasks and are they suitable for surface EMG decomposition?

## 5.2 Pilot Study 1 – Vastus Medialis Longus and Vastus Medialis Obliquus: What are the Functional Differences?

### 5.2.1 Background

There has been a wealth of reports suggesting that the Vastus Medialis is comprised of two differing portions of the muscle, namely the Vastus Medialis Longus (VML) and Vastus Medialis Obliquus (VMO). The investigations and consequent debates over the past four decades are yet to reach an empirically led conclusion on either the anatomical differences or, perhaps more relevantly, whether there is any functional differences between the proposed VM portions. A key aspect in understanding the function of a muscle is its neurophysiological components and consequent behaviour, often investigated by the enquiry of the electrical signal emanating from the muscle using EMG. The placement of EMG sensors on the surface of the skin is a much discussed topic and it has been shown that sensor placement may have a considerable effect on the temporal relationship of the vasti muscles (Wong & Ng, 2006), which has been a commonly investigated variable within the study of patellofemoral pain (Wong, 2009). However, whether there are functional differences exhibited in placing the EMG electrode in differing locations on the muscle, or whether the muscle has differing portions is yet to be substantiated.

### 5.2.2 Objectives

- Determine the motor unit behavioural differences between the two portions of the Vastus Medialis (objective 5.5.1.1.1)
- Establish an optimal placement of the dEMG sensors on Vastus Medialis (objective 5.5.1.1.1)

### 5.2.3 Participants

Six participants, two females and four males, with a mean age of 27.2 years (S.D. = 7.4 years) participated. All participants reported to be free from any pain or pathology affecting the spine or lower limbs at the time of testing. Ethical clearance was obtained from the Faculty of Health Ethics Committee (FHEC) of the University of Central Lancashire (UCLan) (Proposal 522, appendix 12.5). Written informed consent was gained from subjects prior to participation.

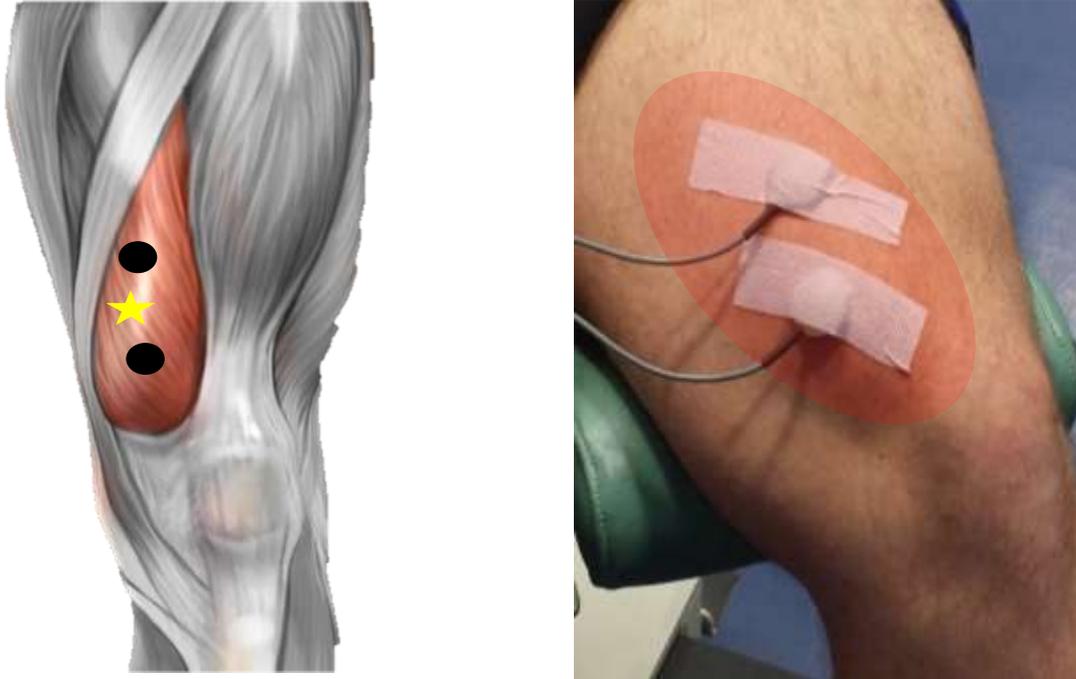
#### 5.2.4 Methods

Participants had the Vastus Medialis (VM) skin prepared by following the steps as described in section 3.4.4. Once the skin was prepared a muscle stimulation device (Compex Mi-SPORT) was used in conjunction with a motor point pen (Compex Motor Point Pen), as seen in Figure 5-1, to help locate the innervation zones within VM. The motor point pen produces a small 2 Hz electrical stimulation, therefore when the end of the motor point pen is placed over the top of an innervation zone a small muscle twitch can be seen and felt by the subject.



**Figure 5-1 The Compex Mi-Sport muscle stimulation device and the motor point pen.**

The innervation zone(s) were marked and sensor locations were then situated avoiding these locations as the characteristics of the EMG signal vary in amplitude and frequency components when the sensor is on or near the innervation zones (Roy et al., 1986).



**Figure 5-2. An example of the sensor and innervation zone locations, in both graphical and real form.**

Participants were asked to perform an isometric knee extension task whilst seated upon a dynamometer (Cybex Norm), straps at the shoulder levels, pelvis and thighs were secured to minimize unwanted or compensatory movement. The anatomical axis of rotation of the knee joint was aligned with the dynamometer axis of rotation with the safety stops placed at 50° and 70°. The dynamometer was positioned to fix the knee joint angle at 60°. Participants were first asked to perform a maximum voluntary contraction (MVC), which consisted of a 3 second maximum knee extension, which was repeated 3 times with at least 60 seconds rest between each repetition. Following the MVC protocol participants performed a knee extension action following the trapezoidal trace with real-time sEMG as a form of feedback, the contraction was maintained at 50% of the previously captured MVC. The knee extension task lasted for 20 seconds with an approximate 3 seconds ramping up and down phase, as described in (Figure 3-22, section 3.6.1). The signals from the four pairs of each sensor electrodes were differentially amplified and filtered with a bandwidth of 20 Hz - 450 Hz, the signals were sampled at 20 kHz and stored on a computer for offline processing.

### 5.2.5 Data Analysis

The raw EMG signals from the four channels of signals were decomposed into their constituent motor unit action potential trains (MUAPTs) using the decomposition algorithm. The individual MUAPTs and their firing instances were then used to calculate the mean firing rate (MFR) for each motor unit, a description of the process can be found in section 4.4. The MFR curves were filtered using a Hanning averaging filter over a 3-second window. The Hanning window has a low pass filtering effect attenuating fast, transient changes in motor unit firing rates (Westgaard & De Luca, 2001). A 5-second period from the constant force region, a portion where there were no large fluctuations in force or newly recruited motor units, was selected for analysis.

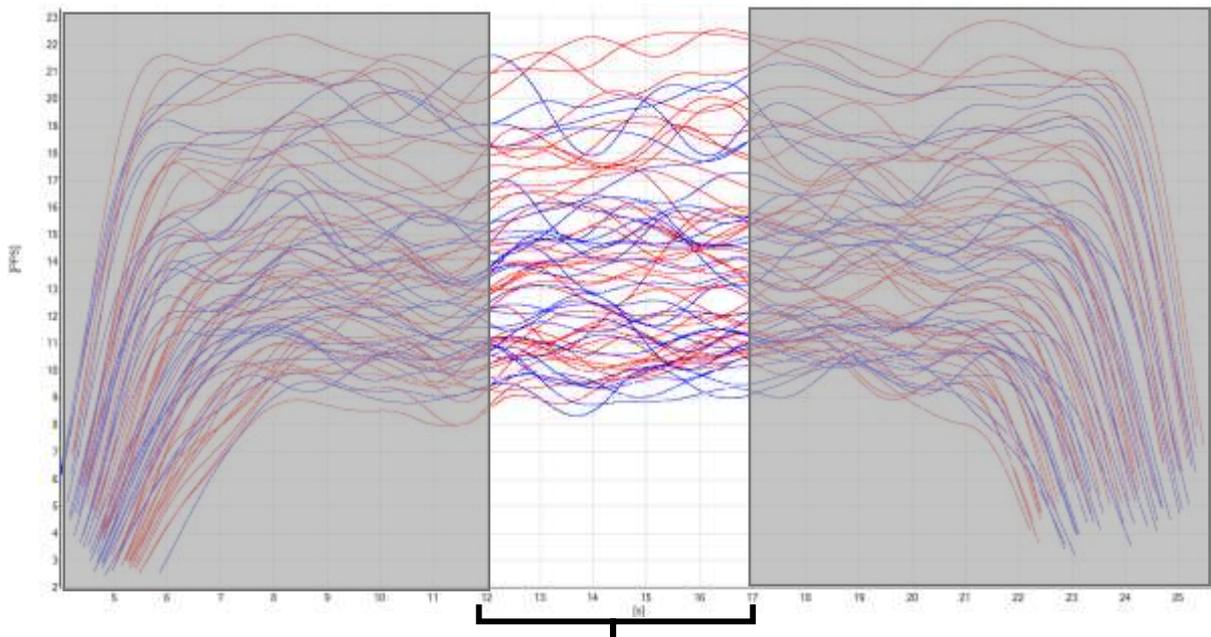
### 5.2.6 Results

The Vastus Medialis proximal and distal areas of the muscle both exhibited comparable mean firing rates. A paired samples t-test was performed on the minimum firing rate (phasic motor units) and the maximum firing rate (tonic motor units). No significant differences were identified between the minimum ( $p=0.372$ ) and maximum ( $p=0.263$ ) mean firing rates motor units of the proximal and distal areas of the muscle. The proximal and distal areas of the muscle also exhibited comparable motor unit yields with no significant differences between the two placements ( $p=0.912$ ). The mean firing rate frequency (pulses per second, PPS) and the motor unit yield for both placements, proximal and distal, are shown in Table 5-1.

**Table 5-1. Mean firing rates and motor unit yields for both Vastus Medialis (VM) proximal and distal placement**

VM Proximal Area			VM Distal Area		
Min MFR (pps)	Max MFR (pps)	MU Yield (Number MUs)	Min MFR (pps)	Max MFR (pps)	MU Yield (Number MUs)
<b>12.4</b> (S.D 2.2)	<b>22.3</b> (S.D 3.9)	<b>24.4</b> (S.D 9.8)	<b>11.4</b> (S.D 1.9)	<b>20.2</b> (S.D 3.8)	<b>24.8</b> (S.D 6.9)

A typical representation of a subjects mean firing rate and motor unit yield from the two sensor placements, both exhibiting similar behaviour, as seen below.



Constant Force Region (5-Seconds)

**Figure 5-3. Mean firing rate (MFR) curves of a typical subject. Proximal placement (Red) and distal placement (Blue).**

### 5.2.7 Discussion

It was found that there were no significant differences in the motor unit mean firing rate or motor unit yield between the two different identified areas, proximally and distally to the innervation zone, of the Vastus Medialis. This is in agreement with neurophysiological reasoning that muscle fibres, and consequently motor units, are evenly distributed throughout the muscle belly (Basmajian & De Luca, 1985). These findings provide neuromuscular evidence that the Vastus Medialis could be seen as acting as a single functional unit, rather than the muscle operating as two distinguishable units. The comparable behavioural characteristics of the motor unit mean firing rate and the motor unit yield are also in agreement with previous literature (Roy et al., 1986; Zaheer et al., 2012) with respect to sensor placement. The dEMG sensor placement should follow the same guidance as sEMG placement being placed approximately in the middle of the muscle belly.

### 5.2.8 Conclusion

The findings from this pilot study provides guidance for the protocol of the main study, that placement of the dEMG sensor can be either proximal or distal to the innervation zone and still provide representative behaviour of the whole muscle. But the more important and clinically

significant finding to take from this study is it provides further evidence that the VM can be considered as one functional muscle.

### 5.3 Pilot Study 2 - Develop a stability challenging and functional relevant task

#### 5.3.1 Background

Closed kinetic chain exercises are extensively used within rehabilitation for a variety of knee conditions, such as patellofemoral pain, often being preferred over open kinetic chain exercises. Closed kinetic chain exercises engage multi-joint systems such as the lower limb functional improvements in coordination, strength and control (Mellor & Hodges, 2005). However, previous investigations using decomposition methods have performed isometric open chain exercises, which may not provide a sufficient neuromuscular challenge or lack functional relevance.

#### 5.3.2 Objectives

Develop a stability challenging and functionally relevant task without compromising the use of surface EMG decomposition methods (objective 5.5.1.1.2)

#### 5.3.3 Methods

Four participants, two females and two males, with a mean age of 29.3 years (S.D. = 9.9 years) participated. All participants reported to be free from any pain or pathology affecting the spine or lower limbs at the time of testing. Ethical clearance was obtained from the Faculty of Health Ethics Committee (FHEC) of the University of Central Lancashire (UCLan) (Proposal 522, appendix 12.5). Written informed consent was gained from subjects prior to participation.

Participants were asked to perform four variations of knee loading tasks; single limb isometric squat, sit-to-stand squat, double limb isometric squat and step down task. These closed chain tasks were designed to challenge the knee joint sufficiently to replicate daily living loading tasks whilst being subjectively acceptable and without comprising the surface EMG decomposition methods.

Participants performed the four tasks, in a randomized order, with 3 repetitions of each task with at least 60 seconds rest period between each repetition and task. The surface dEMG sensors were placed on Vastus Medialis (VM) and Vastus Lateralis (VL) muscles following the skin preparation procedure previously described (section 3.4.4). The sensors were placed

away from the muscle innervation zones, distally to the mid-portion of the muscle as a result of a previous pilot study (section 5.2).

#### 5.3.4 Functional and Challenging Tasks

Different variations of closed chain exercises were selected based upon clinical relevance and previous literature (Kim et al., 2004; Richards et al., 2008; Selfe et al., 2008), details of these tasks can be seen below.

i) Single Limb Isometric Squat

This task begins with the dominant leg resting on a 20cm step in approximately 60° knee flexion and the non-dominant leg being the weight bearing limb. The participant was then instructed to slowly transfer the weight onto the dominant leg until it was fully load bearing, remaining in approximately 60° knee flexion (Figure 5-4).



**Figure 5-4. Subject performing the single limb isometric squat**

ii) Sit-to-Stand Squat

This task begins with the subject seated with the dominant limb at 60° knee flexion. The subject was then instructed to begin to stand from the seat transferring all weight onto the dominant limb, whilst maintaining 60° knee flexion (Figure 5-5).



**Figure 5-5. Subject performing sit-to-stand squat**

iii) Double Limb Squat

Participants began with both limbs fully extended and then when instructed slowly flexed to approximately 60° knee flexion with both limbs sharing the load distribution (Figure 5-6)



**Figure 5-6. Subject performing double limb squat**

iv) Step-down

This task begins with the subject standing upon a 20cm step and the non-dominant limb bearing the full load. When instructed subjects were asked to transfer weight onto the dominant limb and be the load bearing limb. Then subjects were instructed to slowly descend from the step with the heel of the non-dominant limb hitting the ground to avoid plantar flexion of the ankle (Figure 5-7). The task protocol was based upon previous publication (Selfe et al. 2011; Selfe et al. 2008). Although the Delsys dEMG system has strict guidelines and can only be applied to isometric conditions, the algorithm does allow for discrete changes in MUAP shape. This task was included to assess whether the algorithm was capable of decomposing this semi-dynamic task.



**Figure 5-7. Subject performing step-down task**

5.3.5 Data Analysis

The dEMG data were processed using methods as described in the section 4.4. Successful decomposition of the trials was the primary outcome measure, however data outputs were also visually inspected to ensure the motor unit behaviour and motor unit yield was similar to previous data collection sessions and previously published work. These outcomes were then used as indicators to the suitability of the different tasks. Subjects were asked to provide verbal feedback on the tasks being performed, which was noted against each task for face validity.

### 5.3.6 Results

The single limb isometric squat task exhibited the highest number of successfully decomposed trials with 34 from a possible 36 trials. The double limb isometric task was also found to provide a high number of successfully decomposed trials, 29 from a possible 36 trials. The sit-to-stand and step-down tasks were too complex for the decomposition algorithm to resolve and had a high number of failed trials, 13 and 22 failed trials respectively. Subject feedback concluded that the single limb isometric and the step-down tasks were the most challenging of the four tasks performed. The double limb isometric task was reported as not challenging as subjects could share the load distribution through both limbs. The sit-to-stand task was reported difficult to replicate similar movements and maintain the approximate 60° knee flexion.

Visual inspection of the raw and processed decomposition data showed agreement with the subjective feedback of the trials and related to the number of successfully decomposed trials, with the single limb isometric squat being the most optimal.

Table 5-2. The four tasks subjects performed and their success rate of decomposing

Task Trials	Single Limb Isometric Squat	Double Limb Isometric Squat	Sit-to-Stand Squat	Step-Down
Successful Decomposed Trials	34/36	29/36	23/36	14/36

### 5.3.7 Discussion

The study was conducted to develop a stability challenging and functionally relevant task without compromising the use of the surface EMG decomposition methods. The findings of the study showed that the single limb isometric squat task was the optimal solution.

The single limb isometric squat task created a sufficient stability challenge to the subjects as opposed to the double limb isometric squat; subjects reported that during the double limb squat they were able to compensate through distributing the load to the non-dominant limb. The sit-to-stand task created a similar stability challenge to the subjects yet the procedure was difficult

to consistently repeat and control the same knee flexion angle, thus detrimental to the protocol repeatability within and between subjects. The step-down task created a sufficiently challenging task, however due to the change in knee angle as the subject stepped down the EMG signals were too complex for the decomposition algorithms to resolve. The complexity of the EMG signals during the step-down task caused the number of successfully decomposed trials to be significantly reduced when compared to the other tasks. The inability of the decomposition algorithm to accurately decompose these EMG signals is multifaceted, however largely due to two factors. The short contraction period of the muscles, approximately 4 seconds, does not provide sufficient isolated MUAP shapes for the decomposition algorithm to find shapes repeating. Secondly, the movement of the soft tissues underlying the skin where the dEMG sensor is placed causes inaccurate and failed decomposition trials, due to the detection area changing and large MUAP shape changes therefore different groups of motor units were being detected.

#### 5.3.8 Conclusion

This pilot study was aimed at developing a stability challenging yet functionally relevant task without compromising the use of surface EMG decomposition methods. It was found that the single limb isometric squat provided the optimal solution. The task sufficiently challenged the subject, as found through subjective feedback, and was the most successfully decomposed task with all subjects' trials. These findings provide justification for the use of the tasks within the main study protocol.

## 5.4 Pilot Study 3 –Signal Fidelity for Surface EMG Decomposition

### 5.4.1 Background

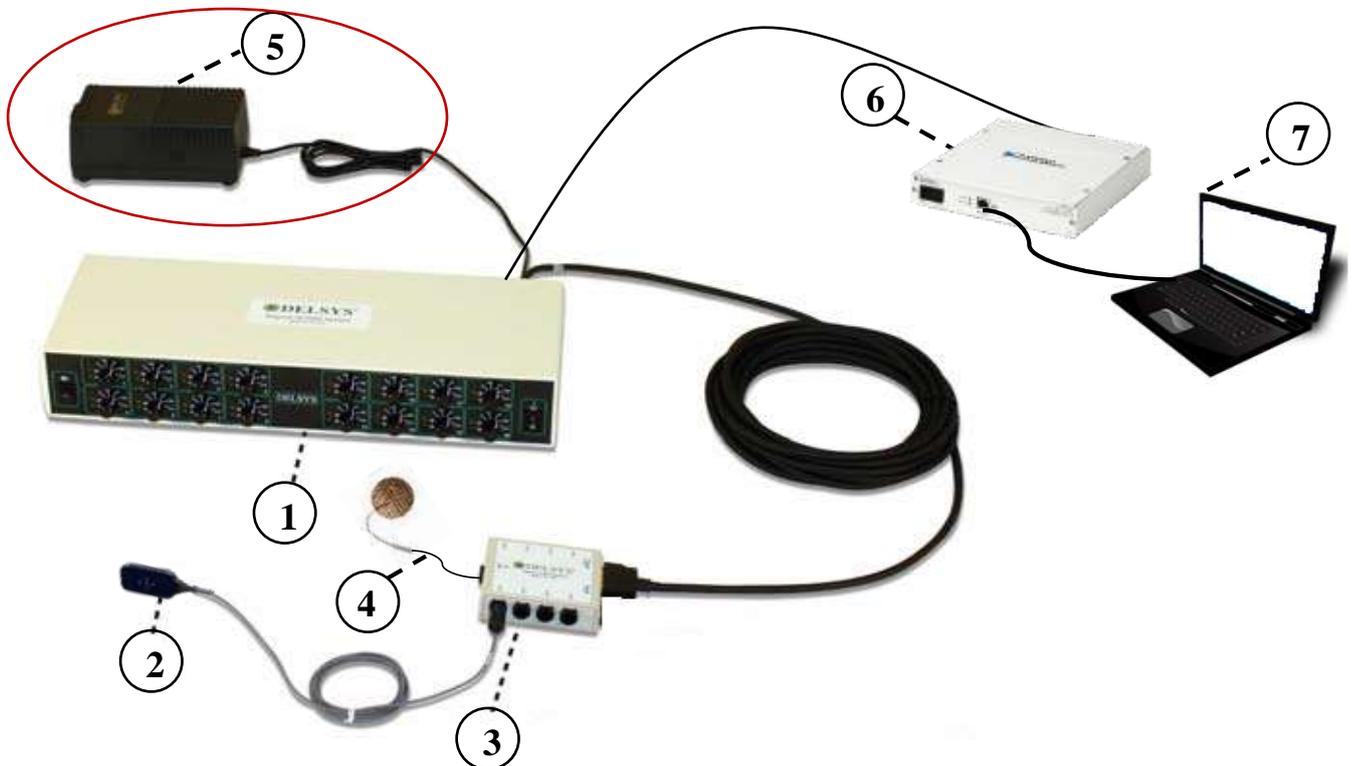
The EMG signal is the result of many physiological, anatomical and technical factors, with some of these factors being managed by proper detection methods and technology whilst other sources can only be considered. The factors affecting the EMG signal fidelity is an extensive and daunting list, yet there are certain external factors which can be controlled and addressed by the astute operator. A key component in gaining a high fidelity EMG signal for decomposition is achieved with a high Signal to Noise Ratio (SNR) (Zaheer et al. 2012), which is comprised of the EMG signal amplitude and the baseline noise component. EMG amplitude can be affected by several factors with sensor location being the overriding factor, as discussed in section 3.4. Likewise the baseline noise component is also affected by various factors, including: skin-electrode interface, fatty tissue and mains line noise to name a few. Decomposing the sEMG signal requires additional preparation techniques and considerations as the variables of interest, motor unit behaviour, can be limited or masked in the presence of a poor fidelity signal. Consequently the signal quality procedure is paramount in producing a high motor unit yielding and accurate firing data set.

### 5.4.2 Objectives

- Investigate the mains line noise and its interference effect on surface EMG decomposition signal quality (objective 5.5.1.1.3).
- Explore skin preparation techniques and determine the most effect for a high fidelity surface EMG decomposition signal (objective 5.5.1.1.3).

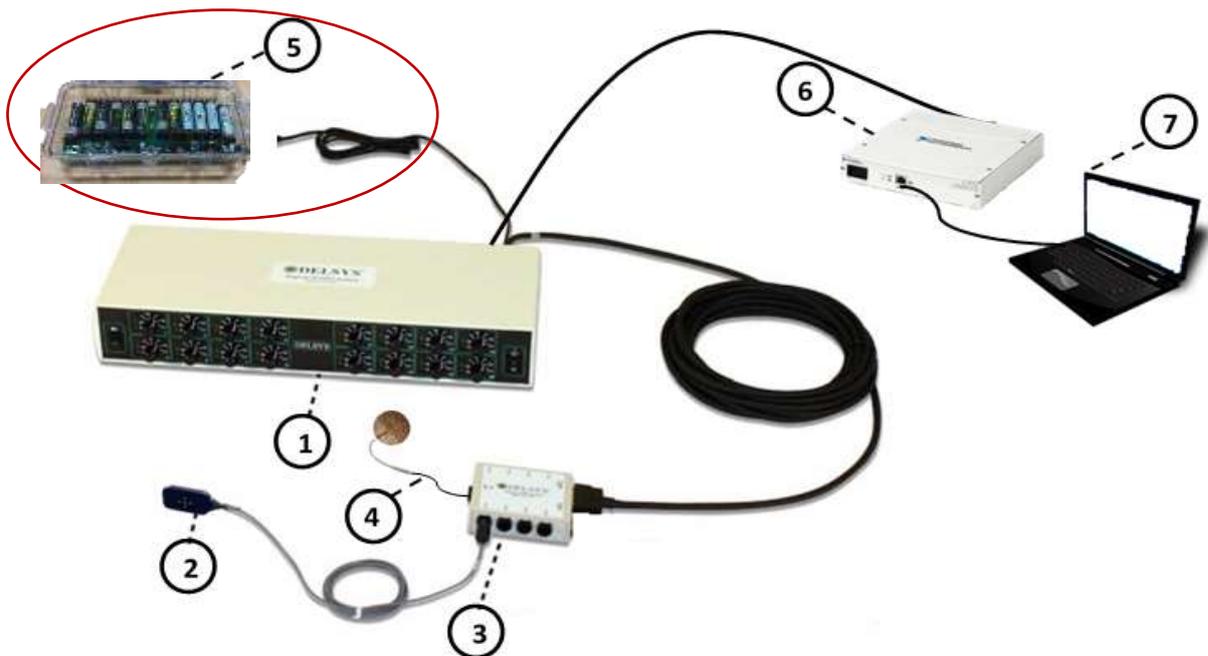
### 5.4.3 Line Interference

The Delsys dEMG system (Delsys Inc., Boston, MA) and its constituent components are powered by a medical grade power supply, being connected to the mains wall socket. This is the manufactures recommended and typical setup for powering and operating the dEMG system, however the typical setup does not account for every environment and may not be suitable for an individuals' setup. In order to assess the suitability of the main line power connection and whether it has a detrimental effect on the EMG signal fidelity the system was setup with two different scenarios, one using the medical grade power supply (Figure 5-8), and the other using a bespoke battery pack (Figure 5-9).



1	Amplifier	4	Reference Electrode	7	Laptop
2	dEMG Sensor	5	<b>Power Supply Unit</b>		
3	Input Module	6	A/D Board		

Figure 5-8 Delsys dEMG setup with mains power supply

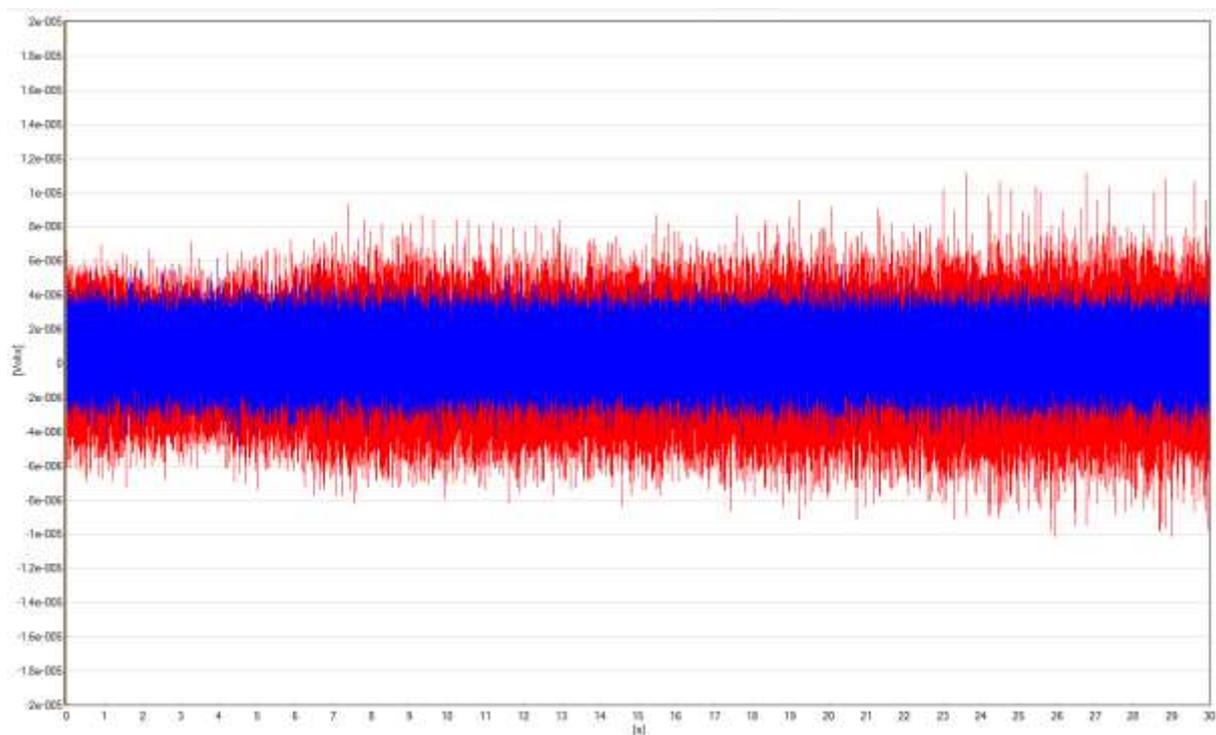


1	Amplifier	4	Reference Electrode	7	Laptop
2	dEMG Sensor	5	<b>Battery Power Pack</b>		
3	Input Module	6	A/D Board		

Figure 5-9 Delsys dEMG setup with bespoke battery pack

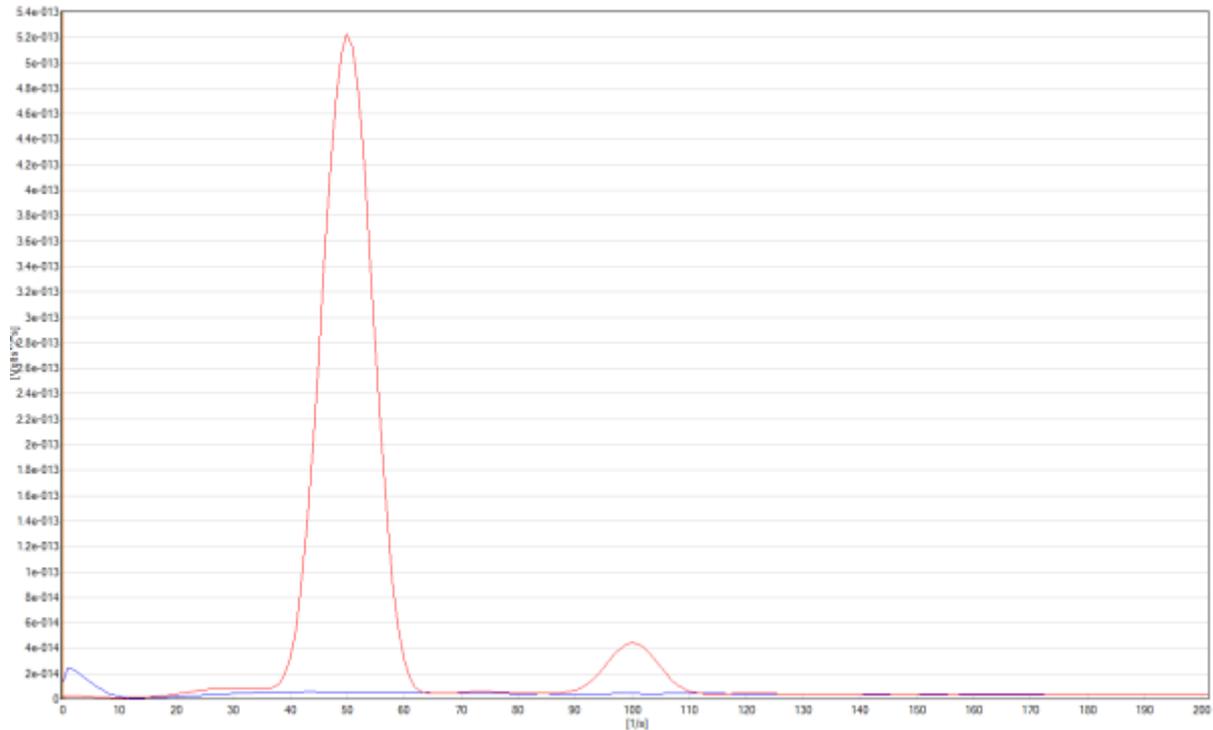
The dEMG sensor was placed directly onto the dermatode reference electrode as a method to remove any noise source coming from the skin-electrode interface, consequently the baseline noise exhibited is isolated to the dEMG system components and the mains power line. Data collection was conducted for 60 seconds within EMGworks Acquisition (Delsys Inc., Boston, MA) for both scenarios (mains power supply unit and battery power pack). The recorded data was imported into EMGworks Analysis for post processing analysis of the baseline noise comparing the two power supply scenarios.

Figure 5-10 shows an overlaid plot of the baseline noise from the two power supply sources, the red plot representing the baseline noise collected when using the mains power supply unit and the blue plot representing the bespoke battery power pack.



**Figure 5-10 Raw baseline noise of the dEMG system with mains line power connection (red) and bespoke battery power pack (blue)**

Further investigation of the baseline noise, through the Power Spectral Density, shows that the main line connection (red line) was contaminated with 50 Hz line interference (Figure 5-11).



**Figure 5-11 Power Spectral Density of the baseline noise for the mains power connection (red) and battery power pack (blue)**

These explorations and findings provide clear evidence of 50 Hz noise entering the dEMG system when the mains power supply is used to power the dEMG system. These issues seem local to the data collection area and difficult to identify and consequently mitigate, however it is also clear that the issue can be avoided when using the bespoke battery power pack for the dEMG system.

#### 5.4.4 Skin Preparation Techniques

The electrode pins and the inter-electrode distance of the dEMG sensors are critical design features but, by their nature, generate more skin-electrode interface noise than traditional sEMG sensors. Attaining a high fidelity EMG signal suitable for surface EMG decomposition requires additional skin preparation considerations in comparison to traditional EMG data collection, which is often satisfied with the application of a 70% Isopropyl pad/wipe.

The skin above the Vastus Medialis muscle was prepared, on a single subject, in three different stages whilst monitoring the effect on the baseline noise component of the signal. The Vastus Medialis was selected as it would be one of the two muscles investigated in the main study and would provide the more challenging task due to the increased adipose tissue and muscle-skin distance in comparison to the Vastus Lateralis. The Delsys dEMG system was setup following the findings from the exploration into the line interference with the battery power pack. The dEMG sensor was placed on Vastus Medialis muscle, following the skin preparation stage, and the dermatode reference electrode was placed on the dorsal aspect of the hand.

Skin Preparation stages:

##### 5.4.4.1 Hair Removal and Alcohol wipe

Hair was removed using a hair removal cream followed by cleansing the application site with a 70% Isopropyl wipe. The typical resulting baseline noise was in the region of 20uV peak to peak.

##### 5.4.4.2 Above including; tape application and removal

In addition to the previous preparations (5.4.4.1) hypoallergenic tape was applied to the application site and swiftly removed in order to remove dead layers of skin, this was repeated 3-5 times. This was followed by re-cleansing the area with an alcohol wipe to remove any tape glue residue. The typical resulting baseline noise was consequently improved and in the region of 16uV peak to peak.

#### 5.4.4.3 Above including; re-hydrate skin, securing the sensor further

In addition to the two previous preparation stages (5.4.4.1 and(5.4.4.2) the application site was hydrated by applying small amounts of water and soap, the skin was given approximately 30 seconds to absorb and rehydrate. The skin was then re-cleansed using an alcohol wipe to remove any remaining soap. In order for the sensor electrodes to make better contact with the skin, a small plastic disc was applied over the top of the sensor to act as a lever and consequently apply additional pressure on the sensor and the skin (Figure 5-12). The typical baseline noise resulting from these skin preparation techniques was in the region of 11uV peak to peak.



**Figure 5-12 The small plastic disc used to compress the sensor onto the skin**

The findings from these explorations into the different skin preparation techniques show that the extensive skin preparations (5.4.4.3) can provide a very low baseline noise level, although the procedures require additional efforts and time the reward is a high fidelity EMG signal. These skin preparation techniques will be applied in all data collection sessions using the surface EMG decomposition system.

#### 5.4.5 Conclusion

The findings from the line interference exploration show that the dEMG system and data collections sessions should be conducted using the bespoke battery power pack as it mitigates the mains line noise that is evident in the laboratory area. The skin preparation explorations also provided a technique that, although rather extensive, provided a low baseline noise and should be used in all dEMG data collection sessions. Both of these explorations have provided optimal techniques and preparations in attaining a high fidelity EMG signal, which will consequently lead to a high yielding motor unit and highly accurate firing data set.

## 5.5 Pilot Study 4 – Open and Closed Chain Activities: MU Characteristics

### 5.5.1 Background

Open kinetic chain (OKC) and closed kinetic chain (CKC) exercises have been a topic of interest for many years in the rehabilitation field. However, there is limited evidence in the neuromuscular, particularly motor unit behavioural, differences between the two forms of exercises. A previous limitation in understanding the muscular control is the inability to record a sufficient representation of motor units from a muscle contraction. But recent developments in surface EMG decomposition (dEMG, Delsys Inc., Boston, MA) provide the ability to reliably record high yields of motor units from the surface of the skin. All previous investigations using EMG decomposition methods have used OKC exercises as a method to study an isolated muscle and the central nervous systems control of the given muscle. The isometric OKC exercises that have been studied using EMG decomposition methods have been shown to be highly accurate and validated methods, however isometric CKC exercises have not been studied and so the accuracy or validity requires exploration.

### 5.5.2 Objectives

- Determine the efficacy of using a closed kinetic chain exercise using surface EMG decomposition methods in comparison to a previous validated open kinetic chain exercise (objective 5.5.1.1.4).
- Explore the motor unit characteristic differences between the open and closed kinetic chain exercises (objective 5.5.1.1.4).

### 5.5.3 Methods

The Delsys dEMG system (Delsys Inc., Boston, MA) was used to collect surface EMG decomposition data and setup in as previously described in section 5.4. The dEMG sensors were placed on the Vastus Medialis and Vastus Lateralis muscles following the skin preparation as outlined in section 3.4.4. Participants were first instructed to perform a maximum voluntary contraction (MVC), which consisted of a 3 second maximum knee extension, being repeated 3 times with at least 60 seconds rest between each repetition. Following the MVC protocol participants were instructed to follow the 30 second trapezoidal tracking paradigm (section 3.6.1), with participants instructed to maintain the held at 50%

MVC constant force region. The force level was chosen as it provided an ample challenge to subjects' knee extension, a lesser contraction may not have provided a sufficient force to challenge the Vasti and a greater challenge could have caused fatigue. Participants performed both open and closed kinetic chain exercises, the order being randomly assigned.

Thirteen participants, 4 female and 9 male, with a mean age of 28.3 years (S.D. = 5.8 years) participated. All participants reported to be free from any pain or pathology affecting the spine or lower limbs at the time of testing. Ethical clearance was obtained from the Faculty of Health Ethics Committee (FHEC) of the University of Central Lancashire (UCLan) (Proposal 522, appendix 12.5.1). Written informed consent was gained from subjects prior to participation.

#### 5.5.3.1 Open Kinetic Chain Exercise

Participants were instructed to perform an isometric knee extension task whilst seated upon a dynamometer (Cybex Norm), straps at the shoulder levels, pelvis and thighs were secured to minimize unwanted or compensatory movement. The anatomical axis of rotation of the knee joint was aligned with the dynamometer axis of rotation with the safety stops placed at 50° and 70°. The dynamometer was positioned to fix the knee joint angle at 60°. Figure 5-13 shows the setup of a participant on the dynamometer with the dEMG sensor placed on the Vasti muscles.



**Figure 5-13 Open kinetic chain exercise participants performed on the dynamometer with the dEMG sensors placed on the Vasti muscles.**

### 5.5.3.2 Closed Kinetic Chain Exercise

Participants were instructed to place and rest their dominant leg on a 20cm step in 60° knee flexion, measured with a goniometer, and allow the non-dominant leg to fully weight bear. The participant was then instructed to slowly transfer the weight onto the dominant leg until it was fully load bearing, remaining in 60° knee flexion (Figure 5-14).



**Figure 5-14 Closed kinetic chain exercise participants performed with the dEMG sensors placed on the Vasti muscles.**

### 5.5.4 Data Analysis

The EMG data was imported into EMGworks Analysis (Delsys Inc., Boston, MA) where all contractions were decomposed using the decomposition algorithm, for details see section 4.2. The Mean Firing Rate (MFR) was computed using a 3-second Hanning window (section 4.4). A 5 second constant force region was selected, ignoring the recruitment and de-recruitment phases of the contraction, where the average MFR was computed. The mean and standard deviation of the MFR were computed for all contractions for individual participants. The mean MFR values for both tasks were statistically analysed using a paired samples t-test (IBM Corp. Released 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.). Six participants' open kinetic chain data were omitted from data analysis due to poor motor unit yield, from the fact of low signal-noise ratio, in the Vastus Medialis muscle. The low signal-noise ratio was not evident in the CKC exercise for the same participants, and was only seen in the OKC exercise.

### 5.5.5 Results

The mean MFR results for the two different tasks, open and closed kinetic chain, showed comparable results with 17.2 pps and 18.1 pps for the open kinetic chain and closed kinetic chain tasks respectively for the Vastus Medialis. Similar results were found for the Vastus Lateralis with mean MFR results of 15.8 pps and 16.7 pps for the open kinetic chain and closed kinetic chain tasks respectively. The paired samples test showed no significant differences between the mean MFR for both Vastus Medialis and Vastus Lateralis with p-values of 0.62 and 0.57 respectively. A summary of these results can be seen in Table 5-3.

**Table 5-3 Results table showing the mean MFR, standard deviations and significance value for the two Vasti during the different tasks.**

<b>Task</b>	<b>Mean MFR (pps)</b>	<b>p-Value</b>
<b>Vastus Medialis</b>		
Open Kinetic Chain (Isometric Knee Extension)	<b>17.2</b> (3.1)	0.62
Closed Kinetic Chain (Single Limb Isometric Squat)	<b>18.1</b> (2.9)	
<b>Vastus Lateralis</b>		
Open Kinetic Chain (Isometric Knee Extension)	<b>15.8</b> (4.1)	0.57
Closed Kinetic Chain (Single Limb Isometric Squat)	<b>16.7</b> (0.8)	

### 5.5.6 Discussion

The aim of this study was to determine the efficacy of using a closed kinetic chain (CKC) exercise with surface EMG decomposition methods and whether any motor unit characteristic differences were evident between the two different forms of exercise, open and closed kinetic chain. After collecting and decomposing surface EMG data from the Vastus Medialis and Vastus Lateralis during both open and closed kinetic chain tasks it was found that there were no significant differences ( $p > .05$ ) for both muscles. As shown in Table 5-3 the motor unit firing rate was comparable between the two tasks, with only a marginal ( $>1$  pps) increase in firing rate in the CKC exercise. The results provide evidence for the viability of using a controlled CKC exercise for surface EMG decomposition methods due to the successful

decomposition of the data set and the comparable motor unit mean firing rates between the two tasks. Poor motor unit yields were found in six subjects' Vastus Medialis data sets and were consequently omitted from the results. This is not thought to be due to any methodological issue as these participants' CKC data sets for Vastus Medialis exhibited a high signal-noise ratio and consequent good motor unit yield. Instead this discrepancy is thought to be due to these participants biasing their Rectus Femoris muscle in the OKC knee extension task and this task not requiring a significant Vastus Medialis contribution, which was required during the CKC exercise.

#### 5.5.7 Conclusion

This pilot study was successful in its objectives in establishing the efficacy for using a closed kinetic chain exercise with the surface EMG decomposition methods. Results provided evidence in showing comparable motor unit characteristics between the much published open kinetic chain exercises for surface EMG decomposition and the newly proposed closed kinetic chain exercise. These findings provide assurances for using the closed kinetic chain exercise, single limb static squat in the main study protocol.

## 5.6 Summary of Findings

The pilot studies satisfied the MPhil objective of developing appropriate and relevant methods to capture the host of neuromuscular and biomechanical measures relevant for the investigation into Patellofemoral Pain. A summary of the main findings from the pilot studies can be seen below:

- It was found that the placement of the dEMG sensor on the Vastus Medialis provides the same motor unit firing behaviour regardless whether it is on the oblique or longus portions, suggesting that the Vastus Medialis can be considered a single functional muscle.
- The newly developed single limb isometric squat task was found to be the optimal task for being both a functionally challenging task and without comprising the surface EMG decomposition methods.
- The dEMG system was found to be best operated with the use of a bespoke battery pack after finding significant line interference with the mains line power source.
- An optimal skin preparation technique was developed providing the lowest baseline noise and consequently allowing a higher fidelity signal.
- It was found that using the surface EMG decomposition technique in a functional closed kinetic chain exercise was comparable to the traditionally used open kinetic chain exercise.

These findings provide a clear justification for the design of the main studies protocol ensuring that the data collected is of high fidelity, comparable to previous work and clinically applicable.

## **6. Method - Non-Symptomatic Subjects**

### 6.1 Introduction

This chapter provides the pertinent information relating to the non-symptomatic subjects data collection methods and procedures.

### 6.2 Subjects

Subjects were recruited from a population of staff and students at the University of Central Lancashire (UCLan). Subjects were provided with a 'Patient Information Sheet' prior to attending any testing session, the patient information sheet provided study information and what was expected of them (see appendix 12.2). Based on previous study by Selfe et al. (2008) who investigating the effect of proprioceptive bracing on biomechanical parameters, mean differences were greater than the standard deviations. The knee transverse plane range of moment yielded a mean difference 0.035 Nm/kg with a standard deviation of 0.03 Nm/kg during a step-down task. A statistical power calculation yields that with an 80% statistical power and a significance level of 5% the sample size needs 12 subjects to detect any significant changes in the biomechanical parameters to be investigated. Sixteen non-symptomatic subjects were enrolled onto the study, with three subjects omitted from the results due to poor data quality (see appendix 12.1.1 for details), leaving 13 non-symptomatic subjects for data processing (4 females and 9 males, aged 30 years (SD 6.5 years), mean weight 74.6 kg (SD 12.5 kg)).

### 6.3 Ethical Approval

The study was approved by the Faculty of Health & Social Care Ethics Committee (FHEC), University of Central Lancashire (Proposal no. 522) (see appendix 12.5.1). Prior to data collection written informed consent (see appendix 12.3) was gained from all subjects.

### 6.4 Recruitment Criteria

#### 6.4.1 Inclusion Criteria

The inclusion criteria of symptomatic subjects being eligible to participate in the study can be seen listed below:

- Males and Females to be included
- Age Range 18-40 years old

- Able to hold a static squat position for at least 8 seconds

#### 6.4.2 Exclusion Criteria

The exclusion criteria of symptomatic subjects being unable to participate in the study can be seen listed below:

- Recent knee surgery or trauma (within 3 months)
- Ligamentous instability and/or internal derangement (Subjects should be referred for arthroscopy or Magnetic Resonance Imaging (Acton & Craig 2000))
- History of patella subluxation or dislocation
- Confirmed osteoarthritis of tibiofemoral and/or patellofemoral joints
- Joint effusion when the mid-patellar girth is 5% or more than the non-involved knee
- True knee joint locking and/or giving way
- Co-existent acute illness or chronic disease
- Bursitis, patella or iliotibial tract tendinopathy, Osgood Schlatter's disease, Sinding-Larsen Johansson Syndrome, muscle tears or symptomatic knee plicae
- Pregnant or breast feeding

#### 6.5 Data Collection Procedures

Testing took place in the movement analysis laboratory (Brook Building, UCLan, Preston Campus, Preston UK). Surface EMG, Surface EMG Decomposition, motion capture and force plates were all used for data collection, see chapter 3 for details pertaining to the technical and setup aspects. Subjects skin were prepared for placement of dEMG sensors and sEMG sensors (see section 3.4.4 for details), followed by placement of retro-reflective markers on the appropriate landmarks (see section 3.5.5). Following camera and force plate calibration (see section 3.5.2 and 3.5.4 respectively) subjects were asked to perform a single limb isometric squat task (Figure 6-1), either beginning with the taped condition or the no tape condition dependent on the randomised order. Subjects were provided with a familiarisation repetition to ensure they understood the instructions and that data collection tools were operating as expected.

Subjects were given clear instructions from the operator which remained the same through all repetitions for all subjects. These ensured that surface EMG decomposition data could follow the tracking paradigm (see section 3.6.1) and that the operator did not influence different

movements through differing instructions or delivery of speech (i.e. pitch, tone, volume). The instructions provided to all subjects were as follows:

- “Place your right/left leg on the step and stand quietly”

Subjects place their measurement limb onto the 20cm wooden step with their weight in the opposing limb, the “quietly” instruction meaning for the subject to remain still and no movement.

- “Begin to ramp up”

Subjects were then asked to transfer the weight from the weight bearing limb onto the measurement limb. The subjects were asked to count to 3 seconds before being fully load bearing.

- “Hold that position”

Subjects held the same knee angle and attempted to remain in the position.

- “Begin to ramp down”

In opposition to the ramping up phase subjects were asked to slowly transfer weight back to the non-measurement limb, again over a 3-second period.

Subjects were asked to perform the single limb isometric squat task 4 times under each condition, tape and no tape, with a 60-second rest period in-between each repetition. Subjects were asked if they felt comfortable and okay to continue after each repetition, however no information was provided on their performance of the task. The test condition order was randomised by using an online randomisation generator (Dallal 2013).

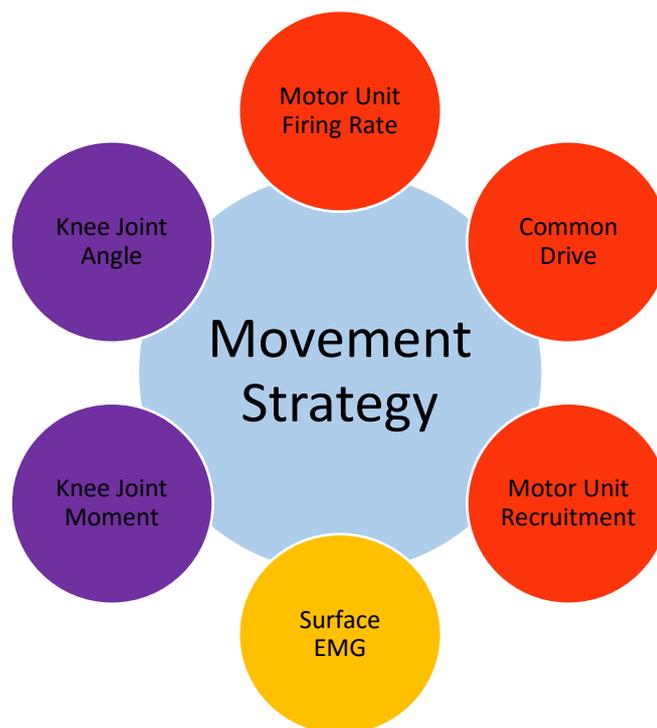


**Figure 6-1 Closed kinetic chain exercise participants performed with the dEMG sensors placed on the Vasti muscles.**

## 7. Results – Non-Symptomatic Subjects

### 7.1 Overview

A battery of differing neurophysiological and biomechanical variables were investigated, Figure 7-1 presents a graphical representation of these measures. All results from the non-symptomatic subjects were grouped together and analysed as such. However, in order to explore whether different strategies are present, individual analysis was conducted. Details of each parameter and their respective findings can be seen in the following chapter, in grouped and individual analyses.



**Figure 7-1 Graphical representation of the variables investigated in the non-symptomatic group**

### 7.2 Knee Joint Biomechanics

In order to investigate the mechanical control of the knee joint kinematic and kinetic data were calculated and extracted for the three planes of movement. For the sagittal plane the mean moment (Nm/kg) and mean angle (degrees) from the constant force region were extracted to provide information on the squat position between the two conditions. Investigations into the coronal and transverse planes of movement explored the range of moment (Nm/kg) and range of motion (degrees) from within the constant force region.

## 7.2.1 Grouped Analyses

### 7.2.1.1 Sagittal Plane

A paired samples t-test was conducted on the sagittal plane mean knee joint moment and the sagittal plane mean knee joint angle. The results showed no significant differences between the two conditions for the mean moment ( $p=0.84$ ) or the mean angle ( $p=0.89$ ). Descriptive statistics of the mean moment and angle can be seen in Table 7-1. These results essentially rule out any change or differences being due to different knee bend depths.

**Table 7-1 Sagittal plane knee joint moment and angle descriptive statistics**

Sagittal Plane Non-symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	1.04 (0.22)	1.03 (0.19)	0.002	-0.03 to 0.03	0.84
Mean Angle (Degrees)	47.80 (5.9)	47.94 (5.7)	-0.14	-2.23 to 1.99	0.89

### 7.2.1.2 Coronal Plane

A paired samples t-test was conducted on the coronal plane range of moment and mean moment as well as the range of motion and mean angle. Results (Table 7-2) did not indicate any significant differences between the two conditions for range of moment ( $p=0.24$ ) or for range of motion ( $p=0.52$ ). Significant differences were seen in the mean knee joint moment ( $p=0.02$ ) and mean joint angle ( $p=0.003$ ), however the mean differences demonstrate marginal mean differences and large standard deviations, in addition taking into account this is the mean measurement the clinical significance of these results should be considered.

**Table 7-2 Coronal plane knee joint moment and angle descriptive statistics**

Coronal Plane Non-symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	-0.24 (0.14)	-0.21 (0.13)	-0.03	-0.04 to -0.01	0.02
Range of Moment (Nm/kg)	0.11 (0.04)	0.10 (0.03)	-0.008	-0.02 to 0.01	0.24
Mean Angle (Degrees)	-0.51 (3.63)	0.06 (3.65)	-0.45	-1.88 to -0.48	0.03
Range of Angle (Degrees)	2.10 (0.84)	2.20 (0.78)	0.056	-1.3 to 2.4	0.52

### 7.2.1.3 Transverse Plane

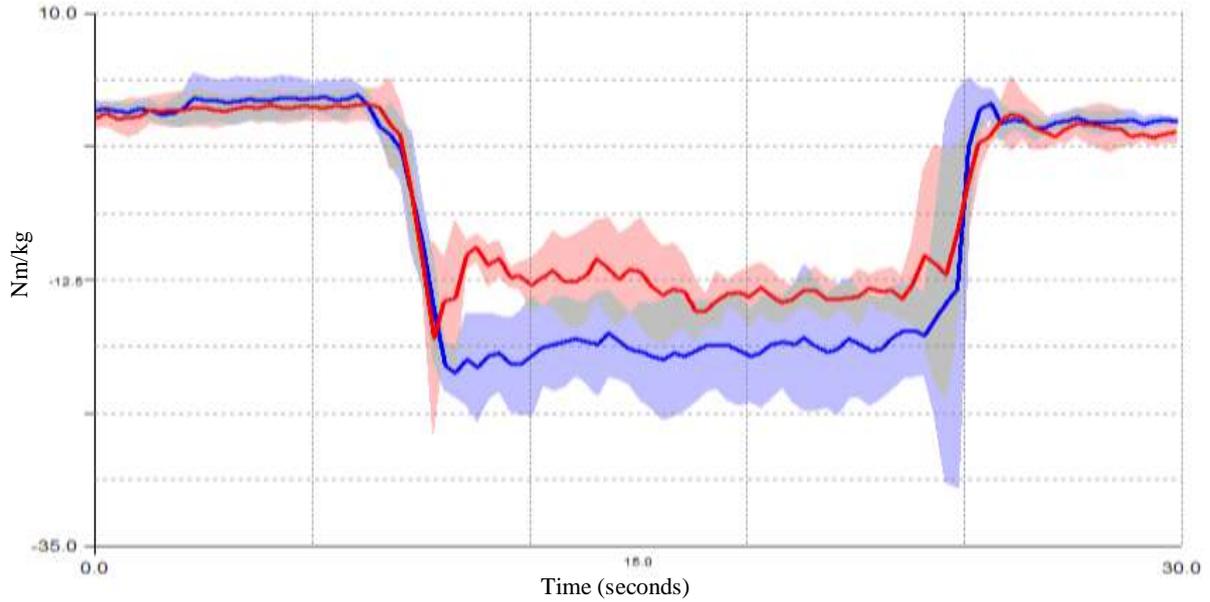
Paired samples t-test conducted on the transverse plane range of moment and range of motion showed that there was a significant decrease in the range of moment ( $p=0.01$ ) in the tape condition. However, the range of motion, mean angle or mean moment for the transverse plane did not show significance. Descriptive statistics of the transverse plane range of moment and range of motion can be seen in Table 7-3.

**Table 7-3 Transverse plane knee joint moment and angle descriptive statistics**

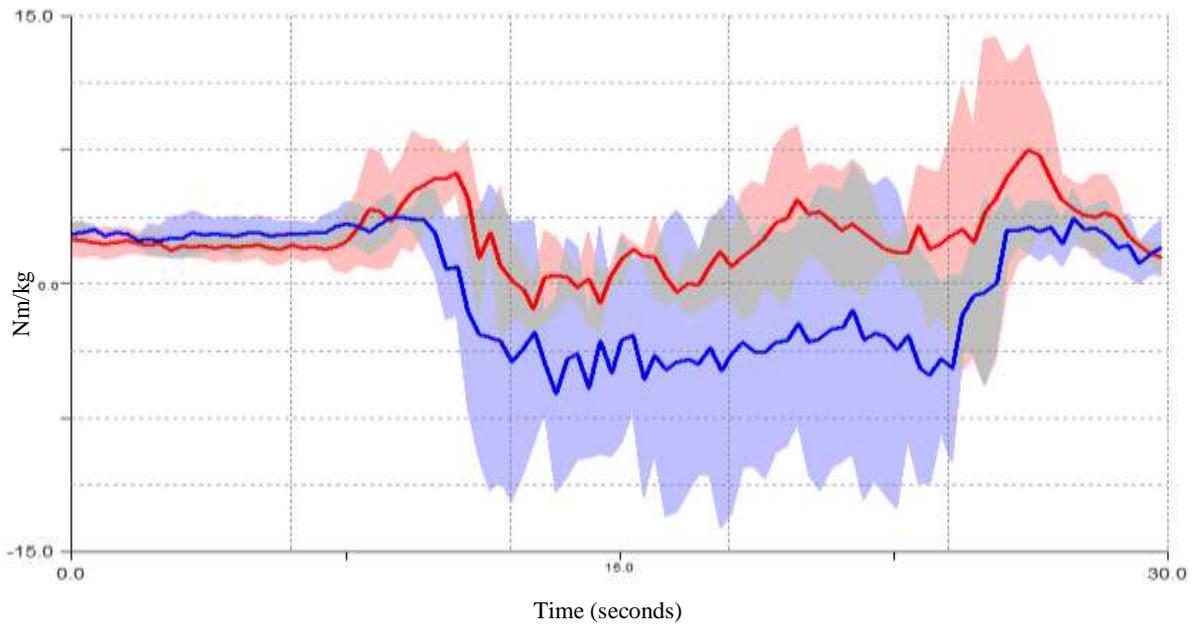
Transverse Plane Non-symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	0.05 (0.04)	0.05 (0.04)	0.0002	-0.006 to 0.006	0.94
Range of Moment (Nm/kg)	0.07 (0.03)	0.05 (0.01)	-0.015	-0.02 to 0.01	0.01
Mean Angle (Degrees)	2.21 (5.77)	1.97 (6.16)	0.24	-1.88 to -0.48	0.55
Range of Angle (Degrees)	2.03 (0.47)	2.08 (0.32)	0.049	1.8 to 2.7	0.64

### 7.2.2 Individual Analyses

The range of moment and range of motion with their respective standard deviations were reported (see appendix 12.1.2) for each subject in the tape and no tape conditions. The results demonstrated inter-subject variability in the response to the tape condition, for example subject 4 exhibited a 37.4% decrease in range of moment in the coronal plane in the tape condition (Figure 7-2), however subject 10 showed a 31.7% increase in the same plane of movement (Figure 7-3). The variability was also shown in the transverse planes range of moment but with a trend towards a decrease in range of moment in response to tape.

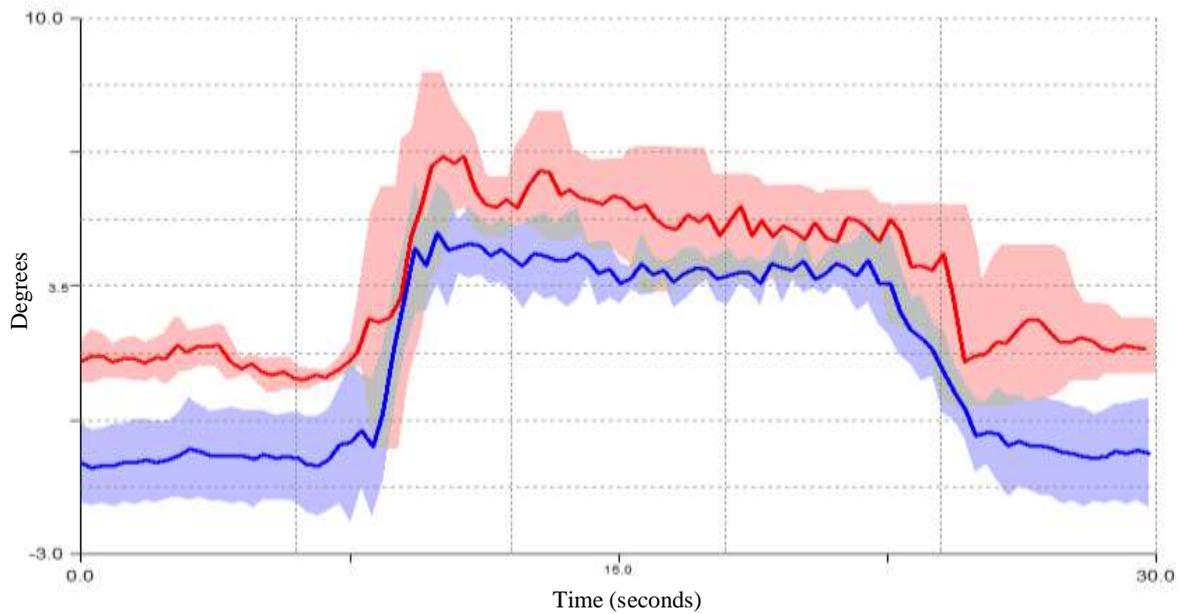


**Figure 7-2** Example of a subject with a large decrease in coronal plane knee moment with tape condition (red) compared to no tape (blue)

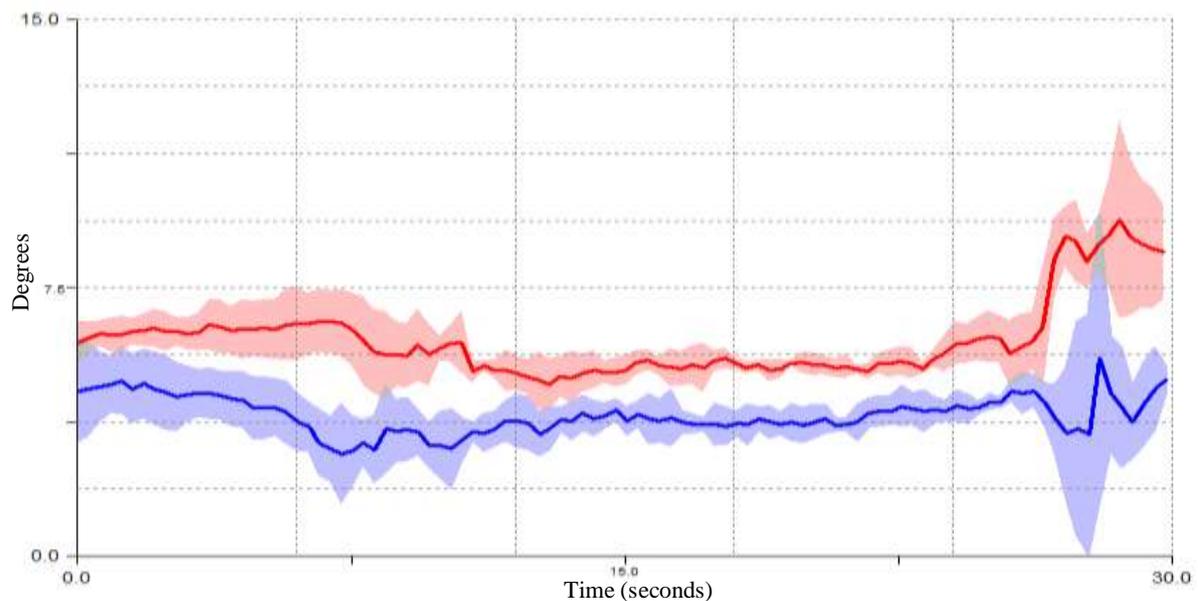


**Figure 7-3** Example of a subject with a large increase in coronal plane knee moment with tape condition (red) compared to no tape (blue)

Similar variability was also seen with the range of motion demonstrating increase and decreases in response to tape, for example subject 9 showed an increase of 23.9% in the coronal plane range of motion in the tape condition (Figure 7-4). Conversely subject 7 showed a decrease of 20.2% in the coronal plane range of motion in the tape condition (Figure 7-5)



**Figure 7-4** An example of a subject increasing coronal plane range of motion in the tape condition (red) compared to the no tape (blue)



**Figure 7-5** An example of a subject decreasing coronal plane range of motion in the tape condition (red) compared to the no tape (blue)

### 7.3 Surface EMG

The normalised Root Mean Square (RMS) EMG data from the constant force region were extracted from EMGworks Analysis to quantify the muscle activity from the Gastrocnemius, Bicep Femoris, Rectus Femoris and Gluteus Medius.

#### 7.3.1 Grouped Analyses

A paired samples t-test was conducted on the EMG data showing that there were not any significant changes in the muscle activity in response to tape. The Gluteus Medius did exhibit a 4.8% decrease in muscle activity in the taped condition and is close to becoming significant, although the large standard deviation of 8.5% shows the variance amongst the subjects with the Gluteus Medius. The other muscles similarly exhibit relatively high standard deviations with respect to their mean values, indicating the inter-subject variability.

**Table 7-4 sEMG results from grouped analysis of the non-symptomatic subjects showing the EMG activity response to the taping intervention**

Mean Surface EMG Activity (% MVC) Non-symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Gastrocnemius	29.3 (8.1)	29.0 (11.2)	0.32	-7.3 to 6.7	0.92
Bicep Femoris	35.7 (11.0)	33.5 (11.4)	2.13	-0.8 to 5.1	0.14
Rectus Femoris	36.7 (12.6)	35.5 (10.9)	1.18	-1.7 to 4.1	0.39
Gluteus Medius	40.1 (13.5)	35.2 (10.9)	4.81	-0.6 to 10.2	0.08

### 7.3.2 Individual Analyses

The mean difference between the two conditions were calculated for each subject for all four muscles to investigate individuals' response to the tape condition. The results (see appendix 12.1.3) highlight the fact that subjects responded in differing magnitudes and direction with each muscle. For example subject 6 showed a reduction of 23 % in their Gluteus Medius, whereas subject 4 increased by 9.9 % with the application of tape. In addition to these large changes in muscle activity it was found that subtle, yet opposite, behaviours can be seen across the muscle groups and subjects for instance 7 subjects exhibited a reduction in Bicep Femoris muscle activity whilst 5 subjects showed an increase.

#### 7.4 Mean Firing Rate

The average MFR was entered into SPSS for descriptive analysis, extracting the mean, standard deviation and range for the tape and no tape condition in both Vasti. As the data was normally distributed the mean, standard deviation and ranges were reported. It was deemed inappropriate for the mean firing rate to be subjected to statistical analyses because the mean firing rate is a detailed and sensitive measure, thus computing statistical analyses may mask the subtle and intricate information that it provides.

##### 7.4.1 Grouped Analyses

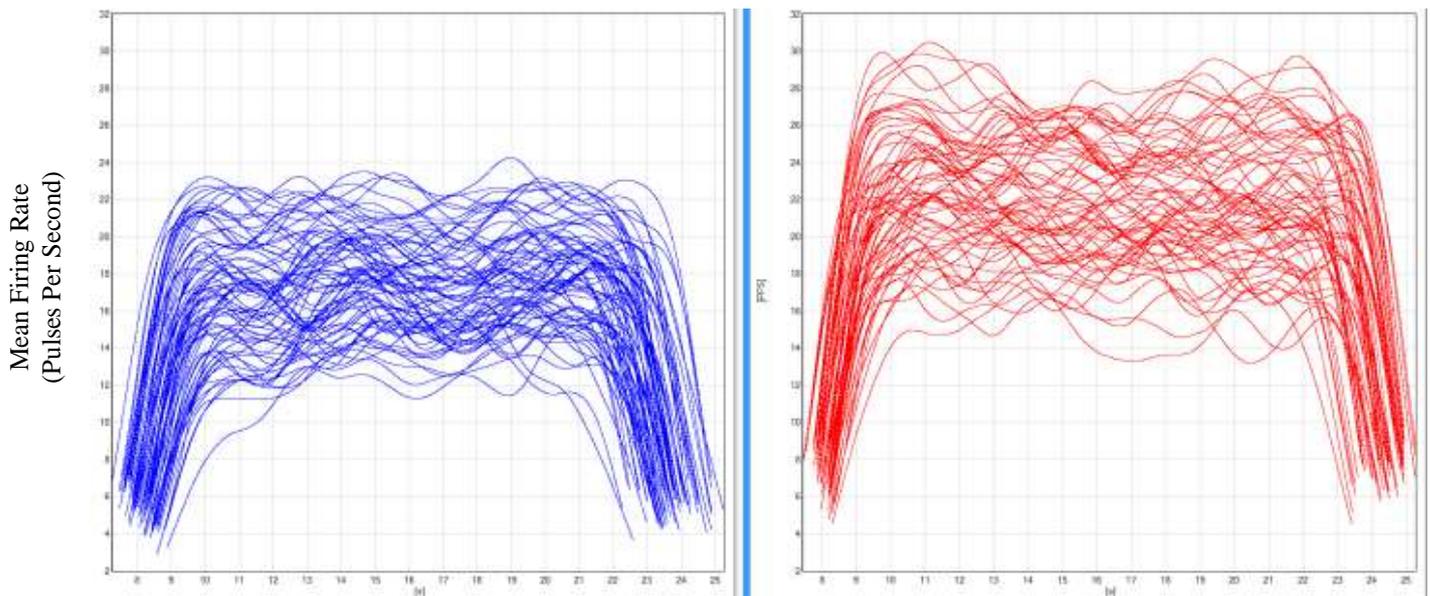
The average MFR results for the non-symptomatic subjects showed little response to the tape condition in the grouped analysis, as shown in table 7-5. The Vastus Medialis exhibited a 0.8 pps increase in its firing rate, representing a 4.5% change in response to tape. The Vastus Lateralis showed a decrease of 0.6 pps in its firing rate, a 3.3% reduction, in response to the taping condition. The decrease in Vastus Lateralis firing rate is also represented in the shift in the range of firing rate from a maximum of 33.6 pps to 30.9 pps and minimum of 6.2 pps to 5.6 pps.

**Table 7-5 Grouped analysis of all non-symptomatic subjects average MFR, standard deviations and MFR minimum and maximum values**

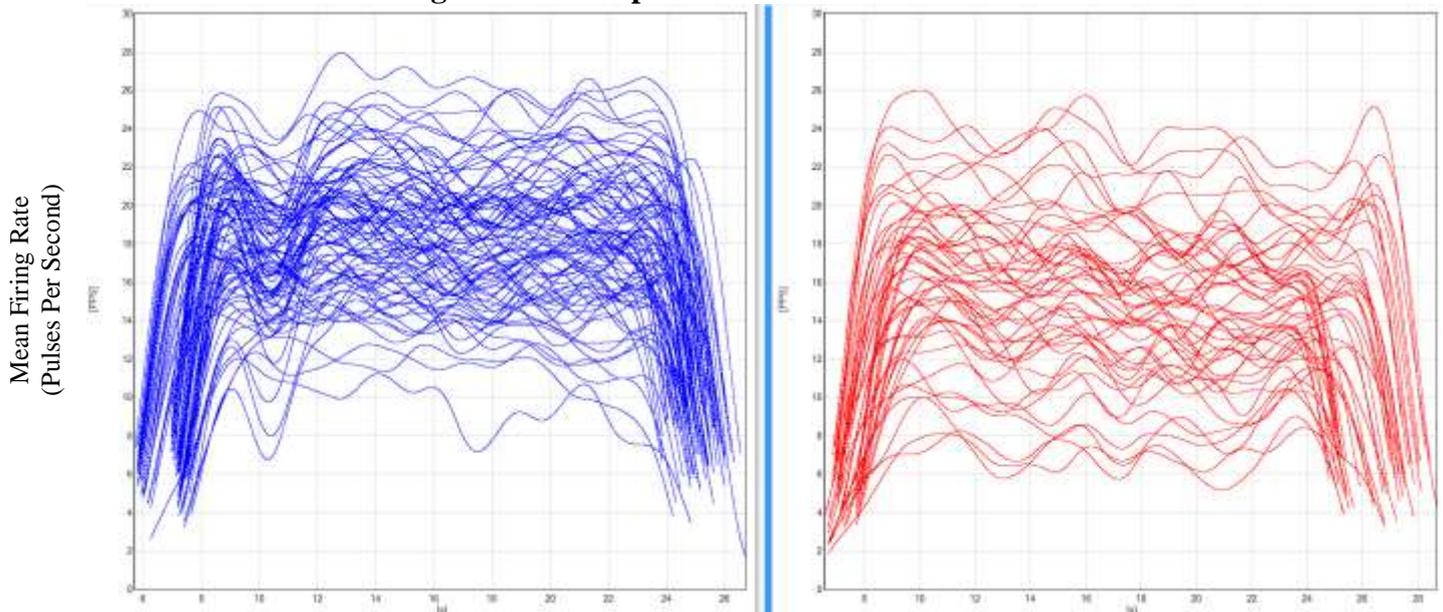
Mean Firing Rate Non-symptomatic Subjects	Average MFR (pps) (SD)	Mean Difference	Confidence Interval of the difference (95%)	Range MFR	p-Value
Vastus Medialis No Tape	17.7 (4.5)	-0.83	-2.37 to 0.71	5.5 - 33.9	0.26
Vastus Medialis Tape	18.5 (4.9)			6.4 - 33.5	
Vastus Lateralis No Tape	18.3 (3.9)	0.61	-0.17 to 1.39	6.2 - 33.6	0.11
Vastus Lateralis Tape	17.7 (4.1)			5.6 - 30.9	

#### 7.4.2 Individual Analyses

The average MFR and standard deviation values were extracted from SPSS for the two conditions and the two muscles (see appendix 12.1.4). There is evidently inter-subject variability within the MFR data set with subjects employing different strategies and responses to the taping condition. Subject 4 for example showed an increase in the Vastus Medialis MFR during the taped condition increasing the firing rate by 4.1 pps or a 23.4% increase (Figure 7-6). However, subject 8 responded to the taping condition with opposite behaviour with a reduction of 3.5 pps or 19.1% in the Vastus Medialis (Figure 7-7).



**Figure 7-6** Example of an individuals response to tape (red) compared to no tape (blue) showing an increase in mean firing rate in the tape condition



**Figure 7-7** Example of an individuals response to tape (red) compared to no tape (blue) showing a decrease in mean firing rate in the tape condition

## 7.5 Common Drive

Common drive is the term coined for the physiological phenomenon that the nervous system controls pools of motor units that can be observed through the common fluctuations in motor unit firings. To extract these common fluctuations the mathematical function called cross-correlation is used. A cross-correlation on pairs of motor units were computed for both Vasti in the tape and no tape condition, if no correlation was found between a pair of motor units it was automatically omitted from further analysis. The peak cross-correlation values from Vastus Medialis and Vastus Lateralis were extracted from EMGworks Analysis and entered into SPSS for statistical analysis. The median and inter-quartile range (IQR) were selected as it was found that the data was not normally distributed and therefore unsuitable for parametric testing.

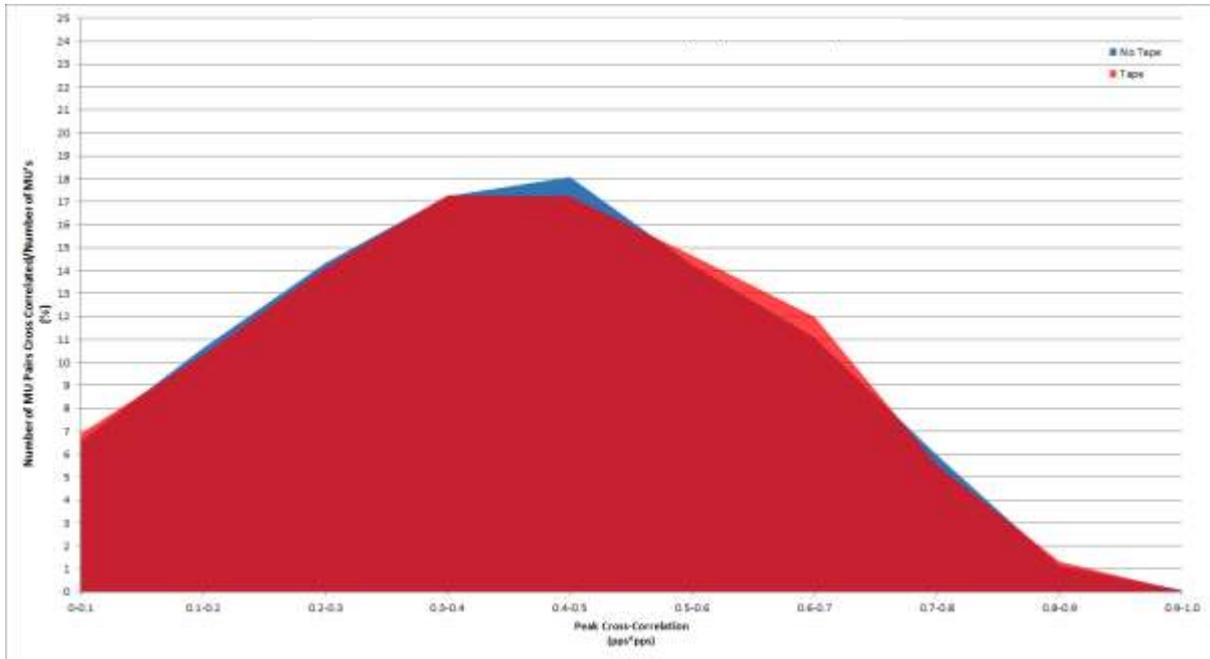
### 7.5.1 Grouped Analyses

Frequencies statistics calculated the median and IQR for each of the four conditions (no tape and tape for Vastus Medialis and Vastus Lateralis) grouping all subjects from the non-symptomatic cohort. Table 7-6 shows the median and IQR (25<sup>th</sup> and 75<sup>th</sup> percentiles) values for each of the two conditions in the two muscles. The median values of the peak cross-correlation function show that there is marginal reduction of 0.01, or 2.4%, in the tape condition for Vastus Medialis. No change within the Vastus Lateralis in the two different conditions were found.

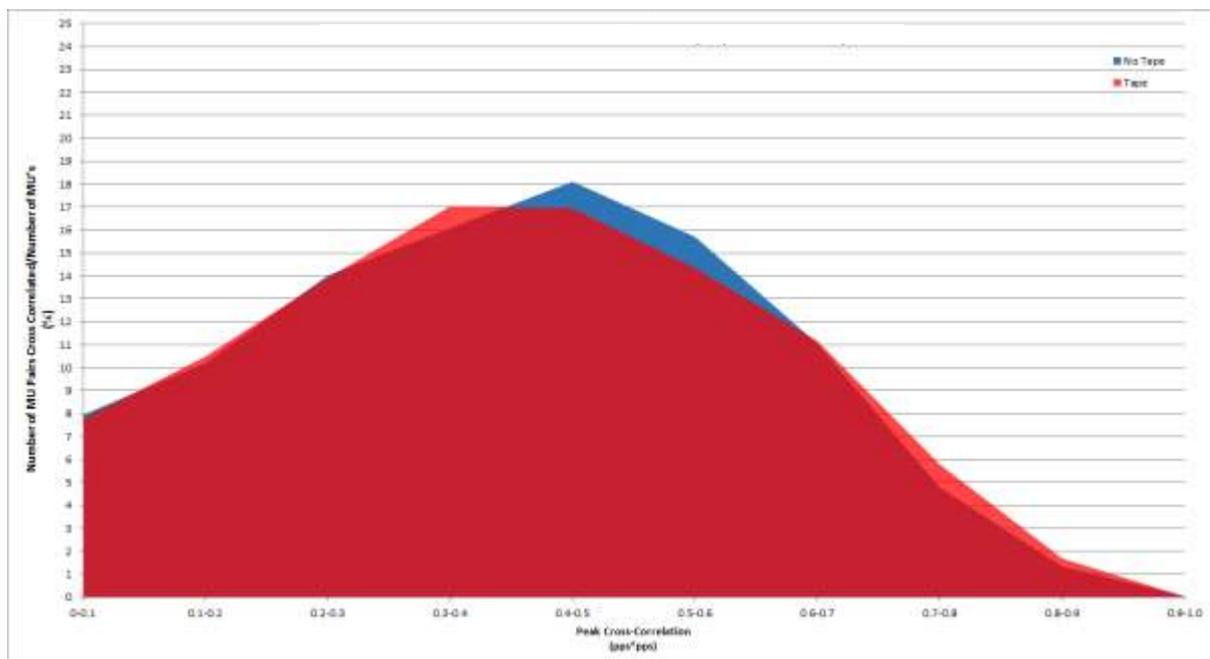
**Table 7-6 Grouped common drive results from the non-symptomatic subjects showing the median and inter-quartile range (25th and 75th percentile) for the two conditions in the two muscles.**

Common Drive	Vastus Medialis (IQR)		Vastus Lateralis (IQR)	
	No Tape	Tape	No Tape	Tape
Non-symptomatic Subjects	0.41 (0.25-0.55)	0.40 (0.25-0.56)	0.41 (0.26-0.55)	0.41 (0.26-0.56)

Figure 7-8 and Figure 7-9 present the normalised (section 4.5.7) cross-correlation data for the Vastus Medialis and Vastus Lateralis respectively, with each figure showing the two conditions. Figure 7-8 shows the grouped non-symptomatic subjects cross-correlation results from the Vastus Medialis and presents the marginal reduction in common drive as shown in Table 7-6 with the peak cross-correlation being shifted to the left in the tape condition.



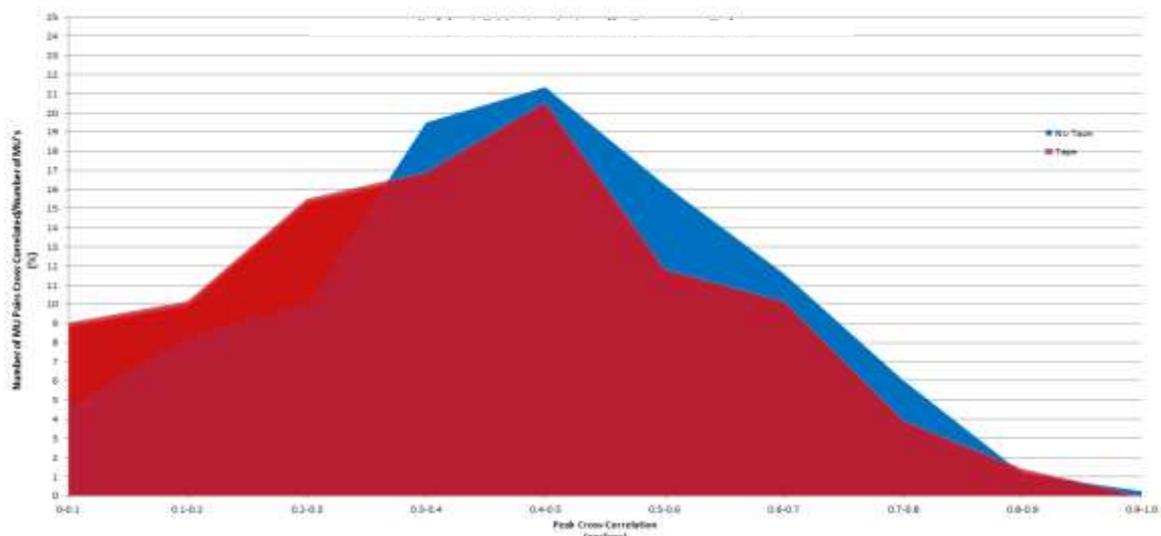
**Figure 7-8 Cross-correlation data from grouped non-symptomatic subjects in the Vastus Lateralis in the two different conditions.**



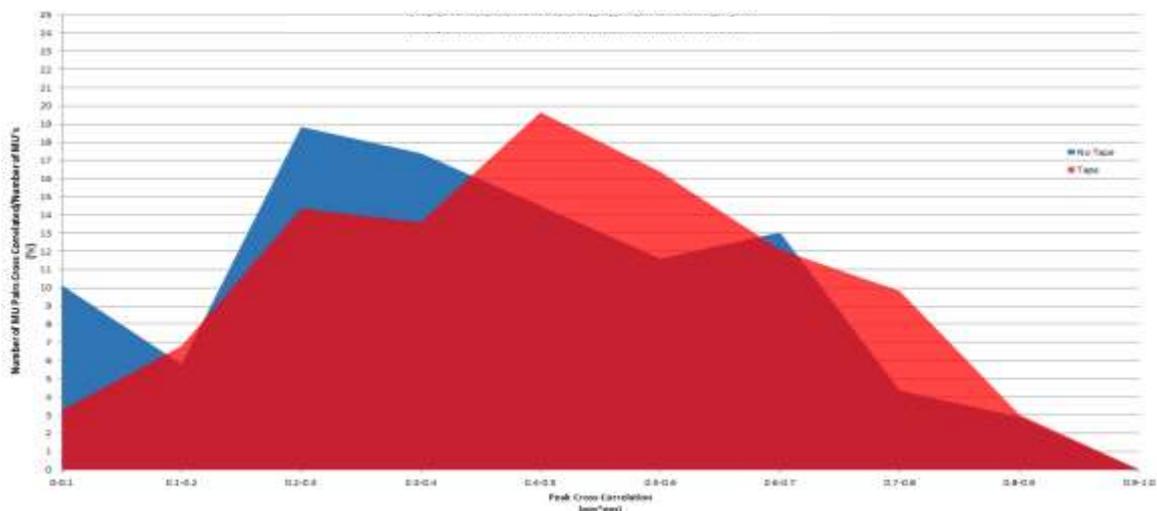
**Figure 7-9 Cross-correlation data from grouped non-symptomatic subjects in the Vastus Medialis in the two different conditions.**

### 7.5.2 Individual Analyses

Further exploration of the common drive in individuals were undertaken by extracting the median and IQRs from SPSS, for each of the non-symptomatic subjects. The results (see appendix 12.1.5) show that different subjects have differing strategies and responses to the taping condition. For example subject 12 exhibited a 0.07 increase in the cross-correlation function to the Vastus Medialis in the taping condition, representing an 18% increase in common drive (Figure 7-11). However, subject 9 did not exhibit any changes in the Vastus Medialis but instead demonstrated a 0.05 decrease in cross-correlation function in the Vastus Lateralis, representing an 11.4% decrease in common drive (Figure 7-10).



**Figure 7-10** Example of a decrease in common drive in tape condition (red) compared to no tape (blue) in the Vastus Lateralis



**Figure 7-11** Example of an increase in common drive in tape condition (red) compared to no tape (blue) in the Vastus Medialis

## 7.6 Recruitment Threshold

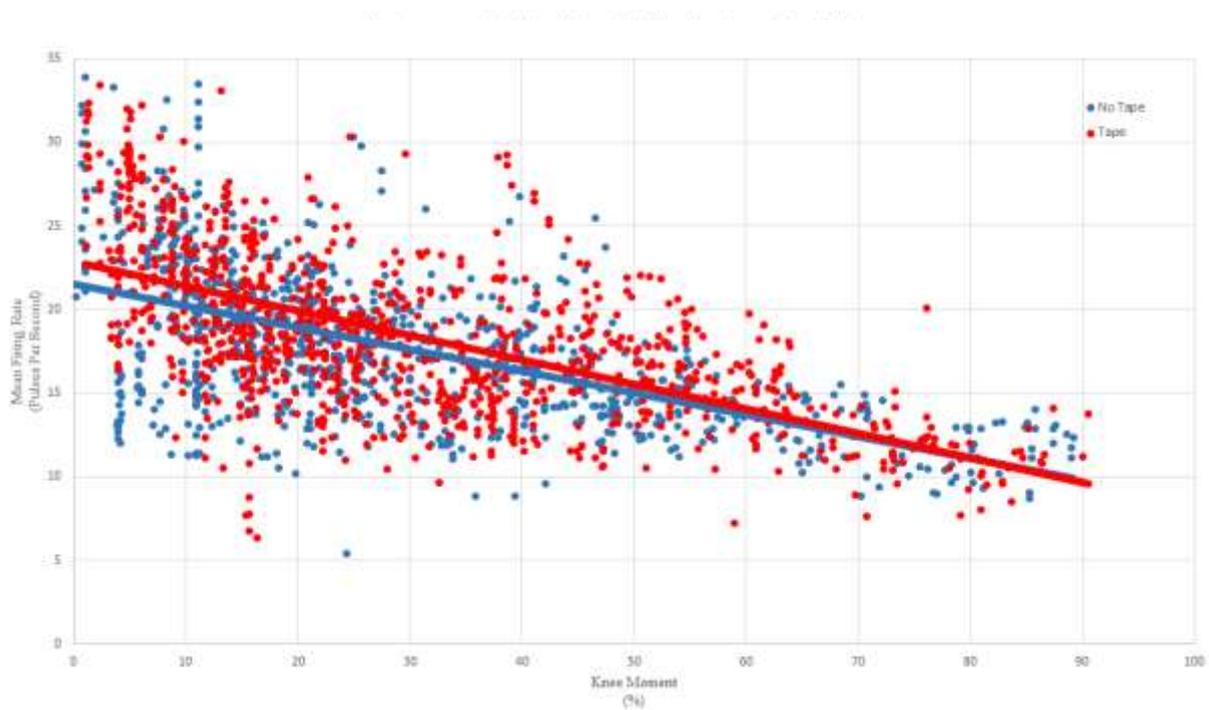
To calculate the recruitment threshold, the excitation point of the muscle at which the motor unit becomes active, the first firing of each motor unit was found and the corresponding MVC percent of the peak knee moment was established. The MUAT calculation script within EMGworks Analysis was used to calculate the recruitment threshold for each motor unit for all subjects. The recruitment threshold of each motor unit and the motor unit mean firing rate were extracted from EMGworks Analysis and a linear regression was performed within SPSS with the recruitment threshold being the independent variable and mean firing rate as the dependent variable. The linear regression will provide information on the recruitment strategy of the muscle and its response to the taping intervention.

### 7.6.1 Grouped Analyses

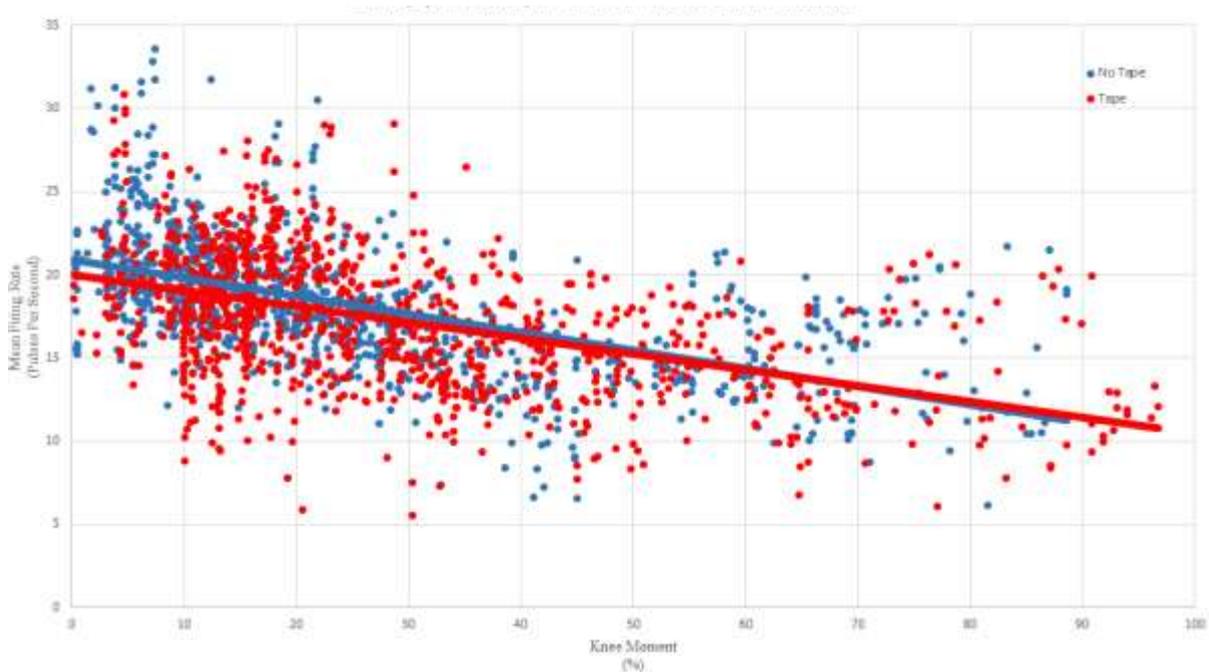
The regressed recruitment threshold and mean firing rate data from all non-symptomatic subjects were calculated. The R Squared for both muscles were computed showing values of 0.37 and 0.51 for the Vastus Medialis and Vastus Lateralis respectively showing that the recruitment threshold of motor units were inversely related to the mean firing rate as seen in previous work (De Luca & Hostage 2010). The intercept and slope results can be seen in Table 7-7 for the grouped non-symptomatic subjects. The results show that the Vastus Medialis intercept point significantly increases in response to the tape condition (Figure 7-12). The Vastus Medialis slope gradient is consequently also significantly different displaying a steeper slope gradient. Although these results demonstrate a statistical change in response to tape the mean firing rate intercept only exhibited a 1.4pps change and the clinical significance of this should be considered and whether this would offer a significantly different strategy. Whereas the Vastus Lateralis exhibited no significant difference in the intercept point or the slope gradient (Figure 7-13). These results offer the first evidence to suggest that a taping intervention may significantly alter the recruitment strategy of the Vastus Medialis, but the clinical significance needs to be considered.

**Table 7-7 Recruitment threshold results from the symptomatic subjects showing the Vastus Medialis and Vastus Lateralis in the tape and no tape condition**

Recruitment Threshold Non-symptomatic Subjects	Vastus Medialis			Vastus Lateralis		
	No Tape	Tape	p-Value	No Tape	Tape	p-Value
Intercept (pps)	21.5	22.9	<0.0001	20.9	20.0	0.18
Slope (Gradient)	-0.13	-0.15	0.05	-0.11	-0.10	0.07



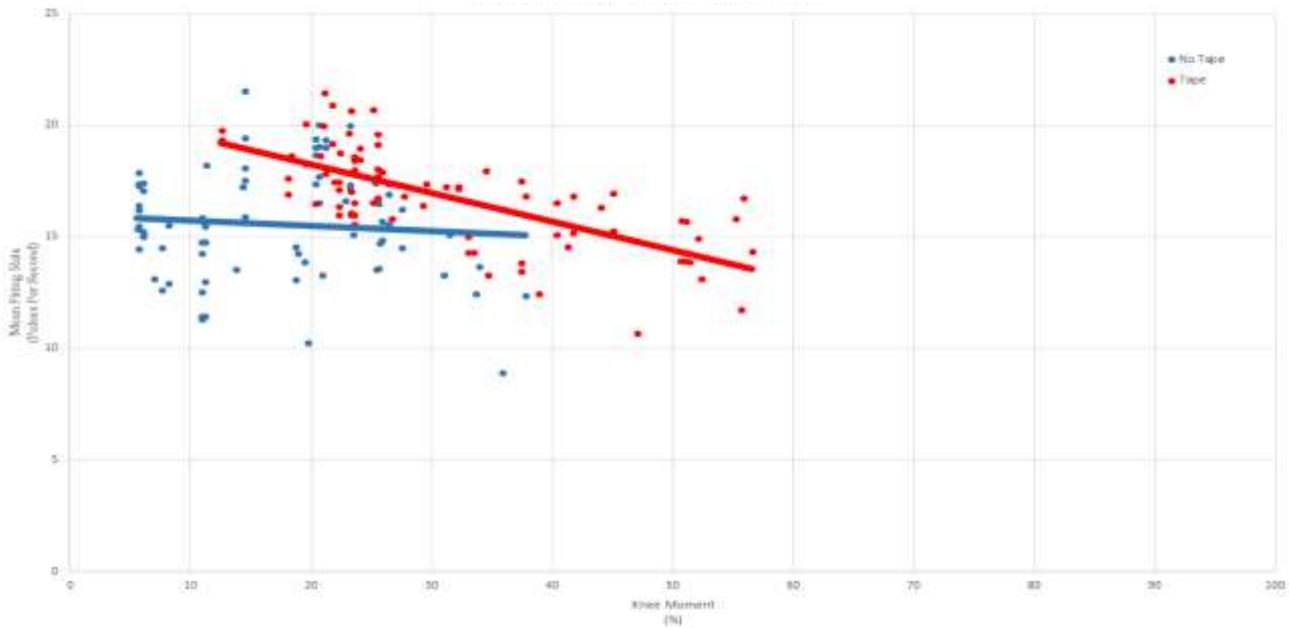
**Figure 7-12 Regression plot of the Vastus Medialis from the non-symptomatic subjects, showing the recruitment threshold differences between no tape (blue) and tape (red)**



**Figure 7-13 Regression plot of the Vastus Lateralis from the non-symptomatic subjects, showing the recruitment threshold differences between no tape (blue) and tape (red)**

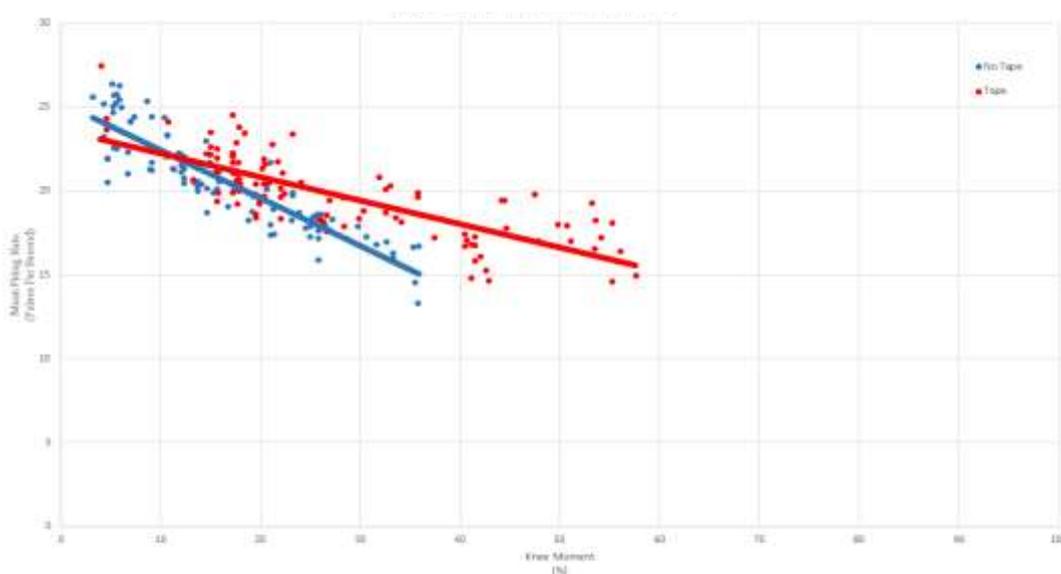
### 7.6.2 Individual Analyses

The results (see appendix 12.1.6) show that subjects responded to the tape condition with different strategies. For example subject 5 exhibited significant responses to tape in the Vastus Medialis, where the intercept was significantly higher ( $p < 0.0001$ ) by 4.9pps and the slope gradient significantly steeper ( $p = 0.002$ ) in the tape condition (Figure 7-14). Subject 5 also exhibited significant responses to the Vastus Lateralis (Figure 7-15) with a significantly reduced intercept ( $p < 0.0001$ ) by 1.6pps and significantly flatter slope gradient ( $p < 0.0001$ ). Subject 10 however showed a significantly flatter gradient slope ( $p = 0.01$ ) in the Vastus Medialis tape condition but the intercept point did not present any significant changes ( $p = 0.068$ ).

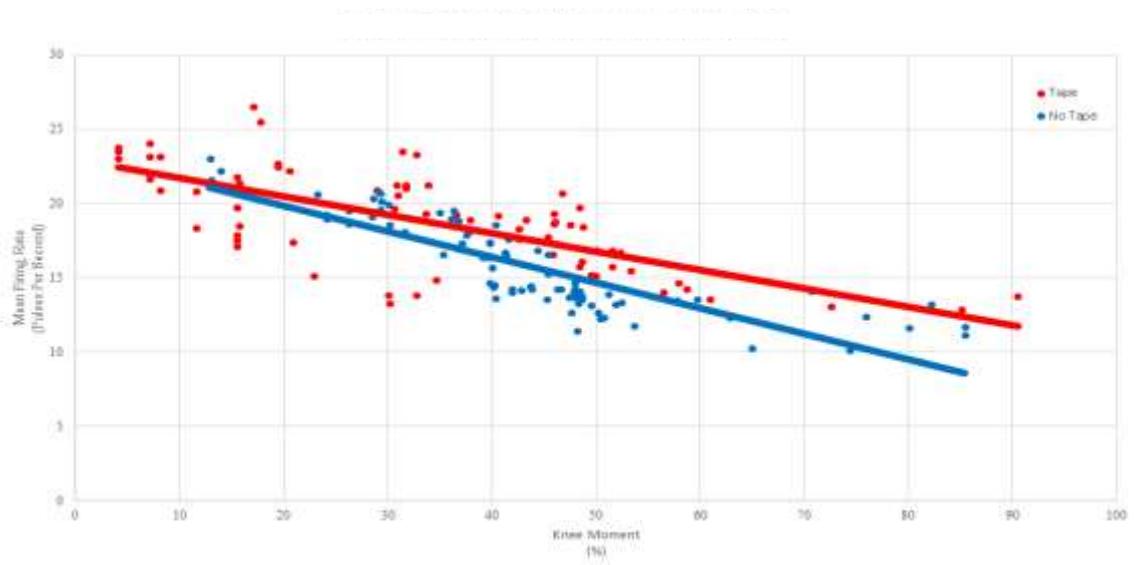


**Figure 7-14** An example of the Vastus Medialis in an individual non-symptomatic subject, showing the recruitment threshold differences between no tape (blue) and tape (red)

However, this subject seemed to utilise a different recruitment strategy by recruiting motor units at an earlier level of excitation/force (Figure 7-16). Other subjects can be seen to make no significant changes in either the recruitment intercept or slope in either muscles. These results present the opportunity for subjects to utilise different recruitment strategies, offering the first insight into how muscles can alter the recruitment in response to a taping intervention.



**Figure 7-15** An example of the Vastus Lateralis in an individual non-symptomatic subject, showing the recruitment threshold differences between no tape (blue) and tape (red)



**Figure 7-16** An example of the Vastus Medialis in an individual non-symptomatic subject, showing the recruitment threshold differences between no tape (blue) and tape (red)

## 7.7 Recruitment Operating Point

The recruitment operating point is defined as the force/knee moment point when the first motor unit in the contraction is recruited. The recruitment operating point for each contraction was extracted from the recruitment threshold calculation and were averaged, providing an average excitation point for the tape and no condition for the Vastus Medialis and Vastus Lateralis.

### 7.7.1 Grouped Analyses

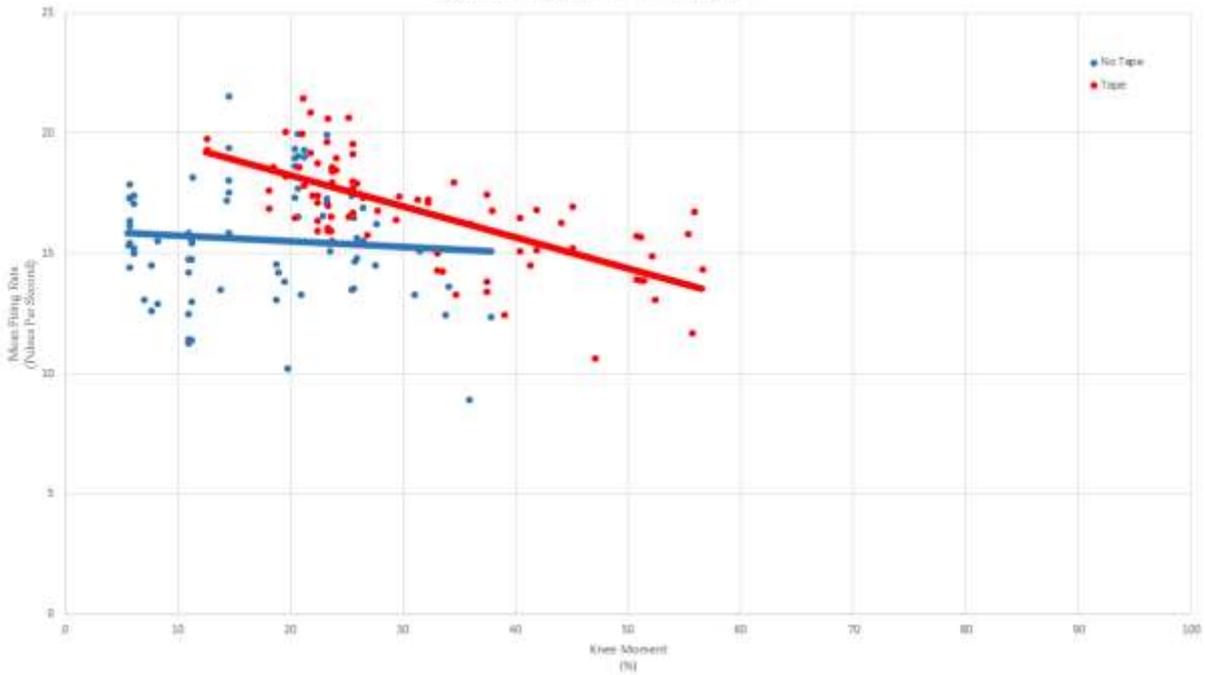
A paired samples t-test was performed on the average excitation point for the Vastus Medialis and Vastus Lateralis in the tape and no condition. No significant differences were found between the tape and no condition for each of the Vasti muscles (Table 7-8). Although no significant differences were found there seems to be a trend to require additional force to recruit the motor units in both the Vastus Medialis and Vastus Lateralis in the tape condition.

**Table 7-8 Descriptive statistics for the grouped recruitment operating point from the non-symptomatic subjects.**

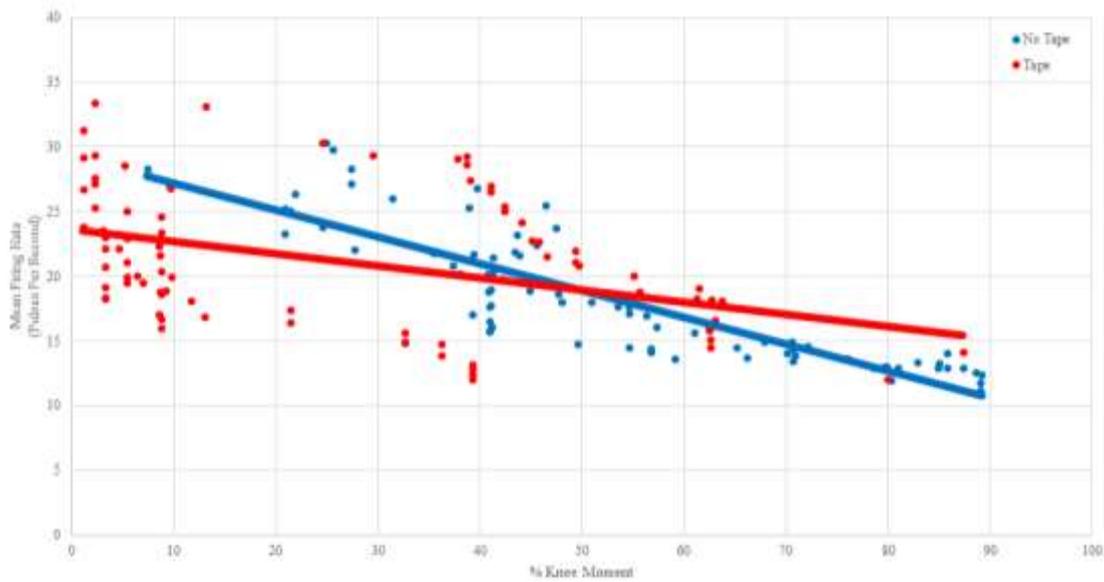
Recruitment Operating Point (% Knee Moment)	No Tape	Tape
	Mean (SD)	Mean (SD)
Symptomatic Subjects		
Vastus Medialis	8.9 (5.3)	10.2 (4.4)
Vastus Lateralis	7.5 (4.3)	8.1 (2.7)

### 7.7.2 Individual Analyses

The recruitment operating point results from each of the non-symptomatic subjects (appendix 12.1.7) show, as with the recruitment threshold results, that there is a non-uniform response to the tape intervention. Subjects seem to be presenting with differing responses to the tape condition, where some subjects present with a strategy to recruit the motor unit pool requiring less force/excitation (subject 9 for example, Figure 7-18). Conversely, some subjects can be seen to present with a strategy to require additional force/excitation to recruit the motor unit pool (Subject 5 for example, Figure 7-17). These findings, for the first time, show that the motor unit pool recruitment can be modified in relation to the respective joint moment, providing key information on recruitment strategies and consequent motor unit control in response to a therapeutic intervention.



**Figure 7-17** An example of a non-symptomatic subject Vastus Medialis requiring additional force/excitation in the tape condition (red) compared to the no tape condition (blue)



**Figure 7-18** An example of a non-symptomatic subject Vastus Medialis requiring less force/excitation in the tape condition (red) compared to the no tape condition (blue)

## 7.8 Traffic Light Results – Non-Symptomatic Subjects

Results from the non-symptomatic subjects clearly demonstrated that subjects exhibited different responses to the taping condition, which were variable across the different biomechanical and neuromuscular measures investigated. In order to explore relationships between the measured variables and their responses to the tape condition a results ‘traffic light’ table was created. The ‘traffic light’ results demonstrate increases (green), decreases (red) and no changes (amber) for the measured variables for individual non-symptomatic subjects (Figure 7-19). Each variable presents a value which represents the percentage change in the tape condition, apart from the recruitment threshold variable that presents whether a significant result in the regression slope was found. The threshold values used to represent an increase or decrease in each variable vary between the different variables. To the authors knowledge there are no publications using this method to explore individual relationships and strategies as most data is analysed in groups, therefore selection of the threshold values could not be guided by previous publication. As the single limb isometric squat task by definition would not reflect any gross movements the expected changes would be discrete in nature and the threshold percentages modestly reflected this with both 5%, 10% and 20% changes in the variables. Each variables threshold percentage is presented with the traffic light results table in Figure 7-19.

	Gender	Diff Change (20%)				Absolute % Change (5%)				Diff Change (5%)		Diff Change (10%)		SIG		Absolute % Change (5%)	
		Moment		Angle		sEMG				Common Drive		Mean Firing Rate		Slope **		Rec. Operating Point**	
		Coronal	Transverse*	Coronal	Transverse	GAS	BF	RF	GMed	VM	VL	VM	VL	VM*	VL	VM	VL
SUB_01	F	8.9	-24.1	-6.4	8.5	-16.1	-6.8	-4	-1.7	-8	0	13.8	1.1			0.6	2.3
SUB_02	M	-0.5	-17.2	12.2	-7.5	-0.5	-3.3	-2.3	-3.5	-9.3	-4.7	0.3	-7.5			-0.3	-3.2
SUB_03	M	5.9	8	18	-4	0.5	5.4	4.5	0.1	-8.7	-9.1	-5.4	-7.8			0.6	3.4
SUB_04	M	37.4	10.5	35.2	66		0.5	5.9	9.9	17.1	5.3	23.4	-8.7			7.8	2.9
SUB_05	F	-29.6	-23.3	-10.9	9.1		-1	-3	-4.7	-14.3	10.3	7.8	-4.4			9.6	5.6
SUB_06	M	33	4.7	-2.7	4.6	-1	-7.4	-4.9	-23	9.9	10.8	29	-3.8			4.9	-12.4
SUB_07	M	-10.9	-14.4	-20.2	-11.8	-6.3	-0.9	-3.8	-6.3	-2.7	-7.1	-2.3	10.4			3.1	-0.5
SUB_08	M	-21.8	-37.5	7.3	-5.6	9.7	1.8	3.2	-9.1	-2.4	27	-19.1	-15.7			-1.4	2.5
SUB_09	M	-18.1	-25.1	23.9	8.2					-1.3	-11.4	13.8	1.5			-10.4	5.6
SUB_10	M	-31.7	-37	-14.1	-30.1	20.7	-6.3	-6.2	-2.7	-9.3	0	18.8	-10.6			-5	-0.1
SUB_11	M	-8.7	-45	-4.8	28.9	-5.2	-4	-4.7	-15.1	-9.5	-2.5	-11.8	-6			-0.6	2.2
SUB_12	F	12.9	-11.1	4.1	19.3	-1.7	4.6	5.8	4	18	4.9	16.2	8.7			4.4	-2.8
SUB_13	F	-11.5	-26.9	16.5	-3.9	-3.4	-8.2	-4.4	-5.7	5.9	8.8	-8.8	-3.6			2.1	1.8

\* Significant results from grouped analyses

\*\* From recruitment threshold calculation

Figure 7-19 'Traffic Light' results for non-symptomatic subjects

## 7.9 Results Summary – Non-Symptomatic Subjects

### 7.9.1 Knee Joint Biomechanics Summary

- Grouped analyses of the transverse plane range of moment exhibited a significant decrease in response to the taping condition. No significant changes were found in the transverse plane range of motion.
- Grouped analyses of the coronal plane range of moment and angle did not present any significant responses to the tape.
- The coronal plane mean knee moment and mean knee angle did demonstrate significant changes, but with marginal mean differences and large standard deviations the results should be contextualised with clinical meaning in mind, where 0.45 degrees is unlikely to provide any impact, especially with the observed non-uniformity in the response when looking at individual subjects.
- Individual analyses of subjects provided evidence of a non-uniform response with mean differences exhibiting changes within coronal and transverse range of moment and range of motion, some increasing and others decreasing.

### 7.9.2 Surface EMG Summary

- Grouped analyses did not present any significant changes in muscle activity in Gastrocnemius, Bicep Femoris, Rectus Femoris or Gluteus Medius.
- The grouped analysis did highlight that there may be large variability in muscle activity and its response to tape with the large standard deviations reported.
- Individual analyses of each subject provided further evidence of inter-subject variability with mean differences exhibiting changes within all muscles in differing directions and magnitudes.

### 7.9.3 Mean Firing Rate Summary

- Grouped analysis of the non-symptomatic subjects showed marginal responses to the tape with a 4.5% increase in the Vastus Medialis and a 3.3% decrease in MFR to the Vastus Lateralis. The parametric analyses did not exhibit any statistical significant differences.
- Individual analyses showed large inter-subject variability with the responses or lack of to the taping condition. Some individuals Vastus Medialis increasing MFR whilst others lacked any response to tape.
- If results are analysed within a group then subtle strategies and responses may not be exposed as the data is pooled together masking individuals unique responses, when viewing as individual responses it is apparent that large modifications can be seen in response to tape either increasing or decreasing their MFR

### 7.9.4 Common Drive Summary

- Grouped analysis of the non-symptomatic subjects showed that the common drive to the Vastus Medialis exhibited a marginal 2.4% reduction with the Vastus Lateralis not exhibiting any response to the taping condition.
- Analyses of individual subjects showed that there are differing responses and strategies of motor unit control through the common drive of the Vasti muscles, which are seemingly masked during grouped analyses.
- Grouping the cross-correlation results may mask the unique common drive strategies individuals present in response to the tape condition.

### 7.9.5 Recruitment Summary

- Grouped analyses exhibited significant changes in the recruitment gradient and intercept point for the VM muscle, thus suggesting that tape may alter the recruitment strategy of motor unit pool. However, the mean differences of 1.4pps questions the clinical significance of such a change.

- As with other results the individual analyses demonstrated that there seems to be different strategies and responses to the tape intervention, where subjects demonstrated surprisingly difference strategies. This then questions the grouped data significant results.
- Another key finding is that subjects present with a never seen before strategy where with the application of tape either additional or less excitation/force is required in order to recruit the motor unit pool.
- The motor unit recruitment results suggest that the recruitment strategy can be altered with the application of tape in non-symptomatic subjects, and altered using different strategies, which have not previously been shown.

#### 7.9.6 Implications for Symptomatic Study

The results from the non-symptomatic study show that there are key changes to the joint kinetics and kinematics in response to the taping condition, that has previously been shown (Selfe et al. 2008; Selfe et al. 2011), but also that they can offer different responses amongst subjects, which has not previously been considered. It was also clear that there are significant and new changes to the motor unit pool and its control, with the application of the tape, suggesting altered force production and control of the Vasti muscles. These findings offer tantalizing potential in understanding how a patient population may present with their motor unit control and joint control strategies. Perhaps more interestingly it may offer insight into how the relationship between these variables and their response to a previously misunderstood clinical intervention.

## **8. Method - Symptomatic Subjects**

### **8.1 Introduction**

This chapter provides the pertinent information relating to the symptomatic subjects data collection methods and procedures.

### **8.2 Symptomatic Subjects**

Subjects were recruited from a population of staff and students at the University of Central Lancashire (UCLan) and patients attending the Lancashire Teaching Hospitals NHS Foundation Trust. Subjects were provided with a 'Patient Information Sheet' prior to attending any testing session, the patient information sheet provided study information and what was expected of them (see appendix 12.2). ). Based on previous study by Selfe et al. (2008) who investigating the effect of proprioceptive bracing on biomechanical parameters, mean differences were greater than the standard deviations. The knee transverse plane range of moment yielded a mean difference 0.035 Nm/kg with a standard deviation of 0.03 Nm/kg during a step-down task. A statistical power calculation yields that with an 80% statistical power and a significance level of 5% the sample size needs 12 subjects to detect any significant changes in the biomechanical parameters to be investigated. Patellofemoral Pain subjects (n=15) were enrolled onto the study, with two subjects omitted from the results due to poor data quality (see appendix 12.1.1 for details), leaving thirteen patellofemoral pain subjects for data processing (5 females and 8 males, age 25.2 years (SD 4 years), mean weight 71.4 kg (SD 12.9 kg)).

### **8.3 Ethical Approval**

The study was approved by the Built Sport Health (BuSH) ethics committee, University of Central Lancashire (Proposal no. 149) for data collection on symptomatic staff and students at the university (see appendix 12.5.2). The study was also approved by National Research Ethics Service (NRES) committee North West (REC reference: 13/NW/0405) for data collection on patients attending Lancashire Teaching Hospitals NHS Foundation Trust, for which NHS Research and Development permission was granted (PIC reference: 017). Prior to data collection written informed consent (see appendix 12.3) was gained from all subjects.

## 8.4 Recruitment Criteria

The complex and multifactorial aetiology of Patellofemoral Pain makes examination and diagnosis difficult, which consequently creates challenges to the researcher in including a 'true PFP' homogenous group to study. However, research has shown that using multiple clinical and functional tests can assist in diagnosing PFP (Haim et al. 2006; Nijs et al. 2006; Cook et al. 2010). The study used a strict and peer-reviewed inclusion and exclusion criteria that was enforced by the researcher, whom is a trained clinician, to ensure a homogenous group were enrolled onto the study.

### 8.4.1 Inclusion Criteria

The inclusion criteria of symptomatic subjects being eligible to participate in the study is based upon Cowan et al. (2002), Syme et al. (2009), Cook et al. (2010), for which can be seen listed below:

- Males and Females to be included
- Age Range 18-40 years old
- Anterior or Retropatellar pain reported on at least 2 of the following activities: Prolonged sitting, ascending or descending stairs, squatting, kneeling, running and hopping/jumping
- In addition to the above, at least 2 of the following clinical examination findings: Pain during resisted quadriceps contraction (static and/or dynamic), Pain during palpation of medial and/or lateral facets of patella, Pain during squatting, Pain during step ascent and/or descent.
- Unilateral or Bilateral Patellofemoral Pain longer than 3 months
- Able to hold a static squat position for at least 8 seconds

### 8.4.2 Exclusion Criteria

The exclusion criteria of symptomatic subjects being unable to participate in the study is based upon Cowan et al. (2002), Syme et al. (2009), Cook et al. (2010), for which can be seen below:

- Recent knee surgery or trauma (within 3 months)
- Ligamentous instability and/or internal derangement (Subjects should be referred for arthroscopy or Magnetic Resonance Imaging (Acton & Craig 2000))
- History of patella subluxation or dislocation

- Confirmed osteoarthritis of tibiofemoral and/or patellofemoral joints
- Joint effusion when the mid-patellar girth is 5% or more than the non-involved knee
- True knee joint locking and/or giving way
- Co-existent acute illness or chronic disease
- Bursitis, patella or iliotibial tract tendinopathy, Osgood Schlatter's disease, Sinding-Larsen Johansson Syndrome, muscle tears or symptomatic knee plicae
- Pregnant or breast feeding

### 8.5 Data Collection

Testing of the symptomatic subjects mimicked the testing of the non-symptomatic subjects and used the same data collection procedures (see section 6.5). The symptomatic subject testing also included additional recordings to understand the clinical presentation, namely the use of the Movement Specific Reinvestment Scale (MSRS) and the Numerical Rating Scale (NRS) (see appendix 12.4). The MSRS and NRS were completed by subjects prior to any other data collection measurements to ensure their responses were not affected by the testing protocols.

## 9. Results – Symptomatic Subjects

### 9.1 Overview

As with the investigations of the non-symptomatic subjects a host of differing neurophysiological and biomechanical variables were investigated with the symptomatic subjects, with the addition of clinical measures. Figure 9-1 shows a graphical representation of these measures. Details of each parameter and their respective findings can be seen in the following chapter for both grouped and individual analyses.



**Figure 9-1 Graphical representation of the variables investigated in PFP group**

### 9.2 Knee Joint Biomechanics

In order to investigate the mechanical control of the knee joint kinematic and kinetic data were calculated and extracted for the three planes of movement. For the sagittal plane the mean moment (Nm/kg) and mean angle (degrees) from the constant force region were extracted to provide information on the position of the squat position between the two conditions. Investigations into the coronal and transverse planes of mechanics explored the range of moment (Nm/kg) and range of motion (degrees) from within the constant force region.

## 9.2.1 Grouped Analyses

### 9.2.1.1 Sagittal Plane

A paired samples t-test was performed on the sagittal plane mean knee joint moment and the sagittal plane mean knee joint angle. The results showed no significant differences between the two conditions for the mean moment ( $p=0.40$ ) but interestingly the mean angle exhibited a significant change ( $p=0.01$ ). Descriptive statistics of the mean moment and angle can be seen in Table 9-1. As the mean knee moment did not exhibit any change in response to the tape it infers that any change or differences seen in other variables is not due to different load through the knee.

**Table 9-1 Sagittal plane knee joint moment and angle descriptive statistics**

Sagittal Plane Symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	1.18 (0.21)	1.15 (0.23)	0.027	-0.04 to 0.09	0.40
Mean Angle (Degrees)	57.11 (8.66)	53.12 (8.12)	3.98	1.34 to 6.63	0.01

### 9.2.1.2 Coronal Plane

A paired samples t-test was conducted on the coronal plane range of moment and range of motion. Results did not indicate any significant differences between the two conditions for range of moment, mean moment, range of motion or the mean angle. Table 9-2 presents the descriptive statistics for the range of moment and range of motion for the coronal plane knee joint mechanics.

**Table 9-2 Coronal plane knee joint moment and angle descriptive statistics**

Coronal Plane Symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	-3.68 (13.11)	-4.07 (12.49)	0.39	-1.82 to 2.59	0.71
Range of Moment (Nm/kg)	0.12 (0.06)	0.11 (0.06)	-0.004	-0.02 to 0.01	0.59
Mean Angle (Degrees)	0.96 (4.86)	1.04 (4.77)	0.08	-0.82 to 0.66	0.82
Range of Angle (Degrees)	2.37 (0.93)	2.20 (0.78)	-0.167	-0.42 to 0.09	0.17

### 9.2.1.3 Transverse Plane

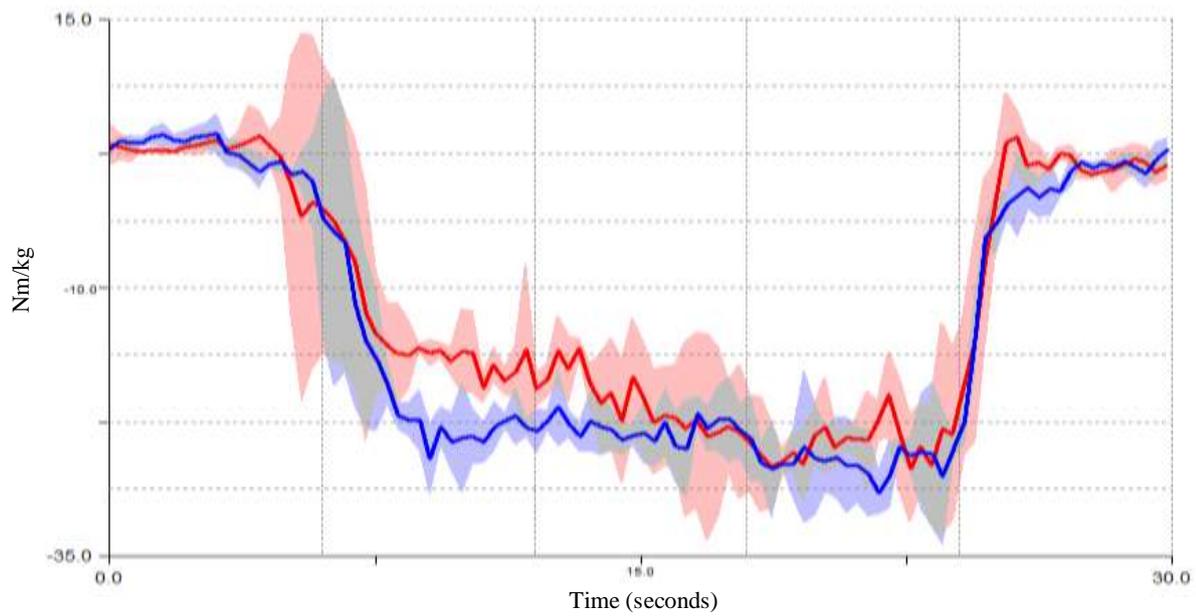
Paired samples t-test conducted on the transverse plane range of moment and range of motion showed that there was a significant decrease ( $p=0.03$ ) with the application of the tape. However, the mean moment, mean angle and range of motion for the transverse plane did not show any significance. Descriptive statistics of the transverse plane range of moment and range of motion can be seen in Table 9-3.

**Table 9-3 Transverse plane knee joint moment and angle descriptive statistics**

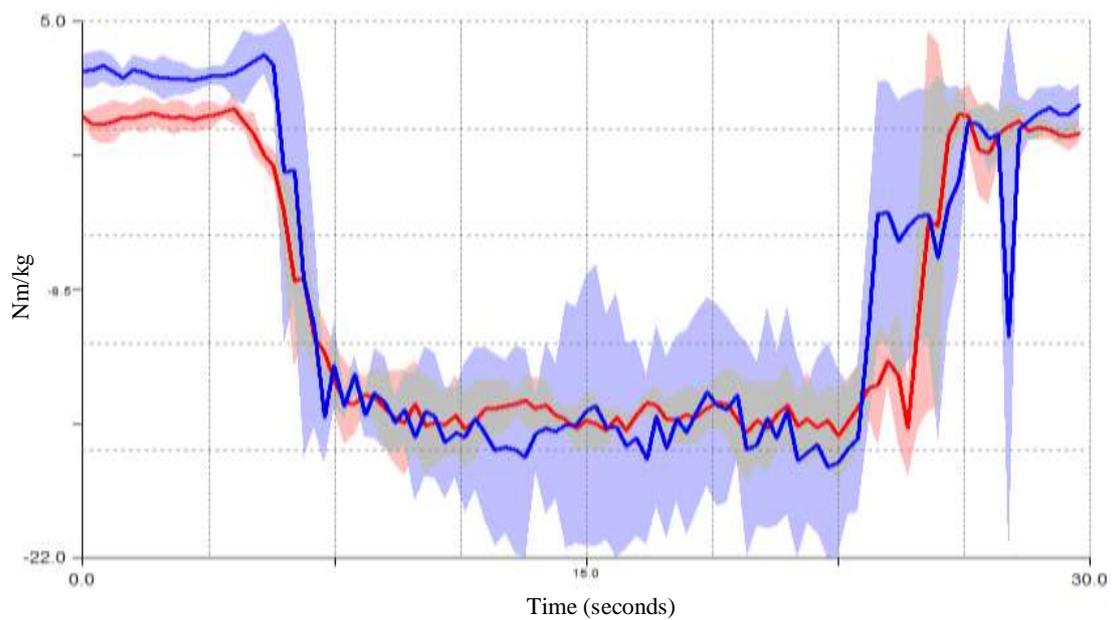
Transverse Plane Symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	0.77 (2.29)	0.54 (2.47)	0.23	-0.05 to 0.52	0.10
Range of Moment (Nm/kg)	0.07 (0.03)	0.06 (0.02)	-0.01	-0.02 to -0.001	0.03
Mean Angle (Degrees)	2.00 (6.99)	2.17 (6.53)	0.17	-1.23 to 0.89	0.73
Range of Angle (Degrees)	2.49 (0.78)	2.57 (1.04)	0.06	-0.39 to 0.54	0.72

### 9.2.2 Individual Analyses

The range of moment and range of motion with their respective standard deviations were reported (see appendix 12.1.2) for each subject in the tape and no tape conditions. The results demonstrated great inter-subject variability in the response to the tape condition, for example subject 4 exhibited a 64.1% increase in range of moment in the coronal plane in the tape condition (Figure 9-2). However, subject 11 conversely showed a 69.5% decrease in the coronal range of moment (Figure 9-3). The variability was also shown in the transverse planes range of moment.

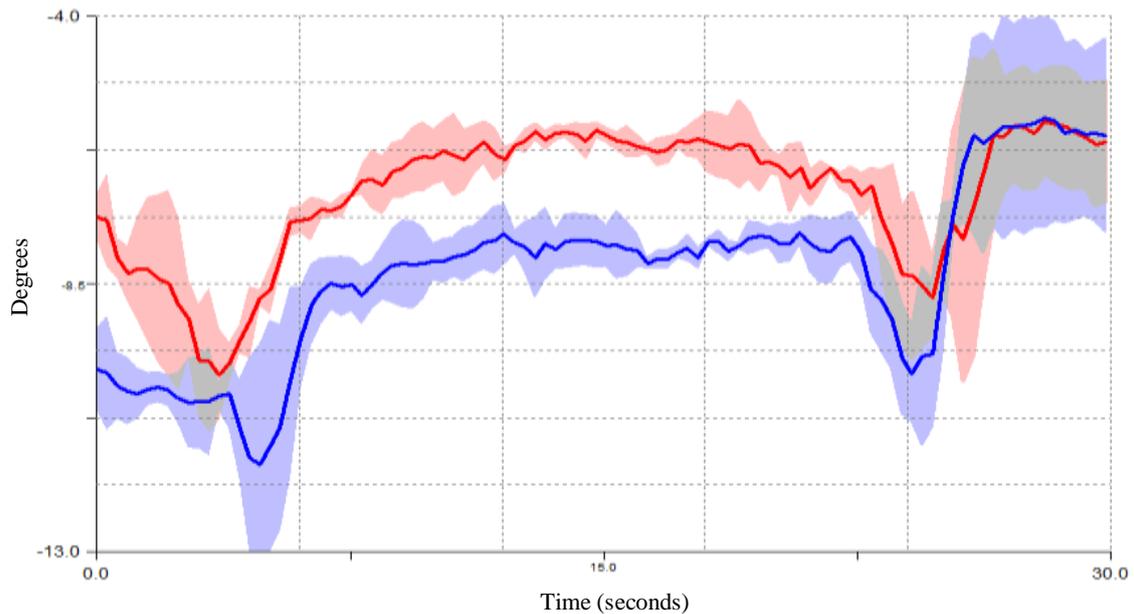


**Figure 9-2** Example of a subject increasing the range of moment in the coronal plane with the application of tape (red) compared to no tape (blue)

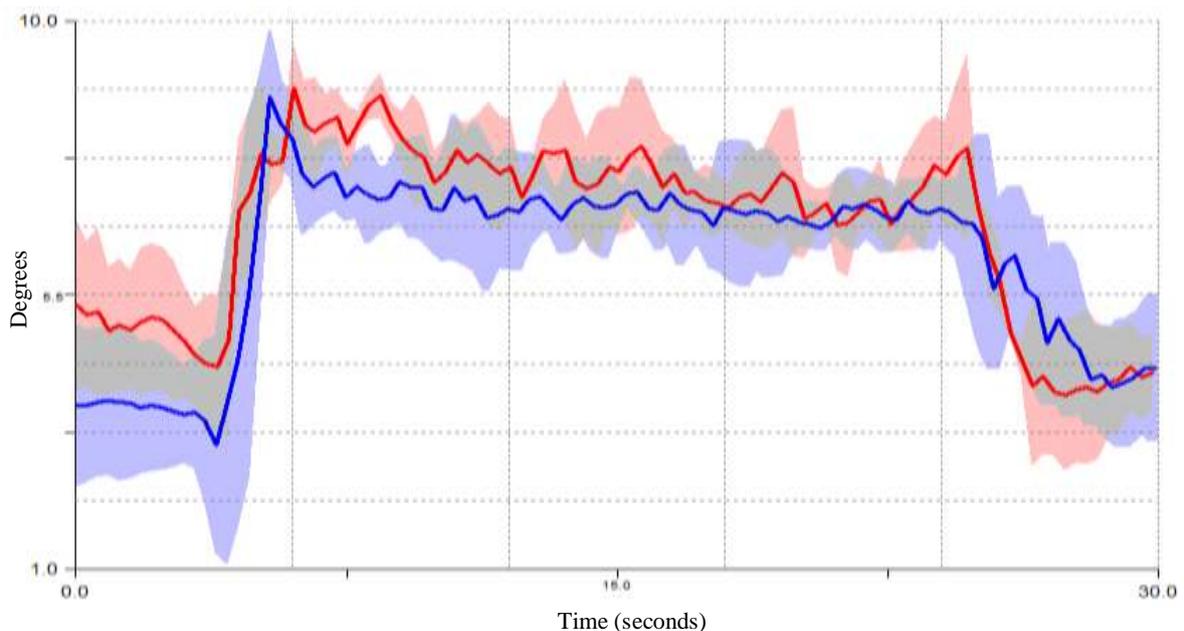


**Figure 9-3** Example of a subject decreasing the range of moment in the coronal plane with the application of tape (red) compared to no tape (blue)

Similar variability was also evident in the angular data with the range of motion demonstrating increase and decreases in response to tape, for example subject 6 showed a decrease of 37.4% in coronal plane range of motion (Figure 9-4), whereas subject 4 showed an increase of 61.7% in the coronal plane range of motion (Figure 9-5).



**Figure 9-4 Example of a subject decreasing the range of motion in the coronal plane with the application of tape (red) compared to no tape (blue)**



**Figure 9-5 Example of a subject increasing the range of motion in the coronal plane with the application of tape (red) compared to no tape (blue)**

### 9.3 Surface EMG

The normalised Root Mean Square (RMS) EMG data from the constant force region were extracted from EMGworks Analysis to quantify the muscle activity from the Gastrocnemius, Bicep Femoris, Rectus Femoris and Gluteus Medius.

#### 9.3.1 Grouped Analyses

A paired samples t-test conducted on the EMG data showed that the Biceps Femoris was the only muscle which presented significantly ( $p=0.03$ ) altered muscle activity following the taping intervention with a 2.2% reduction. The Gastrocnemius, Rectus Femoris and Gluteus Medius exhibited a non-significant response to the tape. Table 9-4 presents the mean EMG activity, standard deviation and p-value for the four muscles in the tape and no tape condition.

**Table 9-4 sEMG results from grouped analysis of the symptomatic subjects showing the mean EMG activity, standard deviation, mean difference, 95% confidence intervals and p-values.**

Mean Surface EMG Activity (% MVC) Symptomatic Subjects	No Tape	Tape	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Gastrocnemius	11.2 (5.7)	11.5 (5.9)	-0.33	-1.44 to 0.78	0.53
Bicep Femoris	17.7 (6.3)	15.5 (7.2)	2.19	0.24 to 4.15	0.03
Rectus Femoris	18.1 (6.5)	17.7 (4.7)	0.43	-2.13 to 2.99	0.72
Gluteus Medius	17.7 (3.9)	16.5 (4.2)	1.12	-0.42 to 2.66	0.14

### 9.3.2 Individual Analyses

The mean difference between the two conditions were calculated for each subject for all four muscles to investigate individuals' response to the tape condition. The results (see appendix 12.1.3) present that only marginal responses were found in the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius muscle activity in response to the tape condition. The results show differing responses, in magnitude and direction, to the taping intervention with the symptomatic subjects. For example PFP subject 12 showed an increase of 8.3% in their Rectus Femoris, whereas subject 4 decreased by 7.7%.

#### 9.4 Mean Firing Rate

The average MFR was entered into SPSS for descriptive analysis, extracting the mean, standard deviation and range for the tape and no tape condition in both Vasti. As the data was normally distributed the mean, standard deviation and ranges were reported. It was deemed inappropriate for the mean firing rate to be subjected to statistical analyses beyond descriptive analysis because the mean firing rate is a detailed and sensitive measure and computing statistical analyses may mask the subtle and intricate information it provides.

##### 9.4.1 Grouped Analyses

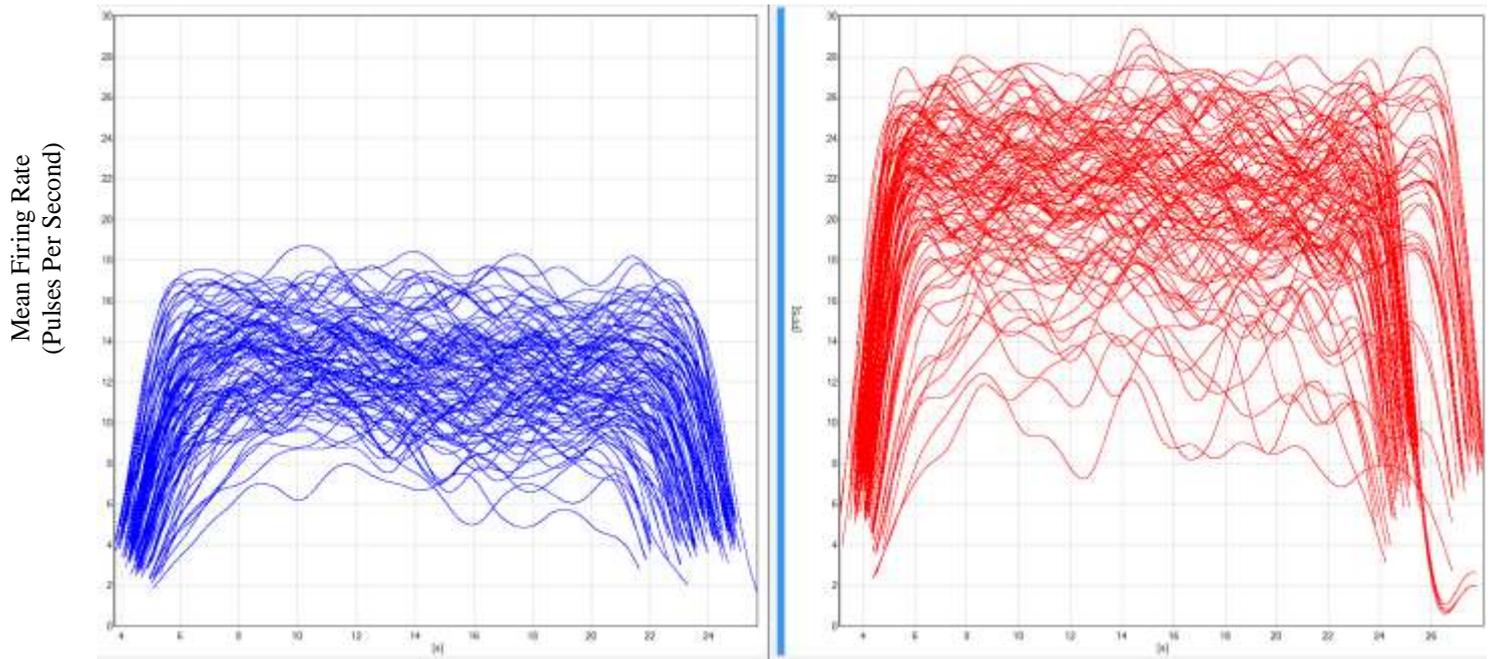
Grouped analysis of the symptomatic subjects showed similar results to the non-symptomatic subjects with marginal responses to the taping condition, as shown in Table 9-5. The Vastus Medialis showed an increase in the firing rate from 17.5 pps to 18.2 pps represented as a 4% change in response to tape. Although interestingly the maximum firing rate showed a 1.1 pps decrease whilst the average MFR increased. The Vastus Lateralis showed a reduction in firing rate of 0.6 pps, represented by a 3.2% decrease in response to tape.

**Table 9-5 Grouped analysis of all symptomatic subjects average MFR, standard deviations and MFR minimum and maximum values**

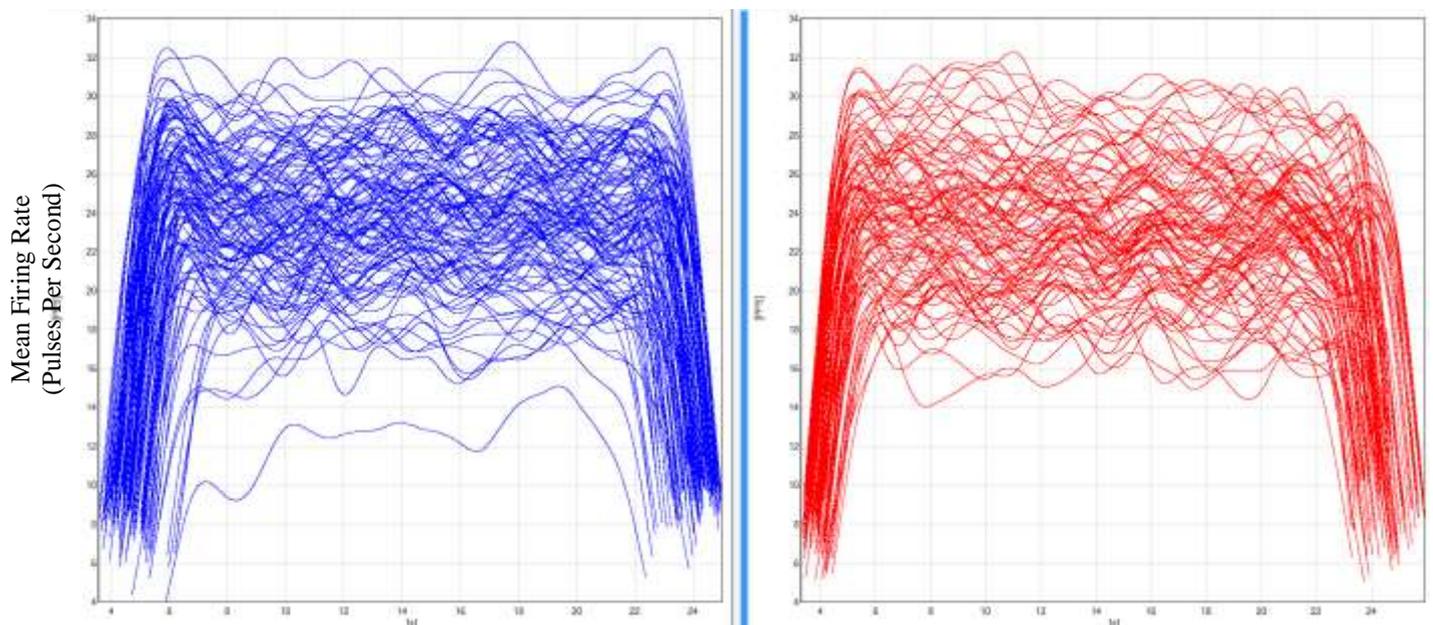
Mean Firing Rate Symptomatic Subjects	Average MFR (pps) (SD)	Mean Difference	Confidence Interval of the difference (95%)	Range MFR	p-Value
Vastus Medialis No Tape	17.5 (4.7)	0.72	-2.85 to 1.40	6.5 - 33.8	0.47
Vastus Medialis Tape	18.2 (4.9)			6.5 – 32.7	
Vastus Lateralis No Tape	18.9 (4.9)	0.51	-0.53 to 1.55	6.9 – 31.2	0.30
Vastus Lateralis Tape	18.3 (5.2)			7.3 – 32.7	

#### 9.4.2 Individual Analyses

The symptomatic subjects' data were analysed individually following the results of the grouped analysis. The average MFR and standard deviation values were extracted from SPSS (see appendix 12.1.4) for the tape and no tape conditions for the Vastus Medialis and Vastus Lateralis. Symptomatic subjects showed a non-uniform response to the taping condition with large increases or decreases in the motor unit firing rate for the Vastus Medialis and/or Vastus Lateralis. For example PFP subject 6 exhibited an increase of 8.9 pps in the Vastus Medialis in response to tape which is equivalent to a 72.3% change (Figure 9-6), however the Vastus Lateralis showed a marginal decrease of 0.4 pps. Although some subjects were showing exponential responses to the taping condition in altering their MFR others seemingly did not respond to the taping condition at all or at least marginally such as PFP subject 5 with only a 0.5 pps change in firing rate of either Vastus Medialis or Vastus Lateralis (Figure 9-7).



**Figure 9-6** An example of a subject whom increases the Vastus Medialis firing rate in the tape condition (red) compared to the no tape (blue)



**Figure 9-7** An example of a subject whom shows no change in the Vastus Lateralis firing rate in the tape condition (red) compared to the no tape (blue)

## 9.5 Common Drive

The Vastus Medialis and Vastus Lateralis peak cross-correlation values were extracted from EMGworks Analysis and entered into SPSS for each subject.

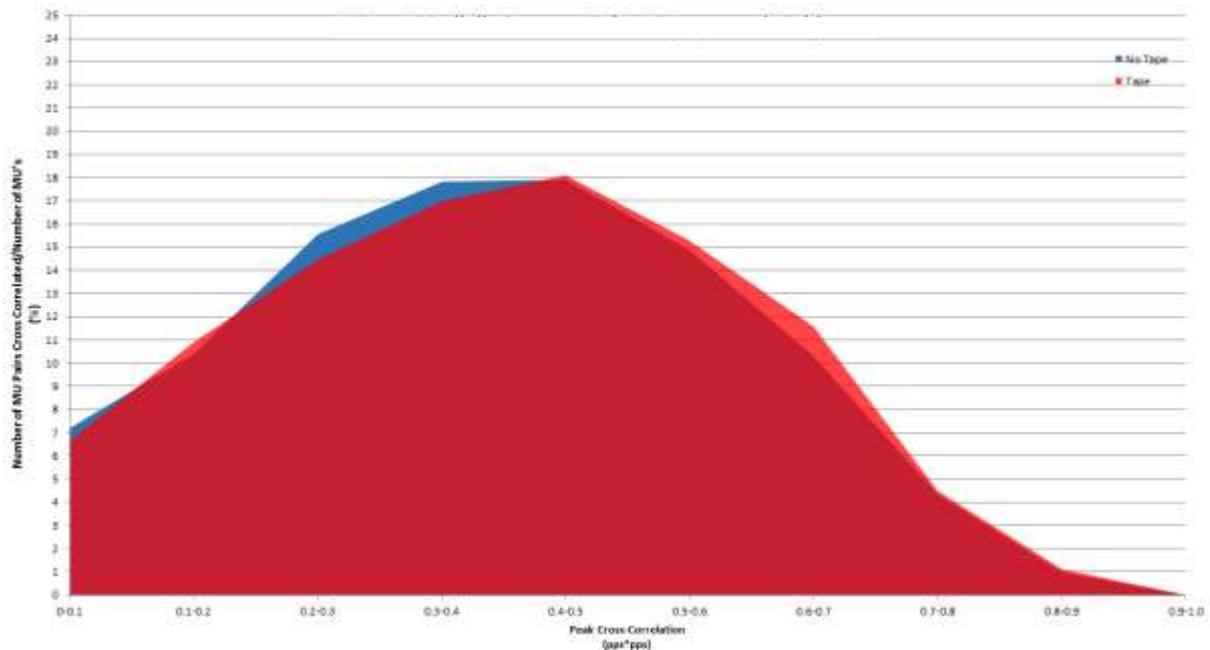
### 9.5.1 Grouped Analyses

Frequency statistics were used to calculate the median, inter-quartile range (IQRs), and the skewness of the data for the tape and no tape condition for the VM and VL. Table 9-6 shows the median and IQR (25<sup>th</sup> and 75<sup>th</sup> percentiles) values for each of the two conditions in the two muscles. The median cross-correlation results for the grouped PFP analysis show that the common drive increases (0.02) to the Vastus Medialis in the tape condition. Whilst the Vastus Medialis exhibits an increase in common drive the Vastus Lateralis cross-correlation results show a reduction (0.04) in common drive in the tape condition. These common drive changes can also be represented by a percentage change between the two conditions and are represented by a 5.1% increase and 9.1% decrease for the Vastus Medialis and Vastus Lateralis respectively.

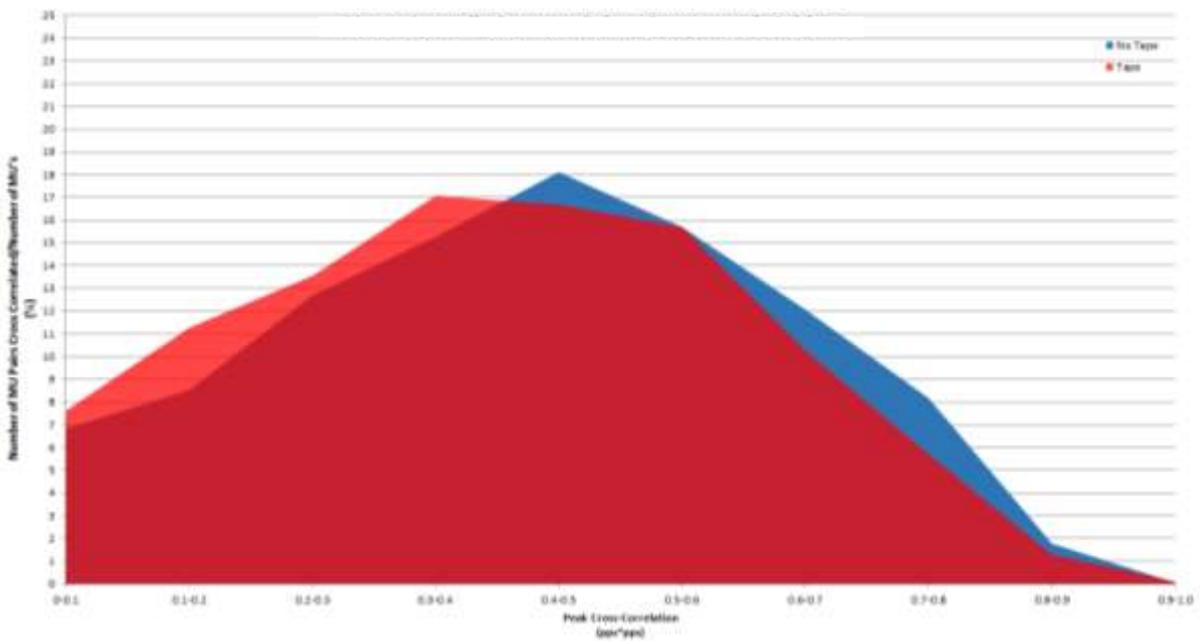
**Table 9-6 Grouped common drive results from the symptomatic subjects showing the median and inter-quartile range (25th and 75th percentile)**

Common Drive	Vastus Medialis (IQR)		Vastus Lateralis (IQR)	
	No Tape	Tape	No Tape	Tape
Symptomatic Subjects	0.39 (0.25-0.54)	0.41 (0.26-0.55)	0.44 (0.28-0.58)	0.40 (0.25-0.56)

Figure 9-8 and Figure 9-9 present the normalised cross-correlation data for the Vastus Medialis and Vastus Lateralis respectively, with each figure showing the two conditions. Figure 9-8 shows the grouped symptomatic subjects cross-correlation results from the Vastus Medialis and presents the increase in common drive as shown in Table 9-6 with the peak cross-correlation being shifted to the right in the tape condition. Figure 9-9 shows the grouped symptomatic subjects cross-correlation results from the Vastus Lateralis and presents the decrease in common drive as shown in Table 9-6 with the peak cross-correlation being shifted to the left in the tape condition.



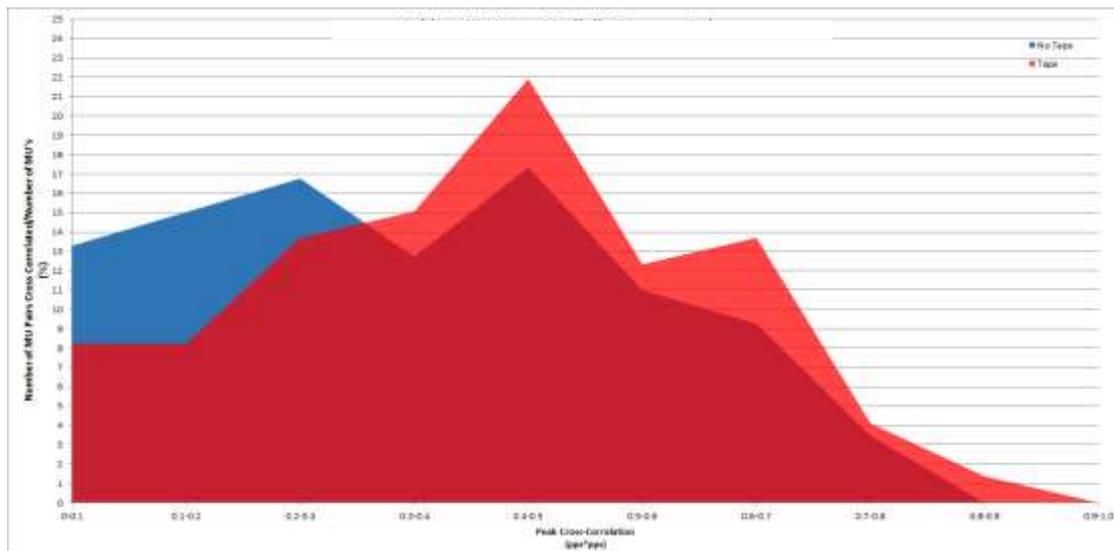
**Figure 9-8** Cross-correlation data from grouped symptomatic subjects in the Vastus Medialis in the two different conditions.



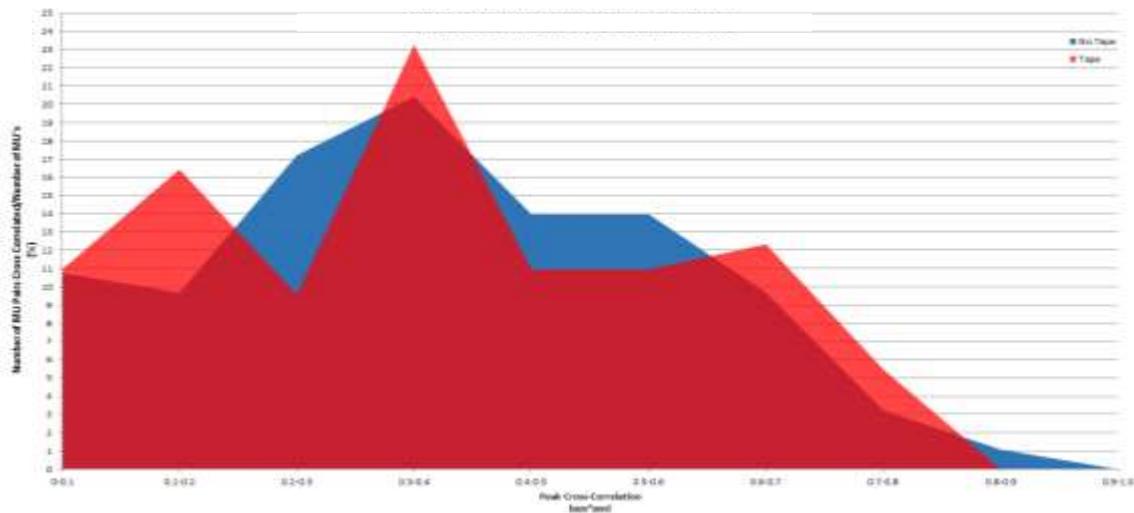
**Figure 9-9** Cross-correlation data from grouped symptomatic subjects in the Vastus Lateralis in the two different conditions.

### 9.5.2 Individual Analyses

As with the individual analysis of the non-symptomatic subjects, the median and IQRs were extracted for each PFP subject to explore the inter-subject variability. Similar to the non-symptomatic subjects' results (see appendix 12.1.5) the symptomatic subjects have different responses and strategies to the taping condition. For example, PFP 13 exhibited a 0.10 increase in the cross-correlation function to the Vastus Medialis in the taping condition, representing a 31.3% increase in common drive (Figure 9-10). Conversely, PFP 8 exhibited a 0.04 decrease in cross-correlation function in the Vastus Medialis, representing a 10.5% decrease in common drive (Figure 9-11).



**Figure 9-10** An example of a subject increasing the common drive to the Vastus Medialis



**Figure 9-11** An example of a subject decreasing the common drive to the Vastus Medialis

### 9.6 Recruitment Threshold

To calculate the recruitment threshold, the excitation point of the muscle at which the motor unit becomes active, the first firing of each motor unit was found and the corresponding MVC percent of the peak knee moment was established. The MUAT calculation script within EMGworks Analysis was used to calculate the recruitment threshold for each motor unit for all subjects. The recruitment threshold of each motor unit and the motor unit mean firing rate were extracted from EMGworks Analysis and a linear regression was performed within SPSS with the recruitment threshold being the independent variable and mean firing rate as the dependent variable. The linear regression will provide information on the recruitment strategy of the muscle and its response to the taping intervention.

#### 9.6.1 Grouped Analyses

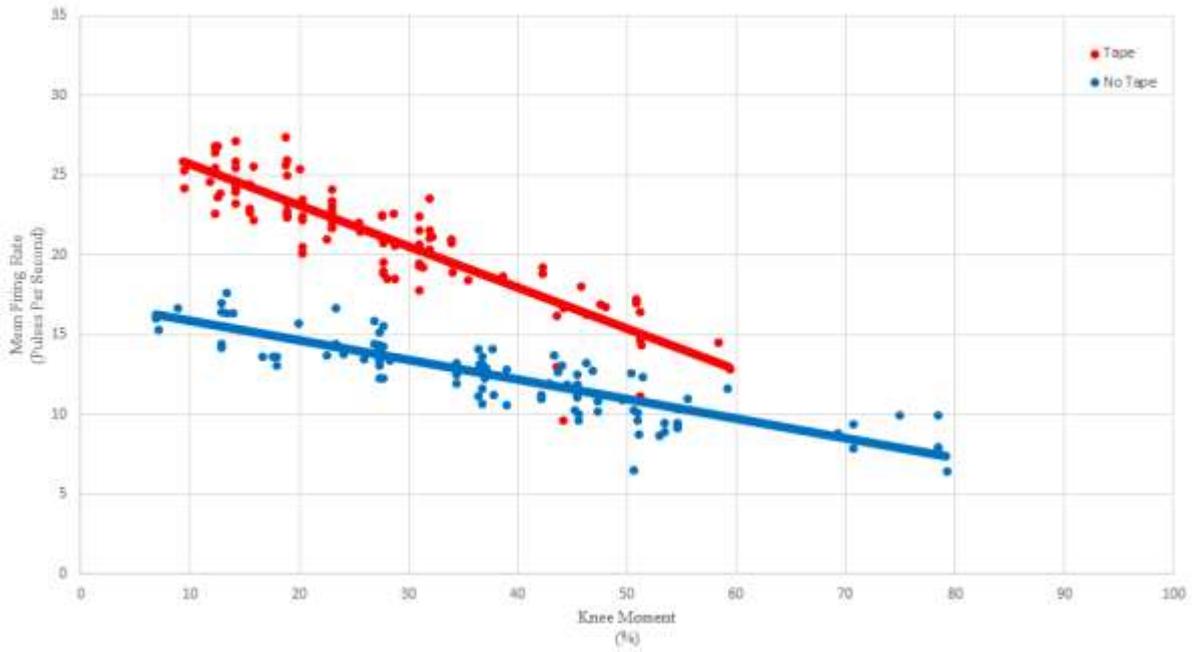
The R Squared results show that although the relationship between the recruitment threshold and the mean firing rate is still inversely related, although relatively weak with 0.11 and 0.10 for the Vastus Medialis and Vastus Lateralis respectively. The results for the slope and intercept with their respective significance values, as seen in Table 9-7, show that no significant differences can be identified in the grouped analysis.

**Table 9-7** Recruitment threshold results from the symptomatic subjects showing the intercept and slope values for the tape and no tape condition from the Vastus Medialis and Vastus Lateralis.

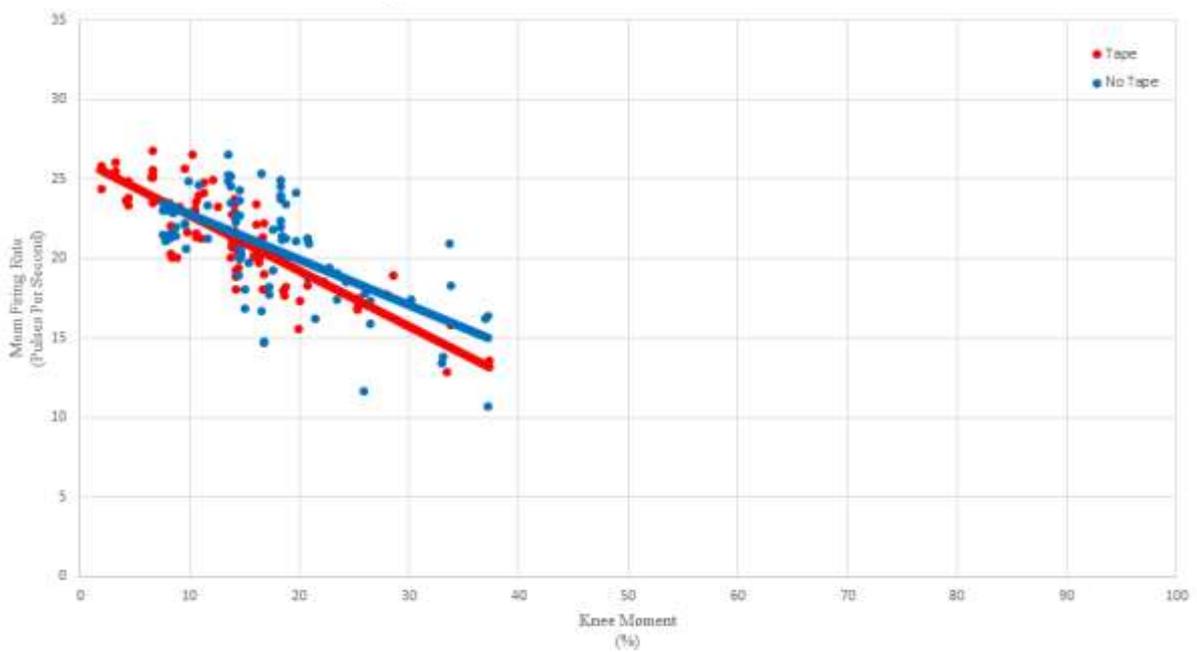
Recruitment Threshold Symptomatic Subjects	Vastus Medialis			Vastus Lateralis		
	No Tape	Tape	p-Value	No Tape	Tape	p-Value
Intercept (pps)	19.8	20.4	0.52	20.6	20.7	0.80
Slope (Gradient)	-0.06	-0.06	0.25	-0.06	-0.05	0.23

### 9.6.2 Individual Analyses

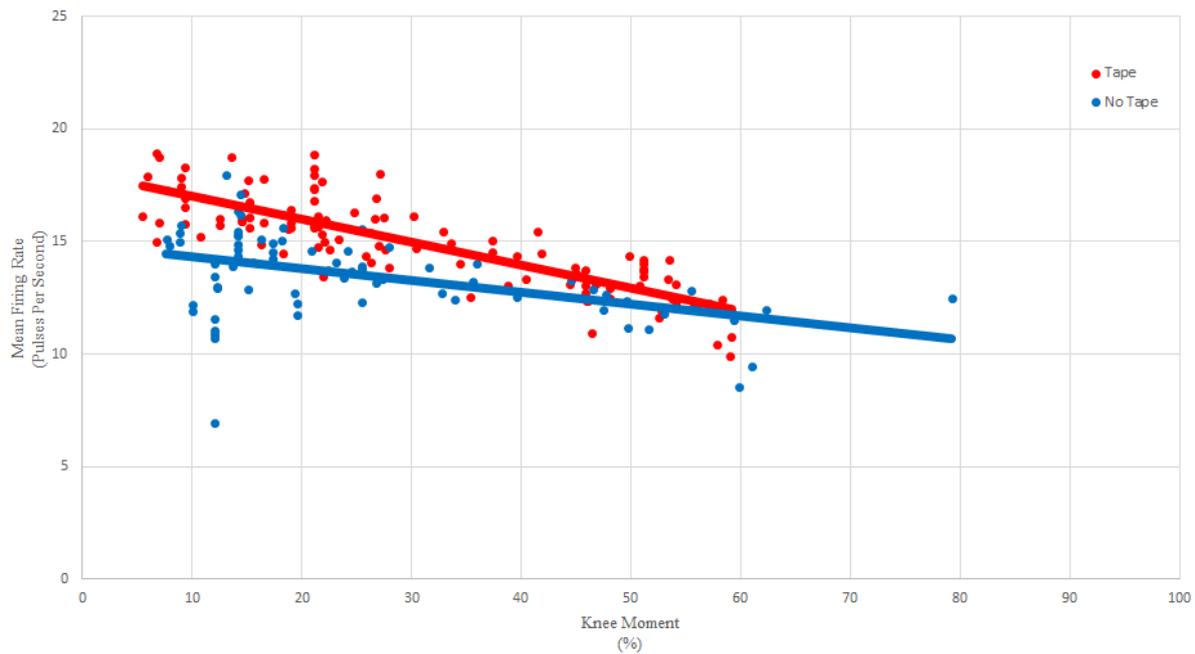
The intercept and slope with their respective p-values were computed within SPSS through linear regression for both Vasti muscles. The grouped analyses of the symptomatic subjects did not show any significant differences in the regression lines for both muscles, however the individual analyses (see appendix 12.1.6) show that some subjects were responding to the taping condition with significant changes exhibited in both the slope and intercept. For example PFP 6 significantly responded to the tape condition within both the Vastus Medialis ( $p < 0.001$ ) (Figure 9-12) and Vastus Lateralis ( $p < 0.05$ ) in the slope and intercept. However, PFP 2 did not exhibit any significant changes in either variable for either muscle (Figure 9-13). Whereas some subjects exhibited significant changes within one of the two muscles, PFP 3 for instance showed a change in the Vastus Lateralis. These results clearly demonstrate that although the grouped analyses did not show any significant changes there are evidently subtle, yet significant, changes amongst the individuals. This suggests for the first time that symptomatic individuals are presenting with different recruitment strategies and consequently may be able to modulate the force and control to the muscle with the application of tape.



**Figure 9-12** Example of a changing recruitment threshold in the Vastus Medialis with tape (red) and no tape (blue)



**Figure 9-13** An example of a subject who did not exhibit any significant change in Vastus Medialis with tape (red) compared to no tape (blue)



**Figure 9-14 Example of a subject who demonstrated significant changes in Vastus Lateralis in response to tape (red) compared to no tape (blue)**

### 9.7 Recruitment Operating Point

The recruitment operating point is defined as the force or excitation level when the first motor unit in the contraction is recruited. The data was extracted from the previously stated Recruitment Threshold calculation (see section 4.6). The recruitment operating point for each contraction were calculated and the three contractions for each condition were averaged, providing an average excitation point for the tape and no condition for the Vastus Medialis and Vastus Lateralis. These results are the first of their kind to provide information on the motor unit recruitment timing in relation to joint moment/force, also offering a unique insight into the response to a therapeutic intervention.

#### 9.7.1 Grouped Analyses

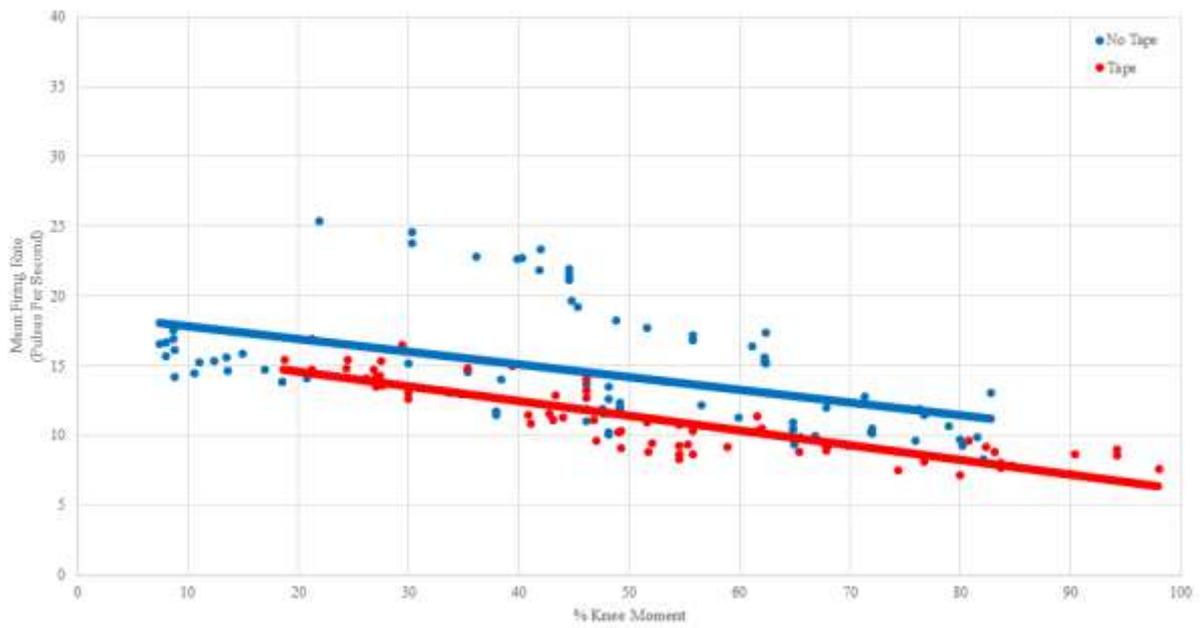
A paired samples t-test was performed on the average operating point for the Vastus Medialis and Vastus Lateralis in the tape and no condition. No significant differences were found between the tape and no condition for each of the Vasti muscles. The descriptive statistics for the symptomatic subjects can be seen in Table 9-8 below.

**Table 9-8 Descriptive statistics for the grouped recruitment operating point from the symptomatic subjects.**

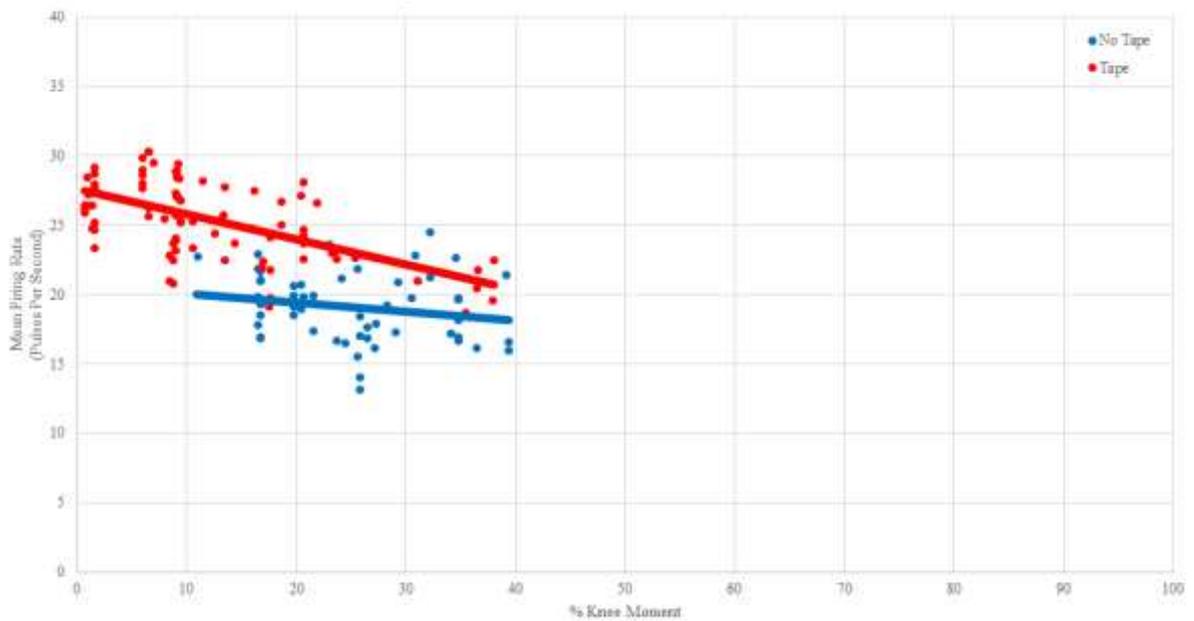
Recruitment Operating Point (% Knee Moment)	No Tape	Tape
Symptomatic Subjects	Mean (SD)	Mean (SD)
Vastus Medialis	15.5 (19.9)	12.9 (14.5)
Vastus Lateralis	11.5 (13.8)	11.5 (10.8)

### 9.7.2 Individual Analyses

The recruitment operating point results from each of the symptomatic subjects (appendix 12.1.7) show, as with the recruitment threshold results, that there is a non-uniform response to the tape intervention. Subjects seem to be presenting with differing responses to the tape condition, where some subjects present with a strategy to recruit the motor unit pool requiring less force/excitation (subject 1 for example, Figure 9-). Conversely some subjects can be seen to present with a strategy to require additional force/excitation to recruit the motor unit pool (Subject 12 for example, Figure 9-).



**Figure 9-15** An example of a symptomatic subject Vastus Lateralis requiring less force/excitation in the tape condition (red) compared to the no tape condition (blue)



**Figure 9-14** An example of a symptomatic subject Vastus Medialis requiring less force/excitation in the tape condition (red) compared to the no tape condition (blue)

## 9.8 Movement Specific Reinvestment Scale

To understand the propensity for conscious involvement in movement the Movement Specific Reinvestment Scale (MSRS) was used. The scale consists of two five-item subscales, one scale measuring the conscious motor processing and the other subscale measuring the movement self-consciousness. The Likert-type scale ranging from one (strongly disagree) to six (strongly agree), with the total for each factor out of 30.

### 9.8.1 Grouped Analyses

Mean and standard deviations for the conscious motor processing and movement self-consciousness were calculated and reported for 12 symptomatic subjects, one subject not completing the questionnaire. The mean conscious motor processing score was 18.8 units or expressed as 62.7% whilst the movement self-consciousness was 11.3 units or 37.7% in patients with patellofemoral pain.

**Table 9-9 Mean and standard deviation values for the conscious motor processing and movement self-consciousness in the symptomatic subjects.**

	Conscious Motor Processing	Movement Self-Consciousness
MSRS	Mean	Mean
Symptomatic Subjects	(SD)	(SD)
	18.8	11.3
	(6.5)	(4.7)

### 9.8.2 Individual Analyses

Grouped data was further explored by extracting individual scores for symptomatic subjects for both the conscious motor processing and movement self-consciousness (see appendix 12.1.8). The mean and standard deviation showed that 66.7% of subjects (8/12 subjects) were above 19.5 units on the conscious motor processing scale, previously been seen as a clinically significant finding in subjects with knee pain (Selfe et al. 2014). The movement self-consciousness results showed large inter-subject variability ranging from 5 up to 20 units on the subscale, with no relationship between the movement self-consciousness and conscious motor processing evident.

### 9.9 Numerical Rating Scale

The Numerical Rating Scale (NRS) was used to measure the average pain intensity of the symptomatic subjects during the past week. The pain rating from each PFP subject was averaged and provided a mean pain rating of 4.2 (SD 1.9), with 0 being “no pain” and 10 being “the worst possible pain imaginable”. Individual pain rating scores (Table 9-10) were extracted in order to appreciate the inter-subject variability. Results showed a range of 1-7 on the NPRS and thus demonstrated that the PFP cohort measured had variable levels of knee pain.

**Table 9-10 Numerical Pain Rating Scale results from symptomatic subjects**

NPRS Symptomatic Subjects	Pain Rating
Subject 1	
Subject 2	7
Subject 3	5
Subject 4	2
Subject 5	3
Subject 6	3
Subject 7	1
Subject 8	7
Subject 9	4
Subject 10	6
Subject 11	6
Subject 12	3
Subject 13	3

## 9.10 Traffic Light Results – Symptomatic Subjects

To explore the relationships between the biomechanical, neuromuscular and clinical changes in individual symptomatic subjects a ‘traffic light’ results table was created (Figure 9-14). As with the non-symptomatic subjects (see section 7.8) the variables were highlighted as either increasing (green), decreasing (red) or no change (amber). The threshold values to determine the increase or decrease in response to tape using the same rationale as with the non-symptomatic subjects. The addition of the Movement Specific Reinvestment Scale (MSRS) and Numerical Rating Scale (NRS) provided two clinically orientated measures, which were not taken with the non-symptomatic subjects. The NRS was a single measure of average pain the subjects experienced and thus a percentage change could not be reported like the other variables. The MSRS also did not present any data for change between the conditions, however a study by Selfe et al. (2014) stated that a score of 19.5 on the Conscious Motor Processing factor of MSRS represented individuals who had experienced knee pain (symptomatic) compared to individuals whom did not have knee pain (non-symptomatic). Therefore a score of 19.5 or greater was highlighted (green) in the ‘traffic light’ results table as a propensity to consciously control movements. Presenting the results of neuromuscular, biomechanical and clinical variables in this method is a new and novel feature aiming at appreciating and understanding the subtle portfolio of strategies symptomatic subjects present with.

	Gender	Diff Change (20%)				Absolute % Change (5%)				Diff Change (5%)		Diff Change (10%)		SIG		Absolute % Change (5%)		Pain (NRS)	MSRS
		Moment		Angle		sEMG				Common Drive		Mean Firing Rate		Slope* **		Rec. Operating Point* **			
		Coronal	Transverse*	Coronal	Transverse	GAS	BF	RF	GMed	VM	VL	VM	VL	VM	VL	VM	VL		
PFP_01	F	-4	-23.8	-2.8	-15.6	-1.9	0.4	-0.7	-0.7	7.1	2.5	-10.2	5.1			-9.6	-1.1		
PFP_02	M	-17.3	-35.3	-2	-15.1	2.7	-6.1	-2.5	-3.1	-3.9	5.4	4.7	-2.6			-4.3	-3.8	7	24
PFP_03	F	10.7	36.7	61.7	1	2.0	-1.8	0.0	0.4	2.7	-11.1	-11.1	10.8			-1.8	0.7	5	28
PFP_04	M	64.1	14.1	-6.6	42.8	0.7	-0.5	-1.0	3.1	5.3	-9.3	16.7	9.8			-4.1	2.5	2	22
PFP_05	M	29	-11.4	-37.4	-29.8	0.4	-2.9	0.4	-2.7	-2.4	-19.2	2.6	-3			-0.5	2.6	3	14
PFP_06	M	-16.6	-18.6	24.8	47	2.0	-6.5	-1.6	-0.6	-9.8	-6.8	72.3	-2.5			1.3	2.5	3	11
PFP_07	M	-2.8	-8.9	-13.7	-15.1	-1.3	-1.3	1.9	1.4	-10.5	0	5.3	-7.4			2.5	7.6	1	21
PFP_08	F	23.2	38.7	-10.4	5.7	2.7	-3.2	-3.5	-2.3	-11.4	-7	11.3	-8.6			4.4	2.8	7	21
PFP_09	M	-31.4	-24.4	-8.9	-20.3	-1.2	3.5	2.3	0.5	4.9	3.8	-15.5	-17.8			2.1	0.5	4	13
PFP_10	M	-69.5	-33.8			-1.5	-5.0	5.0	-5.0	-4.4	-12.8	9.4	3.6			-2.4	-7.4	6	5
PFP_11	F	16.5	-35.9	-25.6	-26.4	1.1	-3.1	-5.9	-0.3	19.2	3.7	11	-6.1			0.6	0.1	6	22
PFP_12	M	-13	5.3	-17	54.4	1.1		8.3	-3.1	7.3	0	-30.5	-23.6			-2.2	8.8	3	26
PFP_13	F	0.8	-32.7	-9.7	24.9	-2.6	-3.2	-7.7	-4.2	31.3	2.6	9.5	4.5			-20.7	-15	3	19

\* Significant results from grouped analyses  
\*\* From recruitment threshold calculation

Figure 9-14 'Traffic Light' results for symptomatic subjects

## 9.11 Results Summary – Symptomatic Subjects

### 9.11.1 Knee Joint Biomechanics Summary

- Grouped analyses of the coronal plane range of moment and angle did not present any significant responses to the tape.
- Grouped analyses of the transverse plane range of moment exhibited a significant decrease in response to the taping condition. No significant changes were found in the transverse plane range of motion.
- Individual analyses of subjects provided evidence of inter-subject variability with mean differences exhibiting changes within coronal range of moment and range of motion, some increasing and others decreasing
- Similar inter-subject variability was found in the transverse plane range of moment and range of motion.

### 9.11.2 Surface EMG Summary

- Grouped analyses of the muscle activity from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius showed that only the Biceps Femoris exhibited a significant, but subtle, response to the taping intervention. The clinical significance of such a response should be questioned as this unlikely to provide any real change to a patient group.
- Analyses of each individual PFP subject exposed the makeup of the grouped data for each of the muscles, showing little response to tape but with differing strategies by marginally increasing or decreasing the different muscles.
- Minimal changes in the muscle activity shown in these muscles highlight that changes seen in the Vasti muscles are not necessarily due to these muscles compensating.

### 9.11.3 Mean Firing Rate Summary

- Patellofemoral Pain grouped analyses exhibited a discrete increase in the firing rate in the Vastus Medialis with a 4% change in response to tape. However, the Vastus

Lateralis showed a 3.2% decreased MFR in response to the tape. The parametric testing did not demonstrate any statistical significance when pooling the data for analyses, however this type of analysis may not demonstrate any individual differences that could be present.

- Investigating each individual PFP subject showed differing responses and strategies, where the Vastus Medialis increased by 72.4% in one subject it decreased in others. Similar findings were also seen for the Vastus Lateralis.
- As with other results the individual analyses exposed the different motor unit firing rate strategies and responses to tape, demonstrating that subjects have the ability to make large modifications in their motor unit firing rate and consequently the force contribution from that muscle.

#### 9.11.4 Common Drive Summary

- Grouped analyses of the symptomatic subjects showed that there was an increase in common drive to the Vastus Medialis by 5.1% and decreased in the Vastus Lateralis by 9.1% in response to tape.
- Individual analyses showed that the symptomatic subjects presented with varying responses to the taping condition, where some subjects exhibited significant increases (31%) in common drive and others significant decreases (10%), whilst others did not respond.
- Common drive results clearly demonstrate that not only the motor units within the Vastus Medialis and Vastus Lateralis are firing in unison but also that the taping intervention can alter the common drive.

#### 9.11.5 Recruitment Summary

- Patellofemoral pain grouped analyses did not present any significant changes in the regression lines between the tape and no tape condition.
- 11/13 symptomatic subjects exhibited significant changes to tape, although no significant changes were identified within the grouped analyses.

- Individual analysis of the recruitment threshold results provide further rationale for exploring individuals' response to the taping intervention and their respective strategies.
- These results show that patellofemoral pain subjects modify the recruitment strategy of the motor unit pool in response to the taping intervention.

#### 9.11.6 Movement Specific Reinvestment Scale Summary

- Grouped analyses showed there is a propensity for conscious involvement in symptomatic subjects' movements, but not for movement self-consciousness.
- Individual analyses also showed that there is a propensity for conscious involvement in movement in most (66.7%) of the subjects with the remaining exhibiting low scores.
- Exploration of individual symptomatic subjects' results showed, as with other results, variability amongst subjects showing different conscious involvement.

#### 9.11.7 Numerical Rating Scale Summary

- The grouped analyses of the pain rating showed a mean score of 4.2/10, showing that the pain levels during the week prior to testing were relatively low but yet still experiencing obvious levels of discomfort
- Exploration of the individuals' pain rating showed that there were variable levels of pain being presented across the subject group, ranging from 7/10 to 1/10.
- Further investigation suggested there were no obvious relationships between the subjective pain rating scale and the objective neuromuscular and biomechanical measures.

#### 9.11.8 Clinical Implications

The findings from the biomechanical investigations show that the symptomatic subject group present with a statistically significant reduction in the transverse plane knee moment with the application of a taping intervention. This suggests that taping could offer a clinical change to the torsional mechanics of the knee joint, as seen in previous publication (Selfe et al. 2008), perhaps offering an insight into the previously reported reduction in symptoms. These findings are complimented by the modifications in the neuromuscular system through the motor unit control, again suggesting that tape is altering the force and control contributions within and across the Vasti muscles. As we are at the advent of furthering our understanding of the complex and delicate neuromuscular system through measurement of large groups of individual motor units, using surface EMG decomposition, the minimal clinical differences are still debatable and relatively unknown. However, within this work a criteria for percentage was devised in an attempt at justifying the changes we have observed (see sections 7.8 and 9.10) whereby depending on the variable a percentage level change was judged as being a potentially clinically important change in the subjects control or behaviour.

This demonstrates a clinically important response to the taping intervention, which have previously eluded researchers and clinicians alike. Although the subjective measures of conscious motor processing and pain do not appear to present distinct strategies they do show that they are important considerations in the management of patellofemoral pain and the relationship to objective measures. The multi-disciplinary approach, aiming at understanding the control of the knee joint, shows that real and clinically significant responses can be seen in response to a common clinically applied taping intervention.

## 9.12 Comparison of Non-symptomatic and Symptomatic Subjects

The biomechanical and neuromuscular variables from the non-symptomatic and symptomatic subjects were compared in order to understand whether symptomatic subjects exhibited differing control mechanisms or strategies with no intervention being applied.

### 9.12.1 Knee Joint Biomechanics

An independent samples t-test of the sagittal plane knee joint mean moment and mean angle can be seen in Table 9-11. The results show that there was a significant difference between the two subject groups with the mean angle. However, there was no significant difference in the mean moment between the groups. The latter result demonstrates that the same mechanical load is experienced through the knee joint. The coronal and transverse plane knee joint range of motion or range of moment did not show any differences between the non-symptomatic and symptomatic subjects as can be seen in Table 9-12 and Table 9-13.

**Table 9-11 Sagittal plane results from the mean moment and mean angle comparing the non-symptomatic and symptomatic subjects**

Sagittal Plane	Non-Symptomatic Subjects	Symptomatic Subjects	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Mean Moment (Nm/kg)	1.04 (0.22)	1.18 (0.21)	0.14	-0.37 to 0.09	0.22
Mean Angle (Degrees)	47.8 (5.9)	57.11 (8.66)	9.31	-18.73 to -2.99	0.01

**Table 9-12 Coronal plane results from the range of moment and range of angle comparing the non-symptomatic and symptomatic subjects**

Coronal Plane	Non-Symptomatic Subjects	Symptomatic Subjects	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Range of Moment (Nm/kg)	0.11 (0.04)	0.12 (0.06)	0.006	-0.05 to 0.06	0.8
Range of Angle (Degrees)	1.99 (0.77)	2.37 (0.93)	0.38	-0.39 to 1.16	0.3

**Table 9-13 Transverse plane results from the range of moment and range of angle comparing the non-symptomatic and symptomatic subjects**

Transverse Plane	Non-Symptomatic Subjects	Symptomatic Subjects	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Range of Moment (Nm/kg)	0.07 (0.02)	0.07 (0.03)	0.001	-0.02 to 0.02	0.9
Range of Angle (Degrees)	1.99 (0.48)	2.49 (0.78)	0.500	-0.10 to 1.10	0.1

### 9.12.2 Surface EMG

An independent samples t-test was conducted on the Gastrocnemius, Biceps Femoris, Rectus Femoris, and Gluteus Medius sEMG results comparing the non-symptomatic and symptomatic subjects. It was found that the sEMG amplitude for all four muscles were significantly ( $p < 0.01$ ) lower in the symptomatic subjects compared to the non-symptomatic subjects. Table 9-14 below shows the significantly lower mean EMG amplitude for the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius in the symptomatic subjects. These results suggest that symptomatic subjects may use a different strategy to manage the same level of load being applied through the knee joint compared to the non-symptomatic subjects, perhaps favouring the Vasti muscles.

**Table 9-14 Surface EMG amplitude results for non-symptomatic and symptomatic subjects**

Mean Surface EMG Activity (% MVC)	Non-Symptomatic Subjects	Symptomatic Subjects	Mean Difference	Confidence Interval of the difference (95%)	p-Value
	Mean (SD)	Mean (SD)			
Gastrocnemius	29.3 (8.1)	12.5 (5.7)	16.8	11.2 to 22.5	<0.0001
Bicep Femoris	35.2 (11.4)	17.1 (6.2)	18.1	10.3 to 25.9	<0.0001
Rectus Femoris	36.7 (12.6)	18.4 (6.6)	15.1	8.7 to 27.9	0.002
Gluteus Medius	40.1 (13.5)	17.9 (3.9)	22.1	12.5 to 31.8	<0.0001

### 9.12.3 Mean Firing Rate

A comparison of the non-symptomatic and symptomatic subjects mean firing rate did not show any differences between the groups for either the Vastus Medialis or Vastus Lateralis as can be seen in Table 9-15 . In the no tape condition both groups exhibited similar MU firing rates, 17.7pps and 17.5 pps for the non-symptomatic and symptomatic groups respectively. The tape condition response both showed a similar increase to 18.3pps and 18.8pps for the non-symptomatic and symptomatic groups respectively.

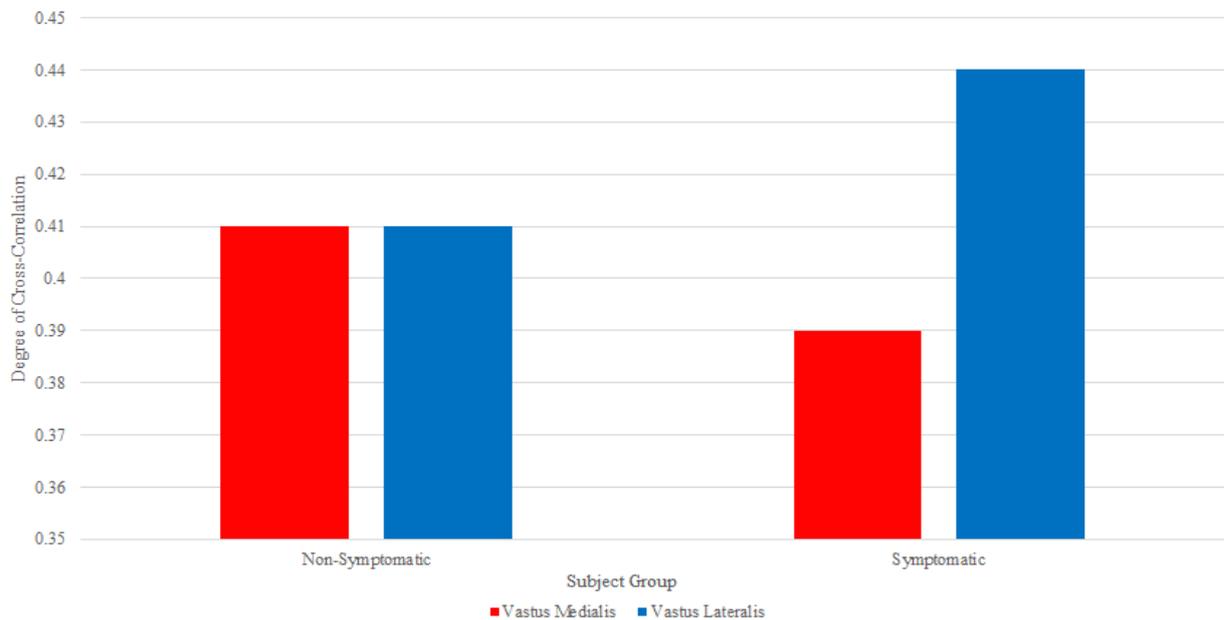
**Table 9-15 Inferential analyses of the motor unit firing rate comparing non-symptomatic and symptomatic subjects**

Mean Firing Rate	Average MFR (pps) (SD)	Mean Difference	Confidence Interval of the difference (95%)	p-Value
Vastus Medialis Non-Symptomatic	17.7 (3.2)	0.13	-2.03 to 2.29	0.89
Vastus Medialis Symptomatic	17.5 (2.7)			
Vastus Lateralis Non-Symptomatic	18.3 (2.6)	0.52	-2.2 to 1.18	0.52
Vastus Lateralis Symptomatic	18.8 (3.9)			

### 9.12.4 Common Drive

A comparison of the median cross-correlation values from the non-symptomatic and symptomatic subjects was conducted to explore whether the common drive differed between the two subject groups assessing whether there were any changes to the control of the motor unit pool. The results show that the Vastus Medialis in the symptomatic subjects had a lower degree of cross-correlation compared to the non-symptomatic subjects demonstrating that the symptomatic subjects exhibited less common drive to the Vastus Medialis. Conversely the Vastus Lateralis showed a higher degree of cross-correlation in the symptomatic subjects compared to the non-symptomatic subjects, thus demonstrating that symptomatic subjects have higher common drive to the Vastus Lateralis. These results (Figure 9-15) are the first of their

kind in being able to demonstrate disproportional control in the motor unit pool between the Vasti muscles in symptomatic subjects and potentially offers key insights into the presentation of symptomatic subjects.



**Figure 9-15 Common drive for non-symptomatic and symptomatic subjects for Vastus Medialis (Red) and Vastus Lateralis (Blue)**

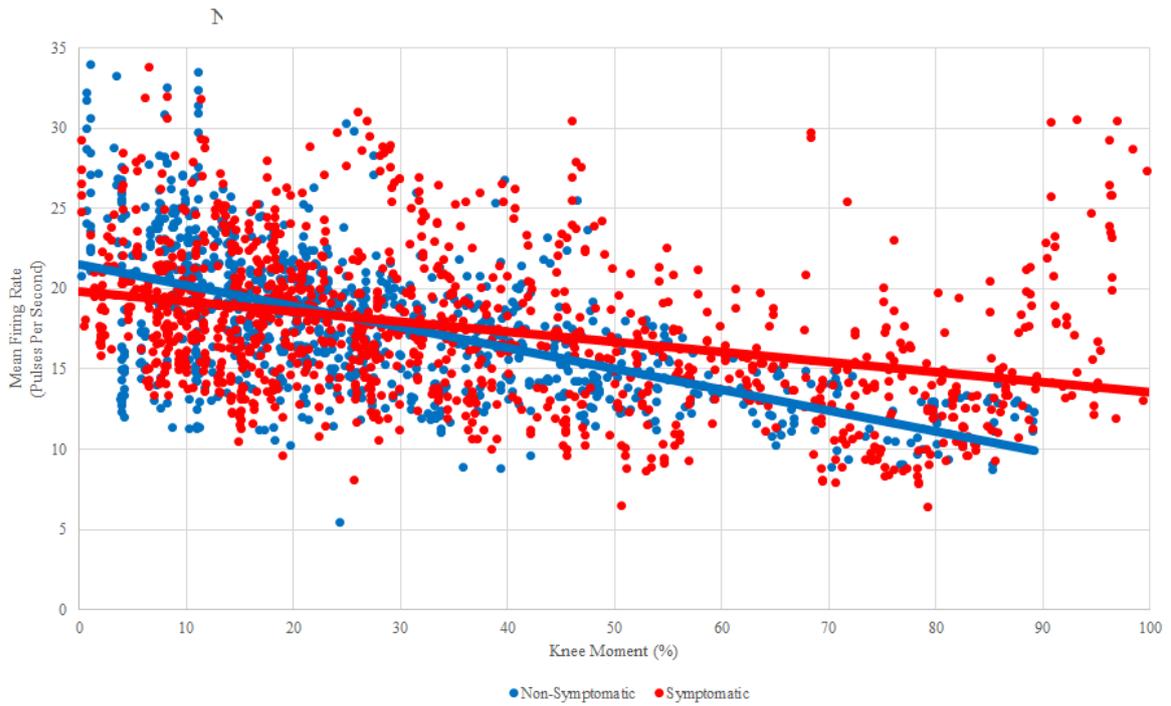
#### 9.12.5 Recruitment Threshold

In order to explore the differences between non-symptomatic and symptomatic subjects a linear regression of the motor unit recruitment threshold and the mean firing rate was performed, comparing the regression lines between the two groups. The results (Table 9-16) show that the symptomatic group recruitment intercept was significantly lower ( $p < 0.0001$ ) than the non-symptomatic subjects indicating that the early recruited motor units for the Vastus Medialis were being recruited at a lower firing rate in the symptomatic subjects. However, the significantly flatter slope gradient ( $p < 0.0001$ ) for the Vastus Medialis in the symptomatic subjects describes that the remainder of the motor unit pool were being recruited at a higher firing rate compared to the non-symptomatic subjects. The results suggest that the Vastus Medialis in the symptomatic subjects is exhibiting an altered recruitment strategy by driving

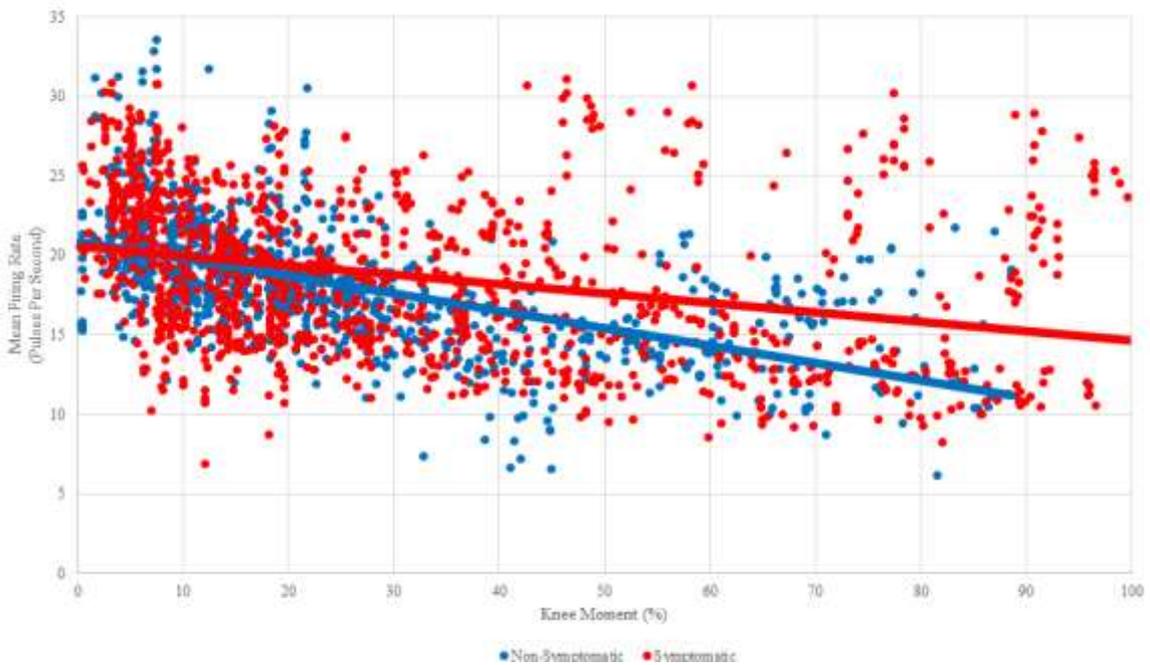
the later recruited motor units to fire faster compared to the non-symptomatic subjects at the same relative force levels (Figure 9-16). These findings show for the first time that the motor unit pool of the Vastus Medialis in symptomatic subjects have a different recruitment strategy compared to non-symptomatic subjects, suggesting an increased force contribution within the muscle. The results from the Vastus Lateralis show that there is no change in the recruitment intercept ( $p=0.27$ ) between the non-symptomatics and symptomatics, however the slope gradient shows that it is significantly flatter in the symptomatic subjects ( $p<0.0001$ ). This shows that the Vastus Lateralis, like the Vastus Medialis, is driving the later recruited motor units to fire at a faster rate consequently suggesting that there is an increased level of force generated within the muscle in symptomatic subjects compared to non-symptomatic subjects (Figure 9-17).

**Table 9-16 Recruitment threshold results comparing the regression lines between the non-symptomatic and the symptomatic subjects with no intervention for the Vastus Medialis and Vastus Lateralis.**

Recruitment Threshold	Vastus Medialis			Vastus Lateralis		
	Non-Symp.	Symp.	p-Value	Non-Symp.	Symp.	p-Value
Intercept (pps)	21.5	19.8	<0.0001	20.9	20.6	0.27
Slope (Gradient)	-0.13	-0.06	<0.0001	-0.11	-0.06	<0.0001



**Figure 9-16 Recruitment Threshold for Vastus Medialis for Non-Symptomatic subjects (Blue) and Symptomatic subjects (Red) with no intervention**



**Figure 9-17 Recruitment Threshold for Vastus Lateralis for Non-Symptomatic subjects (Blue) and Symptomatic subjects (Red) with no intervention**

### 9.12.6 Clinical Implications

A challenge often faced is understanding whether there are any differences in the presentation and behaviour between non-symptomatic and symptomatic subjects. Findings from the comparisons made in this study between non-symptomatic and symptomatic subjects offer several unique differences in the motor control strategy that have not before been seen. The neuromuscular strategies exhibited by symptomatic subjects present for the first time suggestively clinically important differences between the two subject groups and offer a tantalising insight into the presentation of symptomatic subjects.

The significant lower muscle activity of the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius suggests that patients may be preferentially using other muscles, such as the Vasti, to control and distribute the load in comparison to non-symptomatic subjects. This has important clinical implications and perhaps indicating that clinicians should consider directing their treatments at increasing the contribution of the surrounding musculature and/or exploring the control strategies of the Vasti muscles. The findings from the common drive between the non-symptomatic and symptomatic subjects suggest and provide evidence for the Vasti muscles receiving a disproportion level of motor unit pool control. The Vastus Medialis demonstrated receiving a lower level of common drive in the symptomatic subjects compared to the non-symptomatics and a higher level of common drive to the Vastus Lateralis in comparison. These findings show that there may be a clinical difference in the organisation of the motor unit pool of the Vastus Medialis and Vastus Lateralis in symptomatic subjects where clinicians should perhaps consider an intervention such as tape, which is shown to adjust the common drive contribution to the Vasti (see section 9.5). Another key difference presented by the symptomatic subjects is the strategy used to recruit the Vasti, the results showing that symptomatic subjects later recruited motor units were firing at a higher rate and therefore suggesting a modification in the force contribution of the muscles. Complimentary to the significant differences seen in the reduced muscle activity from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius both the Vastus Medialis and Vastus Lateralis seem to be increasing the force contribution within the muscles, suggesting that the symptomatic subjects are biasing the Vasti muscles to control the knee joint. The advent of the novel methods of exploring the sensory-motor control, and specifically being the first work to explore the clinical questions using these methods, means that the Minimal Clinical Important Differences (MCID) are yet to fully explored. This work expressed the changes

observed with the percentage change in response to the intervention and chose an appropriate percentage criteria to illustrate a suggesting clinically important change in the behaviour of the subjects' mechanical, neuromuscular and clinical measures. This coupled with the multi-disciplinary approach the project took allows the exploration of the sensory-motor control and behaviours from different perspectives in an attempt at isolating the important changes, which can be clinically applicable.

These findings for the first time present empirical evidence demonstrating key and suggestively clinically important differences between a non-symptomatic and symptomatic subject consequently offering an insight into the direction and focus of clinical interventions.

## **10. Discussion**

Motor activities in general comprise of unique and complex sensory-motor processes, which when pain and disorder are introduced leads to further complications in understanding the delicate mosaic of pathophysiological processes. Patellofemoral Pain (PFP) is not well understood due to its inherent intricacies and unique presentation among PFP sufferers. In reflection of the known complexities this thesis aimed to better understand PFP and the responses to a common clinical intervention with an inter-disciplinary approach investigating the biomechanical, psychosocial and neuromuscular elements.

### 10.1 Biomechanical

The biomechanical approach to Patellofemoral Pain can offer detailed insight into the efficacy of clinical interventions by studying the 3-dimensional joint mechanics and their respective responses. In order to achieve such insight this study aimed to determine the mechanical control of the knee joint during a single limb isometric squat and its response to a taping intervention, in both non-symptomatic and symptomatic subjects.

Studying the coronal and transverse planes of the knee is a feat that is not often undertaken, especially within the Patellofemoral Pain research where the sagittal plane has for many years been the main focus. The control of the knee has previously been considered as a simple flexion and extension movement with researchers purporting a change in control through a knee flexion-extension moment or angle (Nadeau et al. 1997; Powers et al. 1999; Salsich et al. 2001) without consideration of the other degrees of freedom acting upon the knee. It was found that there were no significant differences in the sagittal plane knee moment between the tape and no tape conditions for both the non-symptomatic and symptomatic subjects. This shows that the flexion moment and consequent load at the knee remained the same regardless of the intervention or subject group, thus indicating that any changes seen in other biomechanical or neuromuscular variables are not due to increased load being applied to the knee in the sagittal plane. Several researchers have however highlighted the importance of studying the coronal and transverse planes of motion when investigating the knee mechanics (Kowalk et al. 1996; Selfe et al. 2008; Karamanidis & Arampatzis 2009; Paoloni et al. 2010; Selfe et al. 2011) where it has been shown that they are key components in understanding the mechanisms involved in the control of the knee joint. Previous work commonly reports maximum or peak values for the kinetic and kinematic outcomes, however in studying the coronal and transverse plane the

maximum value may not provide an accurate representation or indication of control. It has previously been shown (Selfe et al. 2008; Selfe et al. 2011) that studying the range of the kinetic and kinematic variables during the task is a sensitive enough measure to demonstrate a clinically important change. This study therefore measured the range of moment and range of motion in the coronal and transverse plane knee joint biomechanics to determine the mechanical control and response to a commonly applied clinical taping intervention.

The results of this study show that the application of the tape intervention significantly decreased the range of moment in the transverse plane for both non-symptomatic and symptomatic subjects during a single limb isometric squat. These findings suggest that the tape intervention can offer increased torsional control in either non-symptomatic or symptomatic subjects. This is in agreement with previous work (Selfe et al. 2008) where tape was also seen to offer a significant decrease in torsional range of moment during step descent for non-symptomatic subjects. The increase in torsional control found in this study are complimentary to the findings from Selfe et al. (2008) where a neutral taping technique and knee brace were used. However, unlike Selfe et al. (2008) this study did not observe any significant changes in the coronal plane knee range of moment or range of motion for either subject group. Although not significant both subject groups did exhibit a reduction in the coronal plane knee moment in the taping condition, thus complimenting the reduction in transverse plane range of moment. It is thought that these changes may have not exhibited such clear and significant changes as seen in other similar work (Selfe et al. 2008; Selfe et al. 2011) because of the different task that was undertaken. The previous work has typically investigated the knee joint mechanics under dynamic conditions such as walking, running, and step descent where gross dynamic movements occur, with knee range of motion angles in the transverse plane being reported at 8.6 degrees for the step-descent (Selfe et al. 2008). However, this current work explored the knee joint mechanics under semi-static conditions where minimal movement was expected and consequently only reported 2.1 degrees range of motion during the single limb isometric squat in comparison to the step-descent in Selfe et al. (2008). Therefore with this in consideration the significant mechanical changes observed in this study with the tape intervention was rather surprising. As Selfe et al. (2008 & 2011) are the only papers, to the authors knowledge, to measure the range of moment and range of motion in the coronal and transverse planes as an indicator to knee joint control it is difficult to compare results to other work. But importantly the findings do provide complimentary evidence to the

work from Selfe et al. (2008 & 2011) that the application of a taping intervention can provide a clinically important response to the biomechanical control of the knee joint.

Considering the potentially different biomechanical mechanisms and presentations between the two subject groups the data from the non-symptomatic and symptomatic subjects were compared. Significant differences were observed between the two groups with the sagittal plane mean knee angle, which could offer some explanation for differences observed between the groups such as the surface EMG from surrounding muscles. However, there were no significant differences seen in the sagittal plane mean knee moment between the groups and thus offering evidence to demonstrate there was no load difference in the knee joint between the groups. There were no significant differences in the range of moment or range of motion in the coronal and transverse planes could be distinguished between the two subject groups. This is not in agreement with Paoloni et al. (2010) who found that symptomatic subjects, 9 PFP subjects, exhibited an increased knee abductor moment and external rotator moment compared to non-symptomatic subjects. However, these changes were observed during gait where the movements are gross and dynamic compared to the current study that investigated an isometric squat, which by definition did not involve any grossly dynamic movements. The findings suggest that the selected isometric task does not offer any significant or clinically important biomechanical differences when comparing the two subject groups. This has an interesting clinical implication as the mechanical stability/control of an individual is often used as part of a clinical decision process, but these findings using detailed 3-dimensional joint kinematics and kinetics were unable to distinguish any differences between a non-symptomatic and symptomatic subject. Although no differences were found in the biomechanical variables other motor control systems, such as the neuromuscular system may offer further insight into the potential different presentation between the two subject groups.

This study further explored the biomechanical changes already seen in the grouped data by investigating each individuals' response to the taping intervention as it was thought that when grouping the data any subtle or opposing individual responses could have been masked. It was found that individuals from both subject groups had a non-uniform response to the taping condition in the coronal and transverse planes. Surprisingly subjects were sometimes showing complete opposite responses to the tape condition, for example one subject may present with a decreased range of moment in the coronal plane by a large degree (0.07 Nm/kg) whereas another subject may present with an increase in the range of moment in the tape condition by

a large degree (0.06 Nm/kg). The same disparity can be also be seen in the range of motion for the coronal and transverse planes. To the authors knowledge no previous investigation into the biomechanical control of the knee has considered the individuals behaviour or response to a clinical intervention, instead have always presented grouped data. However, these results suggest that both symptomatic and non-symptomatic subjects can present with varying and opposing strategies in response to a tape condition. Similar considerations have been reported in the spine and lower back pain (Mok et al. 2007) where patients presented with variable mechanisms in an attempt to control spinal posture.

The study shows agreement with previous literature (Selfe et al. 2008) presenting a significant reduction in the torsional range of moment within the tape condition, illustrating that clinically important changes can be induced with the application of a taping intervention in both non-symptomatic and symptomatic subjects and perhaps an indication to greater stability. However, no biomechanical differences can be distinguished between the two groups in the isometric squat position. Yet for the first time instead of viewing a subject group as being homogeneous who adapt similarly the biomechanical analysis considered individual variation and their response to a tape intervention. The disparity found with the knee joint biomechanics may be interpreted as there is not a clear and obvious response to the tape intervention, however instead it is being proposed that the results are offering a fascinating insight into potential knee joint control strategies perhaps indicating there may be subgroups or phenotypes. Information about the subjects conscious motor processing and neuromuscular responses, complimentary to the knee joint biomechanics data, could offer additional insight and understanding of the motor control system in both non-symptomatic and symptomatic subjects alike.

## 10.2 Psychosocial

Historically movement control and related disorders have been questioned through mechanical and neuromuscular measurements with less consideration to the psychosocial features. However, it has been shown that psychosocial elements, in-particular pain and fear of pain, can have distinct influences on motor control (Lethem et al. 1983). The premise that pain and movement are inter-related is a well-established phenomenon (Melzack & Wall 1965), which has remained largely unquestioned. This postulate has been the foundation to various proposed theories of the body's response and adaptation to pain, explicitly the Vicious Cycle theory (Roland 1986) and the Pain Adaptation theory (Lund et al. 1991). This study aimed to explore the psychosocial elements of knee pain and movement control using validated and clinically appropriate measures of pain rating (Pagé et al. 2012) and theory of reinvestment (Masters & Maxwell 2008).

The Numerical Rating Scale (NRS) was used in order to gather an understanding of the perceived severity of pain the symptomatic subjects experienced and also whether it would provide any relationship with the objective measures. As a homogeneous group the symptomatic subjects reported with a mean pain rating of 4.2 (1.9)/10, which presents a similar pain rating shown to have altered Vasti motor unit recruitment (Tucker & Hodges 2010). These findings show that subjects had experienced a moderate level of pain during the previous 7 days, including the day of testing, confirming the presence and severity of symptomatic knee pain. Though by averaging across the group it assumes that the symptomatic subjects are all presenting with similar pain and according to previous models, Vicious Cycle and Pain Adaptation, the subjects would present with stereotypical responses. Hodges and Tucker (2010) build upon previous models presenting a new theory of the adaptation to pain that attempts to account for individual and non-uniform responses to pain and/or fear of pain. Findings from this work are in-line with this theory that there may be individual presentations and responses to pain, this is evident by the pain scores reported by symptomatic subjects ranging from 1/10 up to 7/10. Complimentary to this is the individual biomechanical responses found within the symptomatic subject group, yet interestingly there did not seem to be any obvious relationship between the level or even presence of pain and the biomechanical responses. An understanding on the conscious motor processing in addition to the pain rating may offer further insight into the different presentations of the symptomatic group and their individual responses.

The findings show that symptomatic subjects demonstrate a propensity to consciously control their movements, consequently suggesting that Patellofemoral Pain subjects are concerned with the execution and control of their movements. These findings are in agreement with Selfe et al. (2014) whom found that subjects presenting with self-reported knee pain have a higher propensity for conscious motor involvement than their pain-free counterparts. The mean score of 18.8/30 on the Movement Specific Reinvestment Scale (MSRS) (Masters & Maxwell 2008) is below the mean score of 19.5 from Selfe et al. (2014) for symptomatic subjects, however it is confounded by a single subject which when removed would raise the mean score to 20.1 and therefore in-line and in fact higher than the results from Selfe et al. (2014). The evident tendency in this study for the symptomatic subjects to consciously monitor and control their movements has been suggested to disrupt more effective automatic control processes (Masters & Maxwell 2008), which has also been seen in higher falls in the elderly (Wong et al. 2008) and movement impairments in stroke subjects (Orrell et al. 2009). It has also previously been described that individuals may display different psychological traits and responses to pain or the fear of pain, with extreme examples described as being ‘confrontation’ and ‘avoidance’, although is often a mixture of the two (Lethem et al. 1983). The findings from the MSRS show that several subjects reported lower than average scores on the conscious motor processing factor, which could indicate that these individuals are not as concerned with the control and execution of their movements and could be leaning more towards to the ‘confrontation’ trait as described by Lethem et al. (1983). Although perhaps not causative factors in developing or worsening symptoms of Patellofemoral Pain the conscious motor processing and psychological traits should be a point of consideration and reflection in clinical decision processes and form part of the multi-disciplinary and holistic approach.

The psychosocial responses seem to be complimentary to the joint biomechanics findings in that there may be individual and non-uniform responses, although not a complete description it does add to the seductive muse that there may be variable and preferential strategies. A more comprehensive insight could be deduced with the addition of an understanding of the role and involvement of the neuromuscular system.

### 10.3 Neuromuscular

By far, the majority of the studies investigating PFP and its neuromuscular components have done so by observing the gross changes of the surface EMG signal. The heterogeneous findings and purported relationships between and within the Vastus Medialis and Vastus Lateralis have long been studied in an attempt to understand the ‘control’ of the muscles and their respective behaviour (Cowan et al. 2001; Herrington et al. 2005; Rainoldi et al. 2008; Cowan & Crossley 2009; Cavazzuti et al. 2010). However, the gross sEMG measurements typically taken may not be able to offer the intricate details required to understand the control and behaviour of the Vasti muscles, instead these have been sought after through investigations at the single motor unit level (Mellor & Hodges 2005a; MacGregor et al. 2005). Recent developments have allowed the exploration of a larger yield of motor unit and consequently greater representation of the motor unit pool (Nawab et al. 2010). Investigating the voluntary behaviour of individual motor units allow several key features to be explored, namely the firing rate, recruitment strategy and neural drive.

#### 10.3.1 Gross Muscle Activity

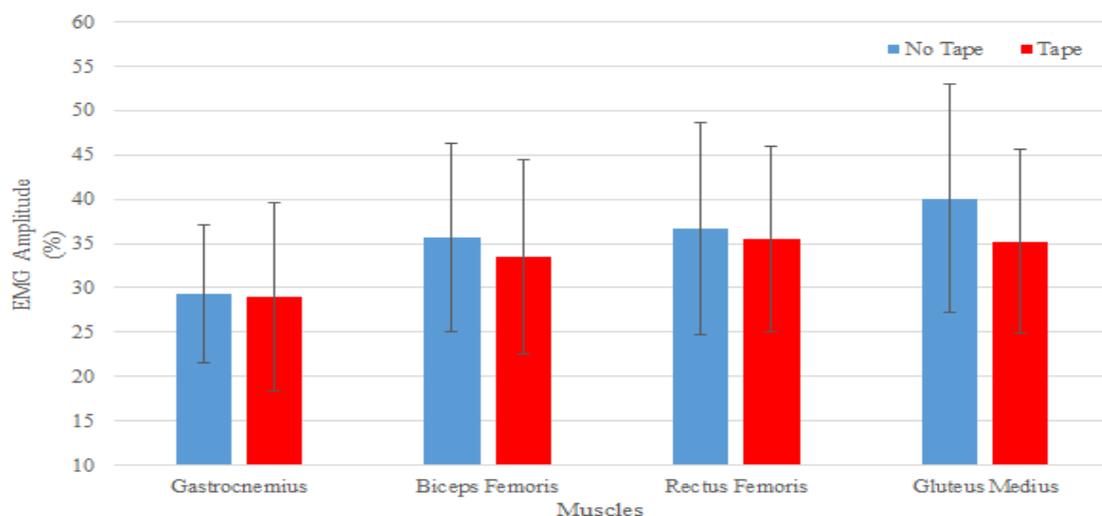
In general more than a single muscle is required to produce a joint moment and the joints consequent movements. This is certainly the case when investigating a closed chain exercise such as the investigated single limb isometric squat in this work where multiple joints and consequently multiple muscles are involved. Therefore four muscles, in addition to the two Vasti, were investigated providing gross muscle activity information on the role of the Medial Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius. The muscle activity was normalised to a reference contraction, the maximal observed signal, so that data are comparable between subjects and trials, was used (as detailed in section 4.7.3).

##### 10.3.1.1 Non-Symptomatic

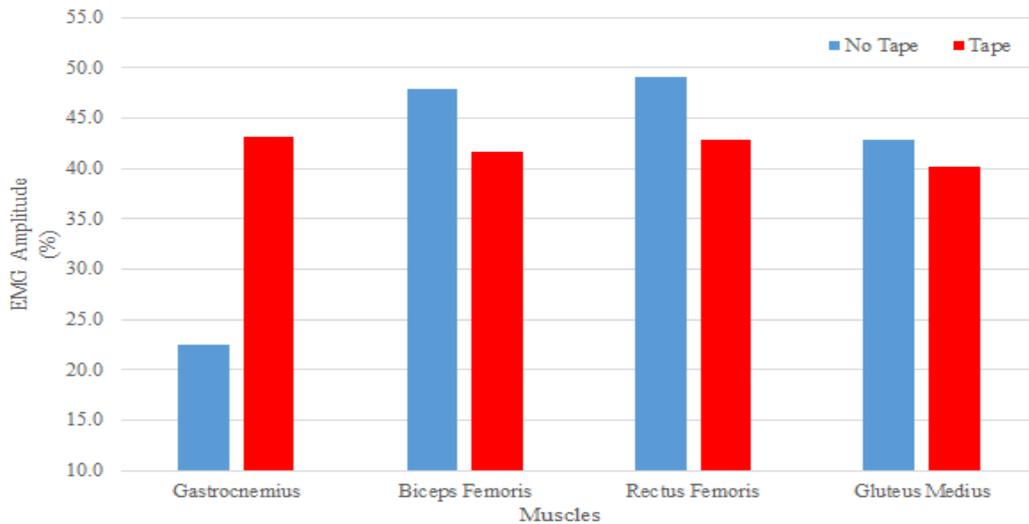
It was found that there were no significant differences in the muscle activity within the tape condition for the Gastrocnemius, Biceps Femoris, Rectus Femoris or Gluteus Medius. There was a trend however to marginally reduce the activity in all muscles in the tape condition, apart from the Gastrocnemius (Figure 10-1). The Gluteus Medius showed the largest response with a 4.8% reduction in muscle activity in the tape condition. The reduction of the Gluteus Medius muscle activity with the tape intervention, although not significant, is interesting as it’s in opposition to the observed significant reduction in the knee joint torsional range of moment.

Previous work (Souza & Powers 2009) would suggest that a reduction of muscle activity at the hip would cause an internal rotation of the femur, which may consequently cause an increased torsional moment at the knee, yet this was not seen within these results. However, the clinical importance of a 4.8% reduction in the Gluteus Medius should be considered as without information on the other muscles surrounding the hip and also with the relatively high contribution of Gluteus Medius EMG activity (approximately 40%) it is questionable whether a <5% change would be of any clinical significance. Nevertheless, the reduction in muscle activity with the application of tape shows that some load may have been re-distributed to other structures or muscles in response to tape.

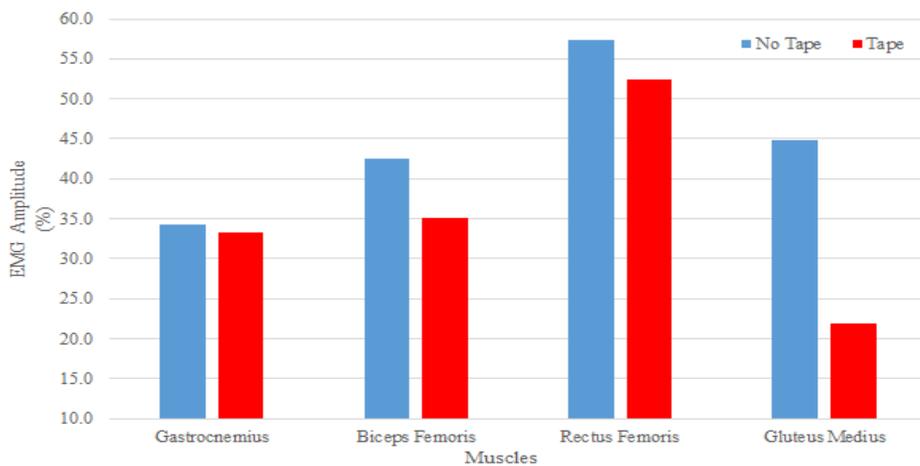
The individual variance should be noted though, as represented by the standard deviations (section 7.3.1) and the error bars in Figure 10-1, it reveals that subjects may have different contributions from the different muscle groups and demonstrate opposing strategies. Exploration of the individuals muscle activity and their response to the tape condition showed a level of disparity. For example Subject 6 presented with similar findings to the grouped analysis, including a large reduction (23%) in Gluteus Medius activity (Figure 10-3). Whereas other subjects presented with varying responses in both magnitude and direction and for different muscles, subject 10 for example demonstrates a large increase (21%) in Gastrocnemius activity and reductions in the other 3 muscles in response to tape (Figure 10-2).



**Figure 10-1** The normalised mean EMG activity for the non-symptomatic subjects from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius and their respective responses to tape (red) compared to no tape (blue)



**Figure 10-2** An example of a subject with differing results from the group in response to the tape (red) compared to the no tape (blue)

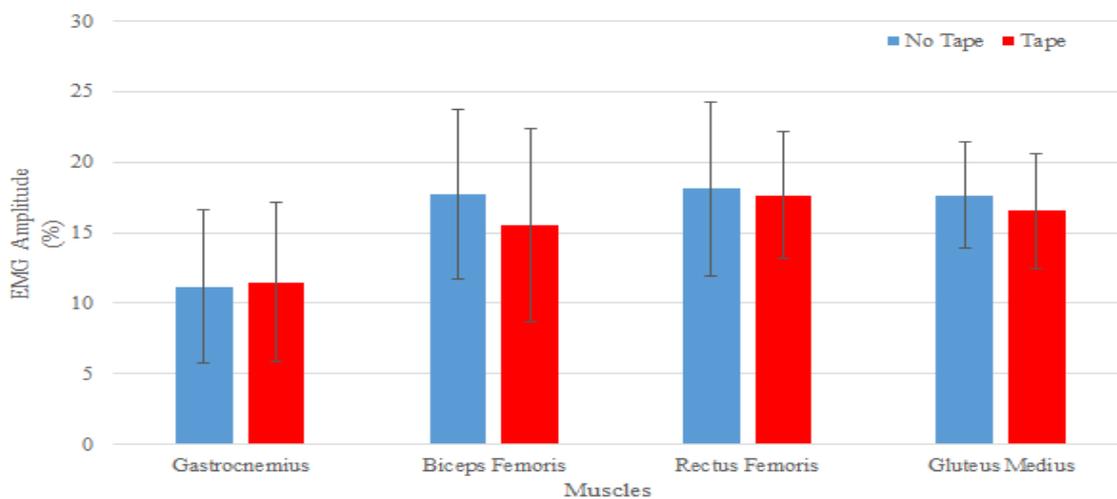


**Figure 10-3** An example of a subject decreasing muscle activity with tape (red) compared to no tape (blue)

These findings demonstrate that the major muscle groups involved in the single limb isometric squat respond to the taping intervention, which has not previously been investigated or considered before even though many therapeutic treatments are directed at stretching, strengthening or massage of these muscle groups. However, the response to tape seems to be non-uniform with varied magnitudes and direction in the different muscle groups. These findings begin to provide evidence that subjects may utilise different muscle strategies in response to tape.

### 10.3.1.2 Symptomatic

It was found that when viewed as a homogenous group the symptomatic subjects significantly ( $p=0.03$ ) reduced the muscle activity of the Biceps Femoris by 2.2% in response to the tape intervention. Whereas the Gastrocnemius showed a marginal increase and the Rectus Femoris and Gluteus Medius demonstrated a marginal decrease in response to the tape intervention (Figure 10-4). Although the Biceps Femoris was found to be significantly reduced with the application of tape, the descriptive analyses showed the mean difference was a negligible 2.2%. An important consideration here is whether the reduction in Biceps Femoris activity is clinically significant and whether a 2.2% change in a single muscle truly reflects all the symptomatic subjects' responses to the tape condition.

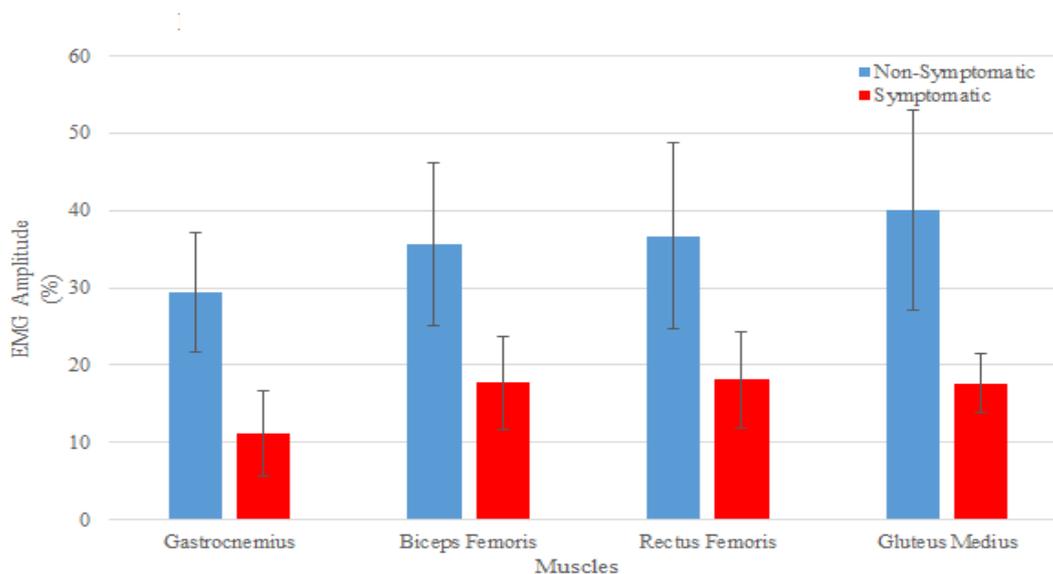


**Figure 10-4 The normalised mean EMG activity for the symptomatic subjects from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius and their respective responses to tape (red) compared to no tape (blue)**

Exploration of the mean differences in individual symptomatic subjects showed there was a degree of variability in the response to the tape condition. However, interestingly the responses did not show the same disparity as the non-symptomatic subjects with only 8/52 muscles showing a <5% mean difference response to the tape condition (Figure 9-14). The marginal response of the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius is somewhat surprising after the disparity found in the biomechanical coronal plane and transverse plane knee moment and knee angles. As there is evidently little response in these muscles with the application of tape, yet largely variable biomechanical responses, there may be other neuromuscular responses and strategies present, such as the involvement and role of the Vastus Medialis and Vastus Lateralis.

### 10.3.1.3 Non-Symptomatic vs Symptomatic

It was found that when comparing the non-symptomatic and symptomatic subject groups the muscle activity from the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius were all significantly less ( $p < 0.05$ ) in the symptomatic subjects. Figure 10-5 shows the EMG differences between the subject groups where the clearly lower muscle activity can be seen.



**Figure 10-5 Mean EMG from Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius in the non-symptomatic (blue) and symptomatic (red) subjects.**

To the authors knowledge no other work has considered the relative muscle activity between symptomatic and non-symptomatic individuals, even though a plethora of work has focussed on physical therapy treatments directed at these muscle groups (Crossley et al. 2002; Sacco et al. 2006; Kaya et al. 2010) and the highlighted importance of the surrounding musculature influencing the control of the knee joint (Andriacchi et al. 1984). With no significance found in the sagittal plane knee moment between the non-symptomatic and symptomatic subjects it suggests that the same load, flexion moment, was being applied to the knee. It is therefore reasonable to infer from these findings that other structures may have a greater responsibility in the movement strategy for symptomatic individuals. These findings show important clinical implications by highlighting the fact that symptomatic subjects present with reduced muscle activity in contributory muscles thought to be involved in the control of the knee. Therefore a strategy may be presenting a disproportionate load to other structures involved in knee control, which should be considered in a clinical decision process such as directing treatments in increasing the contribution of surrounding muscles and/or altering the role of the Vasti.

### 10.3.2 Motor Unit Firing Rate

The firing rate, or discharge rate, of a motor unit is one of the determining factors in producing force within the muscle (Burke 1981). It has previously been shown that the firing rate may be a modifiable factor with taping intervention causing a differential increase in the Vastus Medialis (MacGregor et al. 2005). However, this was severely limited by studying only a small representation of the motor unit pool (5 motor units per subject), and at a low level of force (4 N), with experimentally induced pain and using an invasive EMG procedure. Stock et al. (2012) is the only study to use surface EMG Decomposition methods to simultaneously measure the Vastus Medialis and Vastus Lateralis motor unit behaviour, in doing so was able to analyse a greater representation of the motor pool and up to a maximum force level, but investigated the effects on fatigue on motor unit behaviour in a closed kinetic chain condition. Therefore no previous work has been able to determine the motor unit firing behaviour from a representative motor unit pool in the Vasti, its response to a therapeutic intervention and its relevance in a functional and clinical environment. This work aimed to provide insight by investigating the mean firing rate of the Vastus Medialis and Vastus Lateralis using surface EMG Decomposition methods in both non-symptomatic and symptomatic individuals exploring the firing rate responses to a taping intervention.

#### 10.3.2.1 Non-Symptomatic

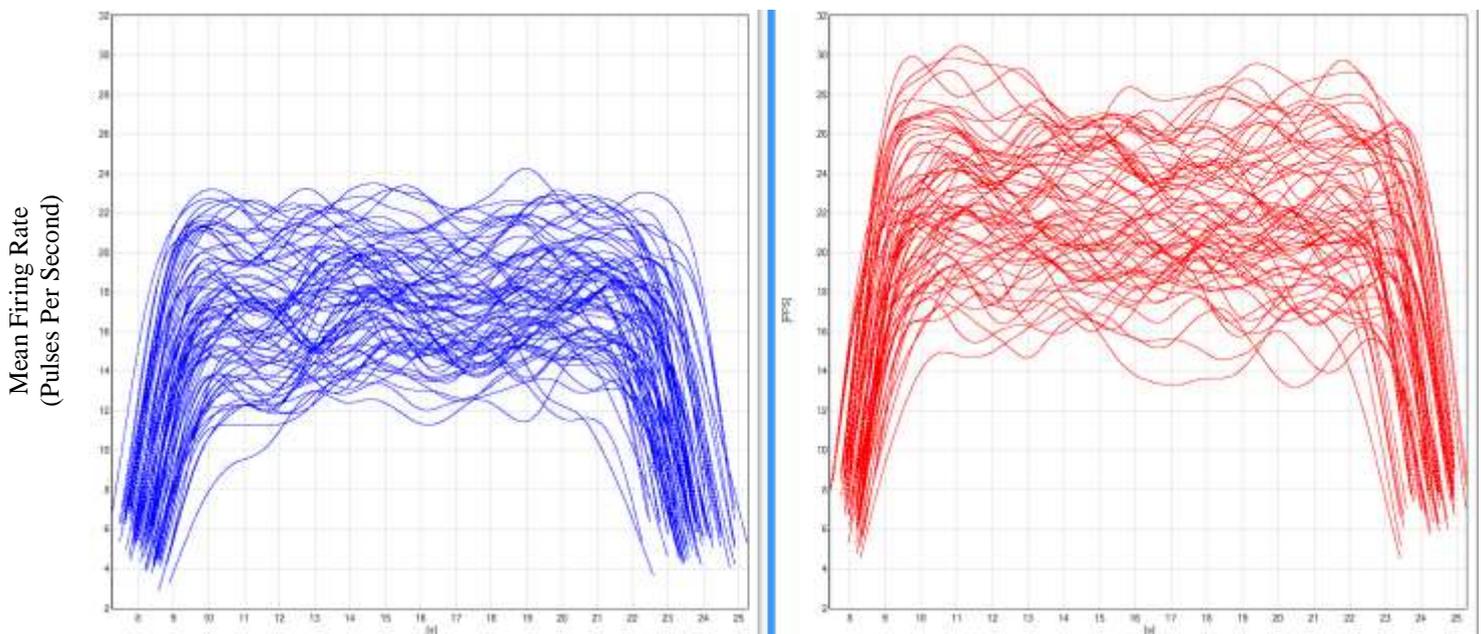
The average MFR showed a marginal response in the non-symptomatic subjects when data were grouped. The Vastus Medialis firing rate showing a 4.5% increase (0.8 pps), whilst the Vastus Lateralis showing a 3.3% decrease (0.6 pps) in response to the taping intervention across all non-symptomatic subjects. Although the relative changes were discrete, not forgetting that these results are from a non-symptomatic population performing a single limb isometric task, it does indicate that there is a trend in non-symptomatic subjects to increase VM and decrease VL firing rates with the application of tape and perhaps suggesting a novel re-distribution of load. The parametric statistical analyses did not exhibit any significant differences between the two conditions, however this type of analysis may not demonstrate any individual differences that could be present. These results are not in agreement with MacGregor et al. (2005) who showed that there was no net increase in the motor unit firing rate, although a trend to increase, from the Vastus Medialis with the application of tape, although changes in individual subjects were seen with approximate 1-2 Hz increases in firing rate. The mean firing rate of a muscle has a relationship with 'gross' sEMG measurements

amplitude of a signal, where the higher MFR could be seen in a higher amplitude sEMG signal. The increase in sEMG signal amplitude has been reported previously in PFP research, MacGregor et al. (2005) for example showed that as well as changes in motor unit firing rate the overall amplitude increased marginally. However, the comparison of the amplitude of a sEMG signal to the motor unit firing rate of individual motor units should be approached with caution as there are more factors that could demonstrate an increase in the amplitude of a signal, such as recruit in new motor units, change in MU force twitch, measurement differences etc. and therefore arguably not a sensitive enough measure to understand the complexities of the neuromuscular system, which is also reflected by the lack of consensus in the PFP literature with sEMG.

It has been demonstrated that cutaneous stimulation of the foot can contribute to the excitation of agonist motor units whilst causing an inhibition to the antagonist motor units (Hargbarth 1952). The term 'inhibition' of a muscle is a well-studied neurophysiological area, which has been an attractive notion for clinicians and researchers alike in an attempt to explain the effects of different taping techniques. The therapeutic investigations have often attempted to substantiate the claims of an inhibited muscle by demonstrating a simple reduction in the surface EMG amplitude (Tobin & Robinson 2000; McCarthy Persson et al. 2009), which arguably is too much of a gross measure to demonstrate such a discrete variable. Instead it is suggested, in combination with the findings from this work, that the behaviour of the motor unit pool is a more sensitive measure in understanding the response of a muscle to a taping intervention and that the term inhibition of a single muscle may be too simplistic to explain the complex and intricate characteristics of the motor control system. Findings from this study suggest that there may be a shift in force contribution between the Vasti muscles with the application of tape, albeit a marginal response, which in combination with other motor unit control strategies could provide new and novel insights.

The individual analyses showed that the VM and VL responses were non-uniform with subjects sometimes showing complete opposing responses to the application of tape. Responses to the tape in some subjects showed large changes in the MFR with increases in the VM by 23.4% (Figure 10-6) yet decreases in VM by 19.1% in another subject (Subject 8). Interestingly the recruitment gradient of the motor unit firing in the tape condition seems to be steeper and could indicate another strategy at work.

The non-uniform responses in the MFR from the Vastus Medialis and Vastus Lateralis were not expected to be seen in such diverse and opposing ways, especially within the non-symptomatic subject population. Previous work (MacGregor et al. 2005) only demonstrated small changes (1-2 Hz) in response to a similar taping technique, but was limited to studying only a small selection of motor units, at a low level force and in symptomatic subjects. Whereas this study demonstrated subjects can exhibit firing rate changes up to 4 pulses per second (pps) (Figure 10-6) in response to tape. The firing rate of a motor unit is one of the key determining factors in the generation of force in the muscle (Burke 1981), thus a change in the motor unit firing rate infers a change in the force produced by the muscle. The findings from this work therefore suggest that non-symptomatic subjects alter the force contributions within each, and sometimes both, of the Vasti muscles in response to a taping intervention. The combination of an increase or decrease in the motor unit firing rate could consequently subtly alter the joint biomechanics and increase the overall stability at the knee.

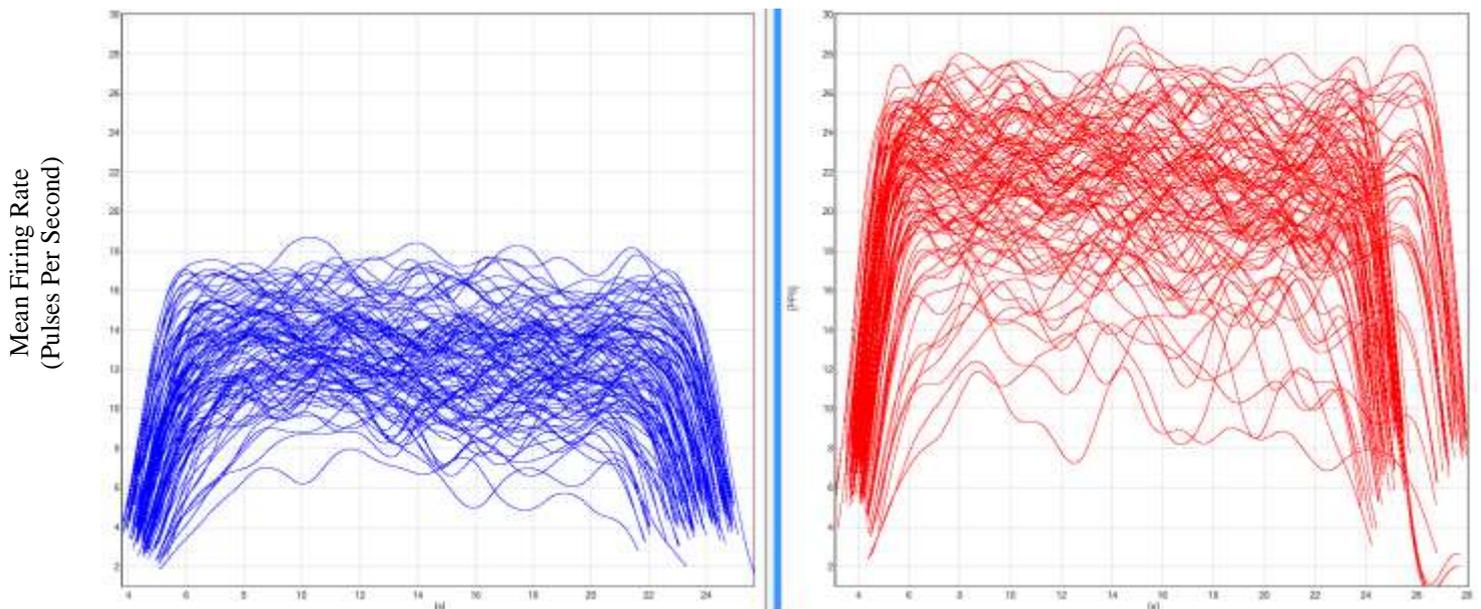


**Figure 10-6 Example of change in Vastus Medialis Mean Firing Rate in response to tape in non-symptomatic subject**

### 10.3.2.2 Symptomatic

The average MFR for all the symptomatic subjects, similarly to the non-symptomatic subjects, showed a marginal change in response to the taping intervention. The Vastus Medialis exhibiting a 4% increase in MU firing rate with the taping intervention, whereas the Vastus Lateralis MU firing rate not showing any response in the taping intervention when the results are pooled. These findings indicate, as with the non-symptomatic subjects, that the force contribution within the Vastus Medialis is marginally increased following the application of the taping intervention.

Upon further exploring the MFR results for each symptomatic individual it is evident that the MU firing rate response to tape is non-uniform. Subjects clearly demonstrate different responses to the taping intervention, often in different magnitudes and directions. For example one symptomatic subject responded with a 72.3% increase in VM MU firing rate (Figure 10-7) whilst another subject exhibited a 30.5% decrease in MFR in their VM MU firing rate. These examples seem to again display a steeper recruitment slope in the recruitment of the motor units and suggesting that a different strategy may be in use. Other subjects can also be seen to either increase, decrease or no change with the MU firing rate. It should be noted that no changes in the knee flexion moment were found, suggesting that the same load was subjected to the knee joint, and only motor units with an accuracy of <90% were included in the analysis, therefore the changes seen can confidently be assumed to be true physiological changes rather than measurement error. The only other evidence to present such dramatic changes in firing rate with an intervention using surface EMG decomposition is when measuring the microgravity induced changes in the motor unit control of astronauts (De Luca et al. 2003). These findings are the first of their kind to present empirical evidence that tape can alter the motor unit firing rate within individuals, suggesting that different subjects' nervous systems maybe offering different strategies in modifying the force contribution within the muscles. This offers key insights into the clinical response of tape seen in symptomatic individuals and provides evidence that tape can perhaps offer a clinically important change.



**Figure 10-7 Example of change in Vastus Medialis Mean Firing Rate in response to tape in symptomatic subject**

### 10.3.2.3 Non-Symptomatic vs Symptomatic

As can be seen from the previous discussion it is apparent that both non-symptomatic and symptomatic subjects exhibited non-uniform and individualistic responses to the taping intervention, regardless whether they were pain-free or presented with knee pain. Interestingly though when comparing the grouped data from the two subject groups the Vastus Medialis average MFR presented with similar pre and post tape intervention firing rates. In the no tape condition both groups exhibited similar MU firing rates, 17.8pps and 17.6pps for the non-symptomatic and symptomatic groups respectively. The tape condition response both showed a similar increase to 18.4pps and 18.6pps for the non-symptomatic and symptomatic groups respectively. This is, to the authors' knowledge, the first empirical evidence to compare Vasti motor unit firing rate between non-symptomatic and Patellofemoral Pain subjects. Trevino et al. (2014) recently demonstrated in a single case study showing significant differences in comparing healthy subjects to a spinal poliomyelitis subject with the firing rate of the Vastus Lateralis being 7.8pps higher in healthy subjects. This demonstrates that the surface EMG decomposition measurements are able to establish clinically important change between non-symptomatic and symptomatic subjects, providing reassurance that the lack of difference between the subject groups in this study is a true physiological. These findings are for the first time able to indicate that the Vastus Medialis MU firing rates, and consequently a method of generating force within the muscle, is the same between non-symptomatic and symptomatic subjects and that perhaps other motor unit strategies are apparent between the subject groups.

### 10.3.3 Motor Unit Common Drive

It has been shown that motor units rather than being controlled individually are in fact receiving a 'common drive' and are being controlled in unison (De Luca & Erim 1994), most likely mediated centrally (De Luca et al. 2009). Erim et al. (1999) eloquently presented the effects of aging on motor unit properties by showing that there is a significantly decreased commonality in the firing of the motor units in the elderly, compared to young subjects, suggesting a less efficient strategy from the CNS. Complimentary to this work De Luca & Erim (2002) demonstrated that common drive exists between motor units belonging to two synergistic muscles and in agreement with earlier work that common drive exists between antagonist muscles (De Luca & Mambrito 1987). Understanding the presence and degree of common drive in the Vastus Medialis and Vastus Lateralis has not before been explored, or has it been considered in Patellofemoral Pain subjects or with a clinical intervention. The notion of a disrupted commonality in the firing rates of symptomatic subjects and the response to a taping intervention is clinically a tantalising prospect, potentially providing information on the control and efficiency of the muscle. This study investigated the presence and degree of common drive in non-symptomatic and symptomatic subjects and their response to a taping intervention.

#### 10.3.3.1 Non-Symptomatic

It was found that the both the Vasti muscles exhibited evidence of a common drive to the pool of motor units, however no significant responses to the taping intervention were found when grouping the data (see section 9.5.1). The Vastus Medialis showed a 2.4% reduction in common drive with the application of tape and the Vastus Lateralis showing the same values between the tape and no tape conditions. These findings indicate that the motor units in the Vasti are controlled through a common drive, evident by the degree of cross-correlation and thus commonality in motor unit firings, however the taping intervention does not offer any significant modification to the common drive in non-symptomatic subjects. It was thought that the taping intervention may, through cutaneous stimulation, offer an altered and perhaps enhanced common drive strategy due to the proprioceptive feedback. However, it may be that the non-symptomatic subjects, as with the young subjects in Erim et al. (1999), already present with the optimal common drive strategy.

As the MU firing rate data presented non-uniform responses and strategies with the application of tape, and the common drive is calculated using the firing rate, the grouped common drive was exposed to investigate individual's responses. It was found that subjects demonstrated differing responses to the application of tape, whereas some subjects were showing large increases in common drive others were showing large decreases. For example subject 4 increased the common drive by 17.1% in the Vastus Medialis, indicating that more motor units were firing in unison with the application of tape. It could then be inferred that this is a more efficient solution provided by the nervous system for this subject. However, the opposite behaviour was also seen where for example subject 5 decreased the common drive by 14.3% in the Vastus Medialis with the application tape, indicating less motor units were firing in unison and a perhaps less efficient solution. No relationship was evident with increasing or decreasing in one muscle and the opposite behaviour seen in the other muscle in individuals. These findings exhibit for the first time that individuals present with variable responses to a clinical intervention in the degree of common drive consequently suggesting that tape can alter the neural drive to the motor unit pool and inferring an altered motor unit control mechanism. The clinical implication of this is that the application of tape cannot just modify the amount of force generated within a muscle but also the amount of control within the generation of force within the muscle. The 'control of a movement' or the 'quality of a movement' is often a mantra heard within clinical practice that is typically not complimented in the variables measured in the research field with studies taking relatively gross measurements such as peak angle and moments, maximum strength and often considered to be more sensitive sEMG measures. These variables are arguably not in line with the clinical message of 'control' and 'quality'. The introduction of the common drive in response to a clinical intervention offers a unique concept and it can be seen from these findings that it presents clinically meaningful differences.

#### 10.3.3.2 Symptomatic

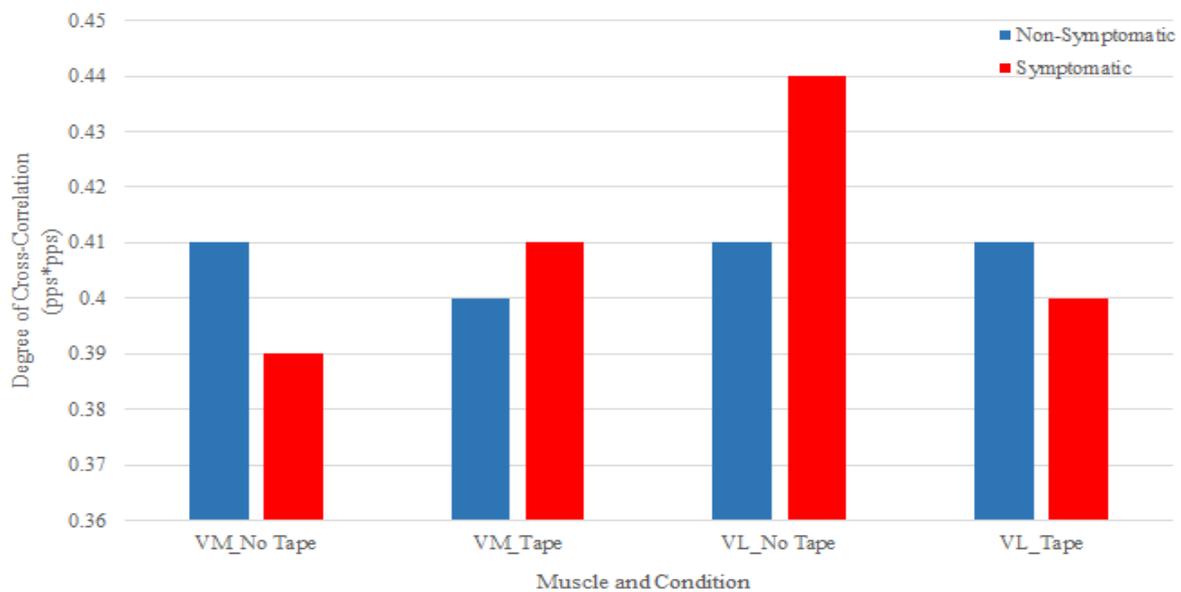
The grouped analyses of the symptomatic subjects found that the Vasti muscles common drive responded with opposing behaviour. The Vastus Medialis increased the common drive by 5.1% across the group of symptomatic subjects, again demonstrating that common drive is present but more interestingly that the taping intervention is modifying the control of the motor unit pool. The Vastus Lateralis presented, opposing the Vastus Medialis behaviour, with a decrease in common drive with the application tape by 9.1%. These fascinating findings

provide additional support for the fact that a taping intervention can alter the control of the motor unit pool either by increasing or decreasing the commonality of the motor unit firings, inferring a more or less controlled generation of force within the muscle. However, the most interesting finding is the increase in the Vastus Medialis and the decrease in the Vastus Lateralis as this infers that there may be a disproportional control response between the Vasti with the application of a taping intervention. The findings would suggest that with the application of tape more Vastus Medialis motor units are firing or 'working' in unison thus seemingly being more efficient when generating force within the muscle. However, at the same time the Vastus Lateralis has less motor units firing in unison and seemingly becoming less efficient at generating force within the muscle. These findings may be presenting an indication as to the inhibition of Vastus Lateralis and complimentary excitation to the Vastus Medialis in response to the application of tape. De Luca et al. (2009) found that the decrease in the degree of motor unit common drive may not necessarily be an indication of decreased common drive from the central nervous system, but rather an inhibitory influence from the peripheral nervous system. It was proposed that the inhibition is being influenced by the proprioceptive feedback with the muscle spindles being primarily responsible, which was also shown in other work (Garland & Miles 1997). These findings could offer an attractive insight into the observed decrease in Vastus Lateralis common drive seen in the taped condition, rather than a centrally mediated decrease in common drive to the motor unit pool the tape is providing feedback to the muscle spindles which in turn the peripheral nervous system modifies the control to the motor unit pool with an inhibitory mechanism.

Individual analyses of the symptomatic subjects highlighted the evidence of some individualistic responses with differing directions and degrees of common drive to the Vasti. Some subjects demonstrated large increases in common drive with the application of tape, a 31.3% in the Vastus Medialis was found in one subject (PFP 13). Yet, other subjects responded with a large decreases in common drive, for example PFP 7 exhibited a 10.5% decrease in the degree of common drive in the Vastus Medialis. Similar findings are also seen in the Vastus Lateralis with a non-uniform response to tape amongst the subject group. These findings again bring to light the importance of an individualistic response and contributes to the thought that there may be different strategies available and actioned in response to the tape intervention. This holds clinical importance as it demonstrates that both groups of and individual symptomatic subjects can present with a form of plasticity within the motor control system.

### 10.3.3.3 Non-Symptomatic vs Symptomatic

The grouped common drive data highlight some tantalising differences between the subject groups. The Vastus Medialis common drive shows that there is a lesser degree of common drive in the symptomatic subjects compared to the non-symptomatics. However, following the application of the tape the common drive in the Vastus Medialis increases to match the same degree of common drive seen in the non-symptomatics. The Vastus Lateralis is also reduced in the symptomatic subjects to match the same common drive in the non-symptomatics. These findings are shown in Figure 10-8 and highlight the apparent adjustment of the common drive to the Vasti muscles in the symptomatic subjects to match the non-symptomatics with the tape intervention.



**Figure 10-8 Common drive results from both subject groups before and after the application of tape.**

Although less of an effect, the differences seen in this study between the non-symptomatic and symptomatic subjects demonstrating a lesser degree of motor unit firing commonality and consequent common drive in the symptomatic subjects Vastus Medialis displays similarities to the findings and considerations of Erim et al. (1999) where there seems to be disruption in the motor unit control. However, the taping intervention then demonstrates a reversal of the disproportion control of the Vasti motor units, presented by an increase in common drive to the Vastus Medialis and decrease in Vastus Lateralis, suggesting that the taping intervention may be causing inhibition of the Vastus Lateralis and excitability of the Vastus Medialis to match

that of the non-symptomatic subjects. These findings are the first of their kind to be able to demonstrate firstly the disproportionate control of the Vasti between non-symptomatic and symptomatic subjects and secondly that a taping intervention can alter the motor unit control mechanisms. The deduction of the apparent modifications are difficult to establish, however it is speculated that the tape on the skin through cutaneous stimulation, skin stretch (MacGregor et al. 2005) or more vaguely proprioception provides feedback to the muscle spindles which through afferent feedback influences both the central and peripheral nervous systems to alter the motor unit firing and their control (De Luca et al. 2009). The findings suggest that the application of tape can modify the control of the motor units to the symptomatic subjects so that it equals the common drive seen in the non-symptomatic subjects. The pre-tape mismatched distribution and degree of common drive to the Vasti suggests that symptomatic subjects may have less efficient organisation of motor unit control, which is consequently modified to be more efficient with the application of tape demonstrating key clinical implications.

### 10.3.4 Motor Unit Recruitment Strategy

Another mechanism of changing the force level of a muscle in a voluntary contraction is the recruitment of motor units (Adam & De Luca 2003) and the strategy used to achieve this. It is well documented that the recruitment of the motor units and the modulation of firing rates is structured and inversely proportional to the mean firing rate of motor units (De Luca & Erim 1994; Erim et al. 1999; De Luca & Hostage 2010; Stock et al. 2012; De Luca & Contessa 2012). The recruitment threshold provides information on the recruitment of the motor unit pool and its strategy to generate force within the muscle through either an altered motor unit firing rate and/or the level of force required to recruit the motor units. Tucker and Hodges (2010) showed that the recruitment strategy of the Vasti motor units changed during pain which then altered the direction of muscle force, however the study was limited as they were only able to measure a small number of motor units at a low level of force and in a non-functional or challenging task. Stock et al. (2012) using surface EMG decomposition methods found that the recruitment threshold of the Vastus Lateralis was altered in a fatigued muscle, demonstrating that the fatiguing protocol either recruited higher threshold motor units or increased the firing rate of the existing higher threshold motor units. These findings once again provide evidence that the Vasti muscles can demonstrate clinically important changes and do so in the presence of pain or fatigue. However, no previous work has investigated the recruitment strategy using surface EMG decomposition methods in Patellofemoral Pain subjects or the effect of a therapeutic intervention such as taping.

#### 10.3.4.1 Non-Symptomatic

It was found that in the taped condition the Vastus Medialis motor units were being recruited driving the motor units to fire faster, represented by a significantly different regression intercept ( $p < 0.001$ ) and slope gradient ( $p < 0.05$ ). These findings suggest that in response to the tape intervention the motor unit pool is being driven to fire quicker at the same level of excitation/force, consequently suggesting that the force within the Vastus Medialis may have increased. Although the analyses demonstrated significant statistical changes the mean differences of 1.4pps for the motor unit intercept should be considered for its clinical significance and whether this marginal, albeit it significant, change represents a true physiological change for the group. The Vastus Lateralis conversely did not exhibit any significant changes in the tape condition and the recruitment strategy remained unaltered. The strategy of the Vastus Medialis motor unit pool to be recruited with higher firing rates presents

a unique and seemingly efficient strategy by the CNS to modify the control of the knee joint in response to tape by altering the force within the muscle, this is the first time that this has been investigated or shown before.

It was found that, like the mean firing rate and common drive, the recruitment threshold strategies differed amongst the non-symptomatic subjects. Although the grouped analyses of the non-symptomatic subjects presented with significant changes towards motor units being driven at a higher firing rate there were subjects within the group who presented with the opposite behaviour. Subject 9 for example presented with a significantly lower intercept ( $p < 0.001$ ) and significantly flatter slope gradient ( $p < 0.001$ ) with the application of tape in the Vastus Medialis. However, this subject instead presented a different strategy of recruiting the Vastus Medialis.

An alternative motor unit recruitment strategy was observed for the first time where the motor unit pool was being recruited at a different level of force/knee moment in response to the taping intervention. In the example of Subject 9 they required less force/knee moment to recruit the Vastus Medialis motor unit pool with the taping intervention. This strategy, termed the recruitment operating point, presents a novel finding that in the same subject and the same muscle the operating point, defined as the firing rate versus the recruitment threshold line (De Luca & Hostage 2010), is able to decrease or increase the required force/knee moment to recruit the motor unit pool in response to the taping intervention. The same hierarchical organisation of the motor unit pool recruitment is still retained as shown by De Luca & Hostage (2010), but perhaps demonstrates the plasticity of the operating point in being able to shift. The adjustment of the muscles operating point seems to be a strategy from the CNS to manipulate the timing of the force production within a muscle and allow the force to be generated earlier or later. This findings have not directly been observed or considered previously and shows for the first time a novel and unique strategy in the response of the muscle in symptomatic subjects and with the application of tape. A plethora of previous work may have found indications of this phenomenon when studying the onset timing of the muscle using traditional surface EMG measurements (Gilleard et al. 1998; Cowan et al. 2001; Cowan et al. 2002; Cavazzuti et al. 2010; Aminaka et al. 2011) showing the onset timing of the Vasti was altered in Patellofemoral Pain subjects and in response to tape. However, the techniques in exploring the timings have been questioned to their validity (Uliam Kuriki et al. 2011) showing that the different methods of establishing the onset show variable and inconsistent findings suggesting that traditional

surface EMG may not be sensitive enough to establish the discrete differences in motor unit recruitment. However, in being able to study individual motor units and their firings it offers a more sensitive measure in determining the onset of the muscle, and perhaps more importantly being able to relate to a physiological measure, the level of knee moment, opposed to a measure of time. Similarities can be drawn between the recruitment threshold and the muscle onset timing, but arguably are unable to be compared due to the galactically different sensitivities in the measurement and outcome variable. As Uliam Kuriki et al. (2011) reported there are various techniques in trying to understand the onset of the muscle, all of which offer difference outcomes depending on the calculation, but by using EMG decomposition to investigate the muscle onset through using recruitment threshold the onset of the muscle is identified by studying the first firing of the first motor unit and uniquely is then able to study the remaining recruitment of the consequently recruited motor units. So although the measures have a relationship it would be unfair to directly compare as would comparing the knee angle from a handheld goniometer to a 3D motion capture system.

These methods and consequent findings provide for the first time a detailed explanation and insight into various methods of recruiting motor units within subjects and their responses to a taping intervention offering potentially key clinical insights into both the presentation and possible responses that subjects display.

#### 10.3.4.2 Symptomatic

Grouped results of the recruitment threshold did not show any significant changes with the application of tape in the symptomatic subjects. Both the regression intercept and slope gradients did not present any significant changes ( $p=0.52$  and  $p=0.25$ ) for the Vastus Medialis respectively or the Vastus Lateralis ( $p=0.80$  and  $p=0.23$ ) respectively. These results infer that as a group the symptomatics subjects do not change their recruitment strategy with the application of tape. These findings are interesting as it was expected that like the non-symptomatic subjects the Vasti would respond to the application of the tape suggesting a degree of plasticity in the symptomatics motor unit recruitment strategy. Instead they did not offer any significant change with the application of tape, which however does offer an interesting finding in that symptomatic subjects may not have the ability to use a different recruitment strategy. However, when investigating the individuals response it became apparent that although no significant changes were seen looking at the grouped data, individuals presented with variable responses to the taping intervention with 9/13 subjects exhibiting a significant

response ( $p>0.05$ ) to the tape. Similar to the non-symptomatic subjects there were individual subjects who had a significantly altered recruitment strategy in either in the Vastus Medialis or Vastus Lateralis, or sometimes both of the Vasti muscles. The two strategies being used were either to alter the firing rates by driving them quicker at the same force/knee moment, or the motor units were being recruited at a lower or higher force/knee moment as seen in the non-symptomatic subjects.

Subject PFP 1 for example demonstrated a 9.6% change in recruitment operating point with the Vastus Medialis muscle being recruited with less force/knee moment requirement, causing force within the muscle to be generated at any earlier point with the application of tape. However, subject PFP 12 demonstrated a different strategy and to reduce the force/knee moment to the Vastus Lateralis, by 8.8% in this example. Both strategies demonstrate that there are various methods the nervous system employs to alter the recruitment of the contributing muscles

#### 10.3.4.3 Non-Symptomatic vs Symptomatic

Significant differences were found when comparing the motor unit recruitment threshold for the non-symptomatic and symptomatic subjects in the Vastus Medialis and Vastus Lateralis (see section 9.12.5). The regression intercept indicated that the Vastus Medialis in symptomatic subjects was being recruited at a significantly ( $p<0.001$ ) lower firing rate compared to the non-symptomatic subjects. An equally fascinating finding was that the Vastus Medialis in the symptomatic subjects exhibited a significantly ( $p<0.001$ ) flatter slope gradient, indicating that the later recruited motor units in the Vastus Medialis were firing at a significantly higher rate for the same level of force/knee moment compared to the non-symptomatic subjects. Interestingly the Vastus Lateralis showed the opposite behaviour to the Vastus Medialis. This was evident by the significantly ( $p<0.001$ ) lower intercept and slope gradient ( $p<0.005$ ). Never before has the recruitment thresholds of the Vasti been compared between non-symptomatic and symptomatic subjects so these findings provide the first evidence that symptomatic subjects may present with a different and potentially clinically significant alteration in the strategy of recruiting the Vasti muscles. The changes exhibited between the subject groups are similar to the findings by Stock et al. (2012) after investigating fatigue of the Vasti it was found that the Vastus Lateralis presented with significantly flatter slope gradient and significantly lower slope intercept in the fatigued condition compared to the

pre-fatigue condition thus demonstrating that the later recruited motor units had a significantly higher firing rate at the same level of force in the fatigued condition. Although Stock et al. (2012) did not see any changes in the Vastus Medialis, this could be due to the open kinetic chain knee extension task performed and perhaps lacking the involvement or stability challenge to the Vastus Medialis, unlike in this study where subjects performed a stability challenging closed kinetic chain exercise.

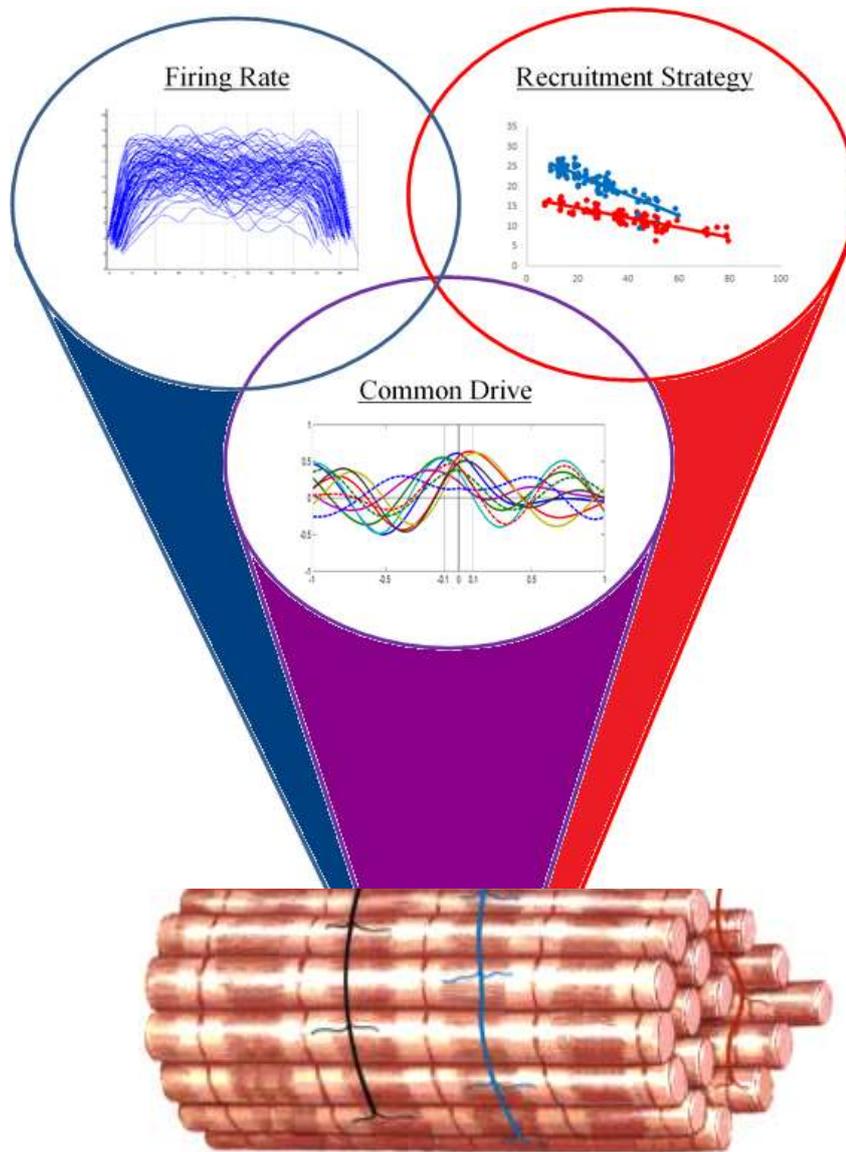
These findings indicate that both the Vastus Medialis and Vastus Lateralis in the symptomatic subjects present with significantly different motor unit recruitment strategies compared to the non-symptomatic subjects. The strategy of the symptomatic subjects is to increase the firing rate of the later recruited motor units at the same respective level of knee moment, which would consequently offer an increased level of force within the two Vasti muscles. These results are in agreement with the previous observations (see section 0) that the surrounding musculature is less active in the symptomatic subjects and consequently the Vasti have a greater responsibility to manage the load of the knee joint, which could cause a greater patellofemoral joint reaction force and consequently pain. These findings perhaps further demonstrate a strategy of the symptomatic subjects to disproportionately bias towards the Vasti compared to the non-symptomatic subjects, regardless it does offer a novel and clinically important presentation of symptomatic subjects and the apparent different strategies.

### 10.3.5 Motor Unit Control Strategy

It is evident from the previous sections that the nervous system presents various strategies in controlling the motor unit pool to the Vastus Medialis and Vastus Lateralis and how it responds to the taping intervention. However, it is also evident that the motor unit firing rate, common drive and recruitment strategy present variable responses amongst individuals which could be offering a portfolio of solutions to achieve the same goal, increasing the force and its control within the muscle.

The different motor unit control strategies can be likened to a cyclist's strategy, whereas one's goal is to increase force and control the other is to increase speed and efficiency. In road cycling the goal is often to cycle the fastest, in order to achieve this there are many factors involved (athlete, conditions, equipment etc.) but for this analogy the athlete, being the most deterministic in achieving the goal, is the discussed factor. In order for the cyclist to be the fastest depends on speed and efficiency, the former of which can be described in terms of cadence and gear selection. For example if the cyclist wants to go quicker they can increase the cadence and/or change to a higher gear, consequently leading to an increase in speed. This is similar to increasing the force within a muscle where the CNS can increase the MU firing rate and/or adjust the MU recruitment, both of which will result in an increased force. The other factor to consider is feedback, in road cycling the team will be in constant communication with the support car feeding back information verbally and through an array of sensor technologies, whom in turn instruct the rest of the team. This can be related to the nervous system as the muscles are providing constant feedback to the CNS via various sensory components which, through common drive, provide instruction to the motor unit pool. Both examples can be improved with more effective and efficient feedback, of which tape may offer significant improvements to the feedback of the nervous system and consequently leading to enhanced control.

The complex inter-relationship between the motor unit firing rate, motor unit recruitment threshold and the common drive offer unique strategies at achieving the same objective in the generation of force and its control within the muscle. As with cycling, individuals may be instructed to ride in a lower gear with a higher cadence and be given constant adjustment through feedback. Similar to how an individual's CNS instructs muscles to alter the recruitment of the motor units, the mean firing rate and/or common drive (Figure 10-9).



**Figure 10-9** Graphical representation of the inter-relationships and contributing factors to force generation and control within the motor unit pool

#### 10.4 Neuromuscular, Biomechanical and Clinical Relationship

Each discipline has its own complex and intricate inter-relationships such as the relationship between an adducting knee moment and internally rotating hip or motor unit firing rate and recruitment strategy. However, instead of considering these differing disciplines to be independent they should be considered as being delicately inter-related and weaved as one multifaceted and redundant motor control system.

It has previously been shown that the knee joint mechanics offers subtle yet significant improvements in movement control with the application of various proprioceptive orientated interventions in non-symptomatic (Selfe et al. 2008) and symptomatic (Selfe et al. 2011) subjects. Following on from previous work this study studied the knee joint biomechanics with a common clinical taping intervention. It was found that the application of the taping intervention offered significant improvements in the knee joint control across the subject groups, however interestingly there was a non-uniform response when exploring the subjects as individuals. Regardless of the direction of the response it shows that a seemingly simple clinical taping intervention has a significant effect on the knee joint mechanics but offers little in understanding on how the changes in mechanics occur.

An often understated factor to movement control and its response to pain are the psychological mechanisms and specifically the conscious motor processing involvement. Selfe et al. (2014) found that subjects presenting with self-reported knee pain have a higher propensity for conscious motor processing than their pain free counterparts, suggesting that subjects experiencing pain have a tendency to consciously control their movements. This study found similar results to Selfe et al. (2014) where symptomatic subjects showed a trend towards consciously controlling their movements, suggesting they are concerned with the execution of their movements. These findings are also in agreement with other work that suggests subjects respond to pain and fear of pain developing avoidance mechanisms (Lethem et al. 1983). Lethem et al. (1983) also suggests that the response may be individualistic with either an 'avoidance' or 'confrontation' response. These suggestions are complimentary to individuals' strategies found within this study, where subjects employed different movement control strategies seen in the biomechanical and neuromuscular findings.

Studying the neuromuscular system, being primarily responsible for movement and control of the joint mechanics, is commonly undertaken to better understand the underlying mechanisms

associated with Patellofemoral Pain. However, previous work has typically taken measurements from just the Vasti and seemingly ignoring the potential importance from surrounding musculature. It was found in this work, through gross EMG amplitude measurements that the Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius are all involved in the control of the lower limb and offer marginal yet non-uniform responses to the application of the taping intervention. However, investigating the relationships between the knee joint mechanics and the gross EMG measurements it is apparent that the two subject groups offer distinctly differing strategies. Whereas the non-symptomatic subjects present with variable EMG responses across the muscles and consequently more controlled joint mechanics, the symptomatics present with less variable EMG responses and consequently more variable knee joint mechanics. These findings show firstly that studying surrounding musculature is an important factor to consider in a movement and condition where multiple muscles are involved, but secondly that symptomatics subjects offer less muscle activity and less flexibility in modifying the activity of the muscles surrounding the knee. However, the mechanisms as to how the change in muscle activity and apparent different strategies are managed cannot be fully determined from monitoring gross EMG and joint mechanics changes. Instead it becomes necessary to gain insight into how the brain and nervous system responds to the effect of a proprioceptive orientated intervention.

Thijs et al. (2010) using functional magnetic resonance imaging (fMRI) investigated levels and areas of brain activation with a knee brace, knee sleeve and without any application. It was found that higher levels of cortical activation were present with the application of the two interventions. Similar findings were later found by Callaghan et al. (2012) with a taping intervention, where significant increase in blood oxygenation level-dependent (BOLD) were found in the taped condition. Both of these studies present evidence suggesting that a peripheral proprioceptive intervention, such as tape or knee braces, influence brain activity in areas of the brain thought to be responsible for proprioception. These findings coupled with previous work investigating the changes with joint mechanics, gross muscular changes and conscious motor processing involvement suggest that tape and other proprioceptive orientated interventions are capable of modifying the sensory-motor processes but still lacks information on the mechanisms of force and control.

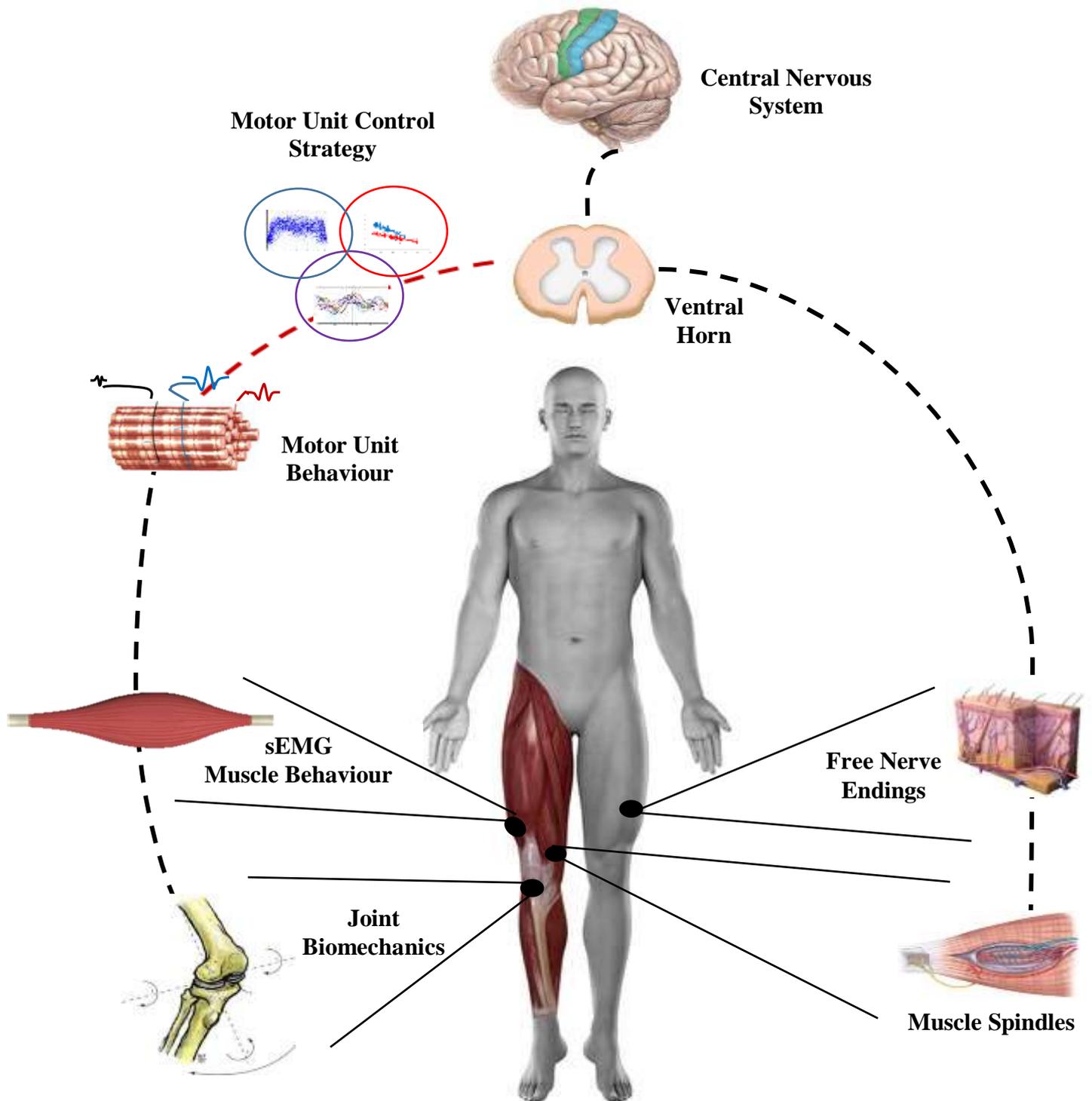
MacGregor et al. (2005) investigated the effect of a taping intervention on the motor unit activity, using intramuscular EMG, finding that a small proportion of Vastus Medialis motor

units increased the firing rate in the taped condition. Similarly Mellor and Hodges (2005a) found that the motor unit synchronisation was reduced in Patellofemoral Pain subjects compared to controls. Both these studies suggest that changes can be found in the control of individual motor units, which suggest that the force generation and control within the motor units and consequently the muscle can be altered. However, both studies were severely limited due to the yield of motor units for study, the lack of a function and clinically relevant task but more importantly the relationship between the different sensory-motor systems. The findings from this work provides evidence of different motor unit control strategies through modifications in the firing rate, common drive and/or recruitment of the motor unit pool in the Vastus Medialis and Vastus Lateralis. It was found that the nervous system offers a portfolio of strategies in order to alter the force and control of the motor units to both symptomatic and non-symptomatic subjects in response to a taping intervention. These findings and postulates are in agreement with recent work by Hodges et al. (2013) in the investigation of muscle control and spine stability during experimentally induced lower back pain. It was found that lower back pain caused a variable pattern of increasing and decreasing trunk muscle activity, leading to an increased estimated spine stability. Suggesting that, unlike previous theories (Roland 1986; Lund et al. 1991), there are many ‘solutions’ available to increase stability rather than a stereotypical response, and perhaps a redistribution of activity within and between muscles (Hodges & Tucker 2011).

The underlying mechanism for the observed findings are unable to be expressed definitively, however it can be deduced from the findings that the application of the tape may be presenting a form of feedback to the muscle, most likely the muscle spindles (De Luca et al. 2009), which both the central and peripheral nervous systems alter the motor unit pool by adjusting the force and its control within the muscle that may consequently adjust the joint mechanics. The key clinical implications for these findings is that the application of tape can offer clinically meaningful change to the motor control system. However, researchers and clinicians should consider the individualistic responses with data analyses and clinical decision processes respectively.

Previous investigations have found significant and clinically important changes in the joint biomechanics, psychosocial factors, brain activity, gross neuromuscular activity and limited findings in the motor unit control, which have all often been studied in isolation. This study’s unique and inter-disciplinary investigation provided a detailed and novel insight into the motor

unit control, biomechanical, neuromuscular and psychosocial factors in understanding the movement control of Patellofemoral Pain subject and the response to a common clinical intervention. The delicate and proposed inter-related motor control system, as first described in section 2.7, can now be seen to hold a fuller description by contributing the novel aspects of the motor unit control strategies (Figure 10-10)



**Figure 10-10 Graphical representation of systems involved in movement control including new motor unit control strategy findings**

## **11. Conclusions**

### 11.1 Summary

In conclusion, this study investigated the neuromuscular, biomechanical and clinical changes associated with control of the knee joint and the response to a taping intervention, in both non-symptomatic and Patellofemoral Pain subjects. The study applied novel methods and techniques to determine the motor unit control of the Vasti muscles combining with a host of complimentary biomechanical and psychosocial measurements to provide a unique insight into the redundantly complex sensory-motor control system.

The application of the taping intervention exhibited significant reductions in the torsional joint range of moment in non-symptomatic and symptomatic subjects, suggesting that tape can offer clinically meaningful improvements in joint stability and control. Non-uniform responses to the tape application in the coronal and transverse planes were observed, indicating individualistic biomechanical schemes form part of the motor control strategy. Significant reductions in the activity from the muscles proximal, distal and surrounding the knee were found in the symptomatic subjects compared to the non-symptomatics, suggesting a disproportion bias to other structures and explicitly the Vastus Medialis and Vastus Lateralis. Complimentary to the objective neuromuscular and biomechanical findings the symptomatic subjects demonstrated a propensity to consciously control their movements indicating that they are concerned and aware of the execution and the movements they carry out. Although no obvious relationships were found with the objective measures it does propose the importance of the psychosocial features in understanding the presentation and subsequent clinical management of Patellofemoral Pain subjects.

The study supplemented the investigations of the joint biomechanics and surrounding musculature with novel explorations of the unique motor unit control schemes and their strategies used to generate, modify and control force within the Vastus Medialis and Vastus Lateralis. It was found that the motor unit firing rate can be manipulated and is responsive to the application of tape demonstrated by an increase in firing rate for the Vastus Medialis and decrease in Vastus Lateralis. Accompanying the change in firing rate it was found that the symptomatic subjects demonstrated an increase in common drive to the Vastus Medialis with the application of tape, indicating more motor units were been controlled in unison and suggesting a more efficient solution in controlling the muscle. The Vastus Lateralis however

displayed the opposite behaviour in response to the application of tape with a decreased common drive, which may be due to an inhibitory mechanism from the peripheral nervous system and suggesting both findings indicate an overall strategy in re-distributing the contribution of Vasti motor unit control with the application of tape. Symptomatic subjects demonstrated significant differences to the recruitment threshold by showing the later recruited motor units were being driven to fire faster compared to non-symptomatic subjects at the same level of force/knee moment. Some subjects also displayed a different and/or accompanying recruitment behaviour by shifting the recruitment operating point so that less or more force/knee moment was required to recruit the motor unit pool. However, as with the biomechanical responses the motor unit responses exhibited individualistic responses to the application of tape. Individuals from both non-symptomatic and symptomatic groups displayed a disparity of increasing and decreasing motor unit firing, common drive and recruitment strategies, suggesting that tape can dramatically and individualistically modify the control and generation of force in the Vastus Medialis and Vastus Lateralis.

The unique explorations and novel findings from this work suggests that the nervous system offers various strategies in order to generate and control the force of the muscles surrounding the knee, also demonstrating its plasticity by offering significant and clinically meaningful responses to a clinical intervention. In combination with the biomechanical responses and psychosocial features this work offers a key insight into the sensory-motor control system which seemingly presents a portfolio of strategies.

## 11.2 Clinical Contributions

The aim of this work was not only to contribute to the research knowledge gap in Patellofemoral Pain, but of equal importance was to contribute to clinical practice providing clinicians with pertinent information about the presentation and observed responses to a therapeutic intervention. Although the methods and equipment used within this work are beyond the scope of most clinical practice the findings from this work can provide clinicians with key insights into some of the potential sensory-motor strategies patients may present with and how they may respond to a therapeutic intervention. A summary of the key clinical messages can be found below:

- Although established anatomical and morphological evidence exists to suggest that the Vastus Medialis has two distinct portions, Obliquus and Longus, explorations into the motor unit control behaviour between the two portions suggest that the muscle is in fact a single functional unit. Indicating that any treatments directed at the Vastus Medialis will affect the whole muscle rather than portions of the muscle.
- Patellofemoral Pain patients present with significantly reduced muscle activity in the Medial Gastrocnemius, Biceps Femoris, Rectus Femoris and Gluteus Medius compared to non-symptomatic individuals. Suggesting that PFP patients may bias other structures, such as the Vasti, potentially increasing the patellofemoral joint reaction force. Treatments should possibly be directed towards enhancing the contribution of the surrounding muscles and/or re-distributing the Vasti load.
- Rotational control of the knee joint mechanics can be enhanced with the application of tape, suggesting that the knee joint may be more stable in a taped condition.
- Patellofemoral Pain patients present with a significantly altered motor unit recruitment strategy in the Vasti, suggesting a higher force contribution from within the Vasti. This may imply that the Vasti muscles in PFP patients are being disproportionately worked in comparison to other muscles.
- Application of the taping intervention increased the control of the motor units in the Vastus Medialis and simultaneously decreased the control to the Vastus Lateralis. The findings suggest the tape provides feedback to the nervous system, which in

turn modifies the controlled firing of motor units possibly by exciting the VM and inhibiting the VL.

- The psychosocial features should be considered in the clinical decision and management, as these findings show that the majority of PFP patients consciously control their movements and is an important contribution towards movement control.
- The presentation of PFP and non-symptomatic subjects and their responses to a taping intervention appear to be individualistic and variable. At this time phenotypes of motor control and responses cannot be established, but it is clear that the sensory-motor control system offers a portfolio of strategies. Management and treatment should consider the presentation and response of each individual subject.

As with all clinically orientated research the clinical significance should be contextualised with the Minimal Clinical Important Differences (MCID) in mind where possible, and understanding the justification if an observed change is clinically significant or could be masked by measurement error, reliability or variability. As the thesis presents new and novel techniques at exploring the neuromuscular system the MCID's have are still debatable, within this work the clinically significant changes were framed within a percentage change (see sections 7.8 and 9.10) and differing criteria depending on the outcome variable. The study design being a combination of biomechanical, neuromuscular and clinical measures allows a fuller description of the behaviour but also confidence in changes observed.

### 11.3 Research Limitations

As with all research there are limitations that need to be announced and considered, and importantly how these were minimised and can be improved in future works. The study counteracted many of the potential limitations by performing a rigorous literature review and a host of complimentary pilot studies, yet some variables could not be controlled.

*Static Task:* The goal of the research was to explore the sensory-motor control processes and their response to a taping intervention, to do which a task that could challenge the stability of the knee joint needed to be used. One of the key limitations is that the task required to be isometric due to the surface EMG decomposition technology unable to resolve the complexities of an EMG signal during dynamic movements. The study used a single limb isometric task that was found to be sufficiently challenging to the subjects whilst at the same time abiding by the limitations of the surface EMG decomposition system. However, this limits the application of the findings of the work to static isometric movements rather than the dynamic, concentric and eccentric, movements that are more functionally placed in normal daily activities and causes of PFP. Future work will be able to make use of the technological evolutions of the surface EMG decomposition technology that will be upon us in the near future. But it should not be forgotten that the static task provides us with a grounding of work in understanding the change in control that can be elicited during non-dynamic situations.

*Algorithm based processing:* Naturally a discussed limitation with advanced technologies is the understanding and trust placed in their complex signal processing, whereby raw data is fed into an algorithm that processes the data and automatically provides a data output. To counteract arguments and suggestions of this as a limitation the researcher should ensure robust and appropriate validation has been undertaken. The technology involved in decomposing the surface EMG signal used within this project has been in development for over 20 years and has a host of technical and application based publications to provide confidence in the data output. Future research should still consider the accuracy and validation with these technologies and understand their limitations, using them in the recommended and appropriate manner.

*Subject numbers:* The study abided by the calculated sample size with having 13 subjects in each group and so was powered adequately, however as can be seen from the individual results additional subject numbers could have assisted with the potential identification of sub-groups with the sensory-motor control strategies. The volume of data collected from an individual

subject (500,000 data points) placed large time constraints on the data collection and processing steps. It is hoped that future work can be more directed in the data processing steps by eliminating the non-significant findings to make the analyses more targeted and reducing the computation times or using new analysis tools that are being developed.

*Intervention effects:* The study was designed to evaluate the immediate changes to the subjects' sensory-motor control behaviours, but we are unable to elicit whether the changes observed have any effects are maintained after removal of the intervention or they have any longer term benefits. Future work should establish whether the subjects' are able to modify their movement control after the removal of the tape and therefore make permanent alterations to the control processes.

*dEMG Reliability:* There is currently no literature on the within-session or between-session reliability of the surface EMG decomposition variables, nor did this work quantify the reliability. Although anecdotal evidence suggests within and between session data provides consistency in the reported outcome variables empirical evidence is needed. The results of the thesis should be viewed with this point in mind.

## 11.4 Further Work

The findings from this work have shown tantalising insights into the sensory-motor control system and its presentation within a Patellofemoral Pain subject group, which creates additional avenues for future research.

### 11.4.1 Current Data Set

The data collection from this work produced a vast and rich set of data that was then segregated for analyses and produced the findings of the thesis, however there remains a host of additional data which may provide further insights into the current findings. A summary of the planned exploration of the current data set is listed below:

- Explore the biomechanical control of the ankle and hip joints and its relationship to the already established findings.
- Further explore the pilot study data (section 5.2) of the Vastus Medialis motor units using two methods:
  - i) Determine the cross-correlation for both portions and whether there may be any differences in common drive between the two portions of the VM.
  - ii) Explore the single motor unit action potential (MUAP) shapes for evidence of the same MUAP in the two portions.
- Determine the cross-correlation of the Vastus Medialis and Vastus Lateralis in relation to the coronal and transverse plane knee moments in order to explore the control of the motor units versus control of knee moment.

### 11.4.2 Future Directions

- The findings would suggest that the tape has a proprioceptive effect, therefore exploring other proprioceptive orientated interventions such as neoprene sleeves, knee braces and/or kinesiology tape may provide interesting and complimentary insights.

- The longer term effects of the taping application could be explored to see whether the sensory-motor control system can be re-educated.
- In combination with the above, the effects of differing rehabilitation protocols on the sensory-motor control system could be explored.
- Although current work was specific to Patellofemoral Pain, the findings suggest similar explorations would be applicable in other patient population groups such as lower back pain or knee osteoarthritic in understanding the motor control and response to clinical interventions.
- Technological advancements in surface EMG decomposition will soon provide the ability to expand the application from isometric muscle contractions to include the facility to decompose both concentric and eccentric muscle contractions. The advent of these significant advancements will open up new possibilities to study the sensory-motor control system in a dynamic situation and building upon the current findings. Explicitly it would be possible to mimic the protocol from Selfe et al. (2008 and 2011) in studying the stability challenging and functional step descent, but with the key addition in being able to study the eccentric muscle behavioural characteristics and its response to various therapeutic interventions.
- The future decomposition developments may also allow the investigation of other high loading activities such as walking and running, perhaps even the possibility of the measurements of more than two simultaneously recorded muscles and in real-world environments.

## 11.5 Final Conclusions

This work, in addition to the main study, offered various insights and contributions to the understanding of the motor control system and the application of novel methods, which could be applicable to future work. A summary of the key contributions can be found below:

- Demonstrating empirical evidence that the Vastus Medialis should be treated as a single functional unit instead of two differing portions through evidence of comparable motor unit behaviour between the Obliquus and Longus portions of the muscle.
- Providing evidence that surface EMG decomposition methods can, through careful thought and consideration, be used in closed kinetic chain exercises rather than previous work which have applied the decomposition methods to open kinetic chain exercises.
- Presenting a method to normalise the motor unit pairing cross-correlation results to provide an accurate and comparable representation of common drive.
- Relating the recruitment of motor units to a more sensitive physiological measurement, knee joint moment, opposed to previous work where it has been related to a gross measurement of force.
- Approaching Patellofemoral Pain with an inter-disciplinary approach by co-investigating the biomechanical, neuromuscular and psychosocial features and their response to a clinical intervention using advanced technologies.

## 12. Appendices

### 12.1 Appendix A – Individual Results

#### 12.1.1 Omitted Data

Following the processing of the data set it was found that 5 subjects, 3 subjects from the non-symptomatic subject group and 2 subjects from the symptomatic group, data did not meet the criteria for motor unit quality as specified in motor unit selection section (4.3.3). The majority of the accuracy values for the motor unit firings were found to be <90%. Consequently the firing rate accuracy indicated that the motor units may not reflect the true behaviour of the motor units and may skew the grouped analyses. The cause of the poor quality data was most likely due to a change in the skin-electrode interface, such as the skin drying out.

#### 12.1.2 Kinematic and Kinetic Results

**Table 12-1 Kinematic and Kinetic results of the non-symptomatic subjects showing the range of moment and range of motion in the coronal and transverse planes**

Biomechanics Non-symptomatic Subjects	Coronal Plane		Transverse Plane	
	Range of Moment	Range of Motion	Range of Moment	Range of Motion
Subject 1	0.36	-0.13	-0.84	0.13
Subject 2	-0.03	0.29	-0.70	-0.19
Subject 3	0.42	0.37	0.26	-0.10
Subject 4	2.0	0.36	0.32	0.75
Subject 5	-2.35	-0.24	-0.85	0.18
Subject 6	2.14	-0.06	0.21	0.01
Subject 7	-0.78	-0.30	-0.60	-0.26
Subject 8	-3.50	0.13	-3.61	-0.14
Subject 9	-1.66	0.43	-0.98	0.13
Subject 10	-3.20	-0.48	-2.42	-0.72
Subject 11	-1.14	-0.18	-3.81	0.50
Subject 12	0.49	0.07	-0.31	0.38
Subject 13	-0.91	0.41	-1.52	-0.11

**Table 12-2 Kinematic and Kinetic results of the symptomatic subjects showing the range of moment and range of motion in the coronal and transverse planes**

Biomechanics Symptomatic Subjects	Coronal Plane		Transverse Plane	
	Range of Moment	Range of Motion	Range of Moment	Range of Motion
PFP 1	-0.01	-0.08	-0.03	-0.54
PFP 2	-0.02	-0.06	-0.02	-0.28
PFP 3	0.01	0.71	0.01	0.02
PFP 4	0.06	-0.19	0.01	1.20
PFP 5	0.02	-0.44	-0.01	-0.50
PFP 6	-0.02	0.40	-0.01	0.58
PFP 7	0.00	-0.38	-0.01	-0.45
PFP 8	0.74	-0.13	0.77	0.10
PFP 9	-0.04	-0.17	-0.02	-0.64
PFP 10	-0.07		-0.03	
PFP 11	0.01	-0.72	-0.02	-0.73
PFP 12	-0.02	-0.62	0.00	1.24
PFP 13	0.00	-0.35	-0.05	0.93

12.1.3 Surface EMG Results

**Table 12-3 sEMG results from the non-symptomatic subjects showing the mean difference % MVC values for each subject.**

sEMG Non-symptomatic Subjects	Mean Difference (% MVC)			
	Gastrocnemius	Bicep Femoris	Rectus Femoris	Gluteus Medius
Subject 1	- 16.1	- 6.8	- 4.0	- 1.7
Subject 2	- 0.5	- 3.3	- 2.3	- 3.5
Subject 3	0.5	5.4	4.5	0.1
Subject 4		0.5	5.9	9.9
Subject 5		1.0	3.0	4.7
Subject 6	- 1.0	- 7.4	- 4.9	- 23.0
Subject 7	- 6.3	- 0.9	- 3.9	- 6.3
Subject 8	9.7	1.8	3.2	- 9.1
Subject 9				
Subject 10	20.7	- 6.2	- 6.2	- 2.7
Subject 11	- 5.2	- 4.0	- 4.7	- 15.1
Subject 12	- 1.7	4.6	5.8	4.0
Subject 13	- 3.4	- 8.2	- 4.4	- 5.7

**Table 12-4 sEMG results from the symptomatic subjects showing the mean difference % MVC values for each subject.**

sEMG Symptomatic Subjects	Mean Difference (% MVC)			
	Gastrocnemius	Bicep Femoris	Rectus Femoris	Gluteus Medius
PFP 1	- 1.9	0.4	- 0.7	- 0.7
PFP 2	2.7	- 6.1	- 2.5	- 3.1
PFP 3	2.0	- 1.8	0.0	0.4
PFP 4	0.7	- 0.5	- 1.0	3.1
PFP 5	0.4	- 2.9	0.4	- 2.7
PFP 6	2.0	- 6.5	- 1.6	- 0.6
PFP 7	- 1.3	- 1.3	1.9	1.4
PFP 8	2.7	- 3.2	- 3.5	- 2.3
PFP 9	- 1.2	3.5	2.3	0.5
PFP 10	- 1.5	- 5.0	5.0	- 5.0
PFP 11	1.1	- 3.1	- 5.9	- 0.3
PFP 12	1.1		8.3	- 3.1
PFP 13	- 2.6	- 3.2	- 7.7	- 4.2

12.1.4 Mean Firing Rate Results

**Table 12-5 Mean Firing Rate for the Vastus Medialis and Vastus Lateralis in the tape and no tape condition for non-symptomatic subjects**

Mean Firing Rate Non-symptomatic Subjects	Average MFR (pps) SD			
	VM No Tape	VM Tape	VL No Tape	VL Tape
Subject 01	<b>22.9</b> (3.3)	<b>26</b> (3.3)	<b>25.1</b> (4.2)	<b>25.3</b> (2.9)
Subject 02	<b>18.2</b> (2.4)	<b>18.3</b> (2.6)	<b>18.4</b> (2.4)	<b>17.1</b> (2.5)
Subject 03	<b>15.1</b> (2.1)	<b>14.3</b> (2.9)	<b>17.4</b> (3.2)	<b>16</b> (3.9)
Subject 04	<b>17.6</b> (2.5)	<b>21.7</b> (3.2)	<b>16.8</b> (4.1)	<b>15.4</b> (3.6)
Subject 05	<b>15.6</b> (2.5)	<b>16.8</b> (2.1)	<b>20.6</b> (2.8)	<b>19.7</b> (2.4)
Subject 06	<b>13.1</b> (3.1)	<b>16.9</b> (4.7)	<b>14.7</b> (2.5)	<b>14.2</b> (2.5)
Subject 07	<b>16.4</b> (3.9)	<b>16</b> (4.2)	<b>16.7</b> (3.5)	<b>18.4</b> (2.9)
Subject 08	<b>18.3</b> (3.3)	<b>14.8</b> (4)	<b>17.7</b> (2.9)	<b>14.9</b> (4.6)
Subject 09	<b>18.5</b> (5.1)	<b>21</b> (5.3)	<b>19.8</b> (2.3)	<b>20.1</b> (2.6)
Subject 10	<b>15.7</b> (3.1)	<b>18.7</b> (3.3)	<b>16.3</b> (3.2)	<b>14.6</b> (2.4)
Subject 11	<b>24</b> (5.4)	<b>24.1</b> (5.2)	<b>16.4</b> (2.6)	<b>15.4</b> (2.7)
Subject 12	<b>14</b> (1.9)	<b>16.3</b> (2.6)	<b>18.3</b> (2.6)	<b>19.8</b> (2.7)
Subject 13	<b>20.1</b> (3.7)	<b>18.3</b> (3.5)	<b>20</b> (3.1)	<b>19.3</b> (3.5)

**Table 12-6 Mean Firing Rate for the Vastus Medialis and Vastus Lateralis in the tape and no tape condition for symptomatic subjects**

Mean Firing Rate Symptomatic Subjects	Average MFR (pps) SD			
	VM No Tape	VM Tape	VL No Tape	VL Tape
PFP 01	<b>19.1</b> (2.5)	<b>17.2</b> (2.5)	<b>24.1</b> (3.6)	<b>25.3</b> (2.8)
PFP 02	<b>20.5</b> (3.3)	<b>21.5</b> (2.9)	<b>19.9</b> (3.2)	<b>19.4</b> (2.7)
PFP 03	<b>13.6</b> (1.7)	<b>12.1</b> (2)	<b>13.5</b> (1.9)	<b>14.9</b> (1.9)
PFP 04	<b>19.4</b> (4.9)	<b>22.6</b> (4.9)	<b>15.6</b> (3.6)	<b>17.1</b> (3.5)
PFP 05	<b>19.6</b> (4.2)	<b>20.1</b> (3.4)	<b>23.9</b> (3.4)	<b>23.4</b> (3.2)
PFP 06	<b>12.3</b> (2.4)	<b>21.2</b> (3.6)	<b>15.6</b> (2.5)	<b>15.2</b> (2.4)
PFP 07	<b>14.1</b> (4.2)	<b>14.9</b> (3.8)	<b>15.7</b> (2.5)	<b>14.5</b> (3.2)
PFP 08	<b>18.4</b> (1.9)	<b>20.5</b> (2.9)	<b>22.1</b> (2.5)	<b>20.2</b> (2.9)
PFP 09	<b>17.3</b> (2.9)	<b>14.6</b> (2.4)	<b>20.3</b> (2.9)	<b>16.7</b> (3.8)
PFP 10	<b>17.4</b> (4.9)	<b>19</b> (4.7)	<b>18.9</b> (3.6)	<b>19.7</b> (4.4)
PFP 11	<b>15.9</b> (2.4)	<b>17.6</b> (3.8)	<b>15.9</b> (2.7)	<b>14.9</b> (2.7)
PFP 12	<b>20.1</b> (5.9)	<b>14</b> (4.5)	<b>14.5</b> (4.2)	<b>11.1</b> (2.6)
PFP 13	<b>20.1</b> (5.3)	<b>21.9</b> (3.4)	<b>25</b> (3.4)	<b>26</b> (2.9)

12.1.5 Cross-Correlation Results

**Table 12-7 Cross-correlation results for the Vastus Medialis and Vastus Lateralis in the tape and no tape condition for non-symptomatic subjects**

Cross-Correlation Non-symptomatic Subjects	VM_NO_TAPE	VM_TAPE	VL_NO_TAPE	VL_TAPE
Subject 01	<b>0.50</b> (0.31-0.63)	<b>0.46</b> (0.31-0.63)	<b>0.45</b> (0.27-0.64)	<b>0.45</b> (0.27-0.61)
Subject 02	<b>0.43</b> (0.28-0.60)	<b>0.39</b> (0.24-0.55)	<b>0.43</b> (0.30-0.56)	<b>0.41</b> (0.26-0.56)
Subject 03	<b>0.46</b> (0.26-0.62)	<b>0.42</b> (0.26-0.53)	<b>0.44</b> (0.29-0.61)	<b>0.40</b> (0.24-0.54)
Subject 04	<b>0.41</b> (0.26-0.55)	<b>0.48</b> (0.29-0.60)	<b>0.38</b> (0.26-0.54)	<b>0.40</b> (0.25-0.57)
Subject 05	<b>0.42</b> (0.24-0.59)	<b>0.36</b> (0.23-0.51)	<b>0.39</b> (0.24-0.54)	<b>0.43</b> (0.27-0.56)
Subject 06	<b>0.36</b> (0.27-0.52)	<b>0.39</b> (0.21-0.55)	<b>0.37</b> (0.23-0.54)	<b>0.41</b> (0.26-0.54)
Subject 07	<b>0.37</b> (0.22-0.51)	<b>0.36</b> (0.22-0.52)	<b>0.42</b> (0.25-0.57)	<b>0.39</b> (0.24-0.57)
Subject 08	<b>0.43</b> (0.28-0.55)	<b>0.42</b> (0.25-0.55)	<b>0.37</b> (0.22-0.49)	<b>0.47</b> (0.32-0.60)
Subject 09	<b>0.40</b> (0.23-0.53)	<b>0.40</b> (0.23-0.57)	<b>0.44</b> (0.31-0.56)	<b>0.39</b> (0.23-0.53)
Subject 10	<b>0.43</b> (0.27-0.60)	<b>0.39</b> (0.23-0.54)	<b>0.39</b> (0.25-0.55)	<b>0.39</b> (0.23-0.54)
Subject 11	<b>0.42</b> (0.25-0.53)	<b>0.38</b> (0.23-0.53)	<b>0.41</b> (0.25-0.55)	<b>0.40</b> (0.26-0.55)
Subject 12	<b>0.39</b> (0.26-0.56)	<b>0.46</b> (0.31-0.61)	<b>0.41</b> (0.27-0.53)	<b>0.43</b> (0.30-0.60)
Subject 13	<b>0.43</b> (0.27-0.56)	<b>0.45</b> (0.29-0.59)	<b>0.40</b> (0.24-0.56)	<b>0.44</b> (0.29-0.58)

**Table 12-8 Cross-correlation results for the Vastus Medialis and Vastus Lateralis in the tape and no tape condition for symptomatic subjects**

Cross-Correlation Symptomatic Subjects	VM_NO_TAPE	VM_TAPE	VL_NO_TAPE	VL_TAPE
PFP 01	<b>0.42</b> (0.29-0.58)	<b>0.45</b> (0.30-0.58)	<b>0.40</b> (0.25-0.55)	<b>0.41</b> (0.26-0.57)
PFP 02	<b>0.39</b> (0.20-0.53)	<b>0.37</b> (0.19-0.52)	<b>0.37</b> (0.21-0.52)	<b>0.39</b> (0.21-0.52)
PFP 03	<b>0.37</b> (0.25-0.53)	<b>0.38</b> (0.25-0.52)	<b>0.45</b> (0.29-0.60)	<b>0.40</b> (0.23-0.56)
PFP 04	<b>0.38</b> (0.23-0.57)	<b>0.40</b> (0.27-0.55)	<b>0.43</b> (0.26-0.55)	<b>0.39</b> (0.23-0.51)
PFP 05	<b>0.42</b> (0.28-0.56)	<b>0.41</b> (0.29-0.56)	<b>0.52</b> (0.34-0.66)	<b>0.42</b> (0.27-0.55)
PFP 06	<b>0.41</b> (0.23-0.57)	<b>0.37</b> (0.23-0.52)	<b>0.44</b> (0.29-0.56)	<b>0.41</b> (0.27-0.57)
PFP 07	<b>0.38</b> (0.24-0.53)	<b>0.34</b> (0.18-0.53)	<b>0.38</b> (0.21-0.50)	<b>0.38</b> (0.22-0.53)
PFP 08	<b>0.44</b> (0.27-0.56)	<b>0.39</b> (0.25-0.55)	<b>0.43</b> (0.28-0.57)	<b>0.40</b> (0.29-0.55)
PFP 09	<b>0.41</b> (0.28-0.54)	<b>0.43</b> (0.28-0.61)	<b>0.40</b> (0.31-0.52)	<b>0.42</b> (0.23-0.56)
PFP 10	<b>0.45</b> (0.22-0.59)	<b>0.43</b> (0.27-0.56)	<b>0.47</b> (0.30-0.62)	<b>0.41</b> (0.24-0.57)
PFP 11	<b>0.39</b> (0.25-0.51)	<b>0.47</b> (0.28-0.60)	<b>0.41</b> (0.25-0.55)	<b>0.43</b> (0.26-0.58)
PFP 12	<b>0.41</b> (0.26-0.56)	<b>0.44</b> (0.28-0.56)	<b>0.38</b> (0.28-0.57)	<b>0.38</b> (0.29-0.65)
PFP 13	<b>0.32</b> (0.19-0.50)	<b>0.42</b> (0.26-0.55)	<b>0.38</b> (0.21-0.52)	<b>0.39</b> (0.21-0.57)

12.1.6 Recruitment Threshold Results

**Table 12-9 Recruitment Threshold results for the Vastus Medialis and Vastus Lateralis showing comparison regression lines with their intercept and slope values for non-symptomatic subjects**

Recruitment Threshold  Non-symptomatic Subjects	Vastus Medialis				Vastus Lateralis			
	Intercept		Slope		Intercept		Slope	
	Value	P-value	Value	p-value	Value	P-value	Value	p-value
Subject 1	3.23	< <b>0.001</b>	-0.06	0.21	0.81	0.54	0.02	0.81
Subject 2	-0.19	0.79	0.07	0.81	0.08	0.88	-0.08	< <b>0.001</b>
Subject 3	1.12	0.13	-0.03	0.33	0.07	0.89	0.08	< <b>0.001</b>
Subject 4	4.24	< <b>0.001</b>	-0.05	< <b>0.05</b>	-0.77	0.38	-0.04	0.20
Subject 5	4.85	< <b>0.001</b>	-0.11	< <b>0.05</b>	-1.64	< <b>0.001</b>	0.15	< <b>0.001</b>
Subject 6	10.15	< <b>0.001</b>	-0.11	< <b>0.001</b>	-1.01	0.88	-0.00	0.99
Subject 7	2.4	< <b>0.001</b>	-0.03	0.09	3.78	< <b>0.001</b>	-0.04	< <b>0.05</b>
Subject 8	-2.83	0.07	-0.10	0.23	-4.92	< <b>0.001</b>	0.11	< <b>0.05</b>
Subject 9	-5.68	< <b>0.001</b>	0.11	< <b>0.001</b>	0.06	0.93	0.08	< <b>0.05</b>
Subject 10	-0.33	0.68	0.05	< <b>0.05</b>	-2.96	< <b>0.001</b>	0.03	0.09
Subject 11	-1.89	0.09	-0.14	0.08	-1.69	< <b>0.001</b>	0.024	< <b>0.05</b>
Subject 12	4.67	< <b>0.001</b>	-0.04	0.29	0.39	0.66	0.08	< <b>0.05</b>
Subject 13	-1.32	0.26	0.01	0.78	2.76	0.062	-0.17	< <b>0.001</b>

**Table 12-10 Recruitment Threshold results for the Vastus Medialis and Vastus Lateralis showing comparison regression lines with their intercept and slope values for symptomatic subjects**

Recruitment Threshold Symptomatic Subjects	Vastus Medialis				Vastus Lateralis			
	Intercept		Slope		Intercept		Slope	
	Value	P-value	Value	p-value	Value	p-value	Value	p-value
PFP 1	2.07	0.10	-0.21	<b>&lt;0.001</b>	-0.84	0.18	0.10	<b>&lt;0.05</b>
PFP 2	0.57	0.48	-0.06	0.17	-1.39	0.09	-0.05	0.33
PFP 3	-0.57	0.31	-0.03	0.19	3.16	<b>&lt;0.001</b>	-0.05	<b>&lt;0.001</b>
PFP 4	-0.73	0.36	0.02	0.24	1.73	<b>&lt;0.05</b>	-0.01	0.34
PFP 5	-0.94	<b>0.05</b>	0.00	0.99	0.04	0.94	-0.06	<b>&lt;0.05</b>
PFP 6	11.20	<b>&lt;0.001</b>	-0.34	<b>&lt;0.001</b>	-1.73	<b>&lt;0.05</b>	0.04	<b>&lt;0.05</b>
PFP 7	-0.83	0.38	0.02	0.19	1.53	<b>&lt;0.05</b>	0.02	0.33
PFP 8	3.01	<b>&lt;0.001</b>	0.06	<b>&lt;0.05</b>	-2.10	<b>&lt;0.001</b>	0.20	<b>&lt;0.001</b>
PFP 9	-3.6	<b>&lt;0.001</b>	0.07	<b>&lt;0.05</b>	-1.73	<b>&lt;0.05</b>	0.00	0.99
PFP 10	3.05	<b>&lt;0.001</b>	0.01	0.53	-1.98	<b>&lt;0.05</b>	0.04	<b>&lt;0.05</b>
PFP 11	0.93	0.21	0.00	0.99	-2.80	<b>&lt;0.001</b>	0.18	<b>&lt;0.05</b>
PFP 12	-8.12	<b>&lt;0.001</b>	0.05	<b>&lt;0.05</b>	-2.01	0.10	-0.12	0.50
PFP 13	7.47	0.07	-0.08	0.14	1.39	0.38	-0.02	0.27

12.1.7 Recruitment Operating Point Results

**Table 12-11 Recruitment operating point results for the Vastus Medialis and Vastus Lateralis showing the percentage at which the first motor units were recruited for the non-symptomatic subjects**

Recruitment Operating Point Non-Symptomatic Subjects	Vastus Medialis		Vastus Lateralis	
	No Tape (% Force)	Tape (% Force)	No Tape (% Force)	Tape (% Force)
Subject 1	3.07	3.61	3.94	6.23
Subject 2	12.34	12.06	10.13	7.02
Subject 3	9.91	10.44	4.02	7.39
Subject 4	0.43	8.22	1.12	4.01
Subject 5	7.52	17.12	4.28	9.8
Subject 6	12.87	17.73	17.03	4.65
Subject 7	8.64	11.7	6.14	5.69
Subject 8	11.57	10.17	7.34	9.75
Subject 9	16.17	5.83	6.67	12.19
Subject 10	18.45	13.54	10.37	10.28
Subject 11	4.87	4.34	4.68	6.82
Subject 12	3.89	8.21	11.97	9.26
Subject 13	7.13	9.15	10.18	11.96

**Table 12-12 Recruitment operating point results for the Vastus Medialis and Vastus Lateralis showing the percentage at which the first motor units were recruited for the symptomatic subjects**

Recruitment Operating Point Symptomatic Subjects	Vastus Medialis		Vastus Lateralis	
	No Tape (% Force)	Tape (% Force)	No Tape (% Force)	Tape (% Force)
PFP 1	17.94	8.43	6.24	5.16
PFP 2	9.65	5.4	7.17	3.42
PFP 3	8.4	6.64	8.83	9.45
PFP 4	22.81	18.78	15.36	17.76
PFP 5	4.56	4.13	2.37	4.9
PFP 6	10.74	11.95	8.8	11.27
PFP 7	19.96	22.41	10.5	18.08
PFP 8	3.54	7.94	2.85	5.56
PFP 9	2.11	4.13	4.46	4.91
PFP 10	9.36	7.05	10.81	3.46
PFP 11	2.29	2.87	3.37	3.46
PFP 12	12.84	10.71	12.63	21.39
PFP 13	77.85	57.16	55.64	40.72

### 12.1.8 Movement Specific Reinvestment Scale Results

**Table 12-13 Results from the Movement Specific Reinvestment Scale (MSRS) for the movement self-consciousness and conscious motor processing**

MSRS Symptomatic Subjects	Factor 1 Movement Self-Consciousness	Factor 2 Conscious Motor Processing
Subject 1		
Subject 2	16	24
Subject 3	16	28
Subject 4	20	22
Subject 5	5	14
Subject 6	7	11
Subject 7	11	21
Subject 8	10	21
Subject 9	12	13
Subject 10	5	5
Subject 11	8	22
Subject 12	17	26
Subject 13	9	19

### 12.1.9 Numerical Rating Scale

**Table 12-14 Numerical Rating Scale results from symptomatic subjects**

NPRS Symptomatic Subjects	Pain Rating
Subject 1	
Subject 2	7
Subject 3	5
Subject 4	2
Subject 5	3
Subject 6	3
Subject 7	1
Subject 8	7
Subject 9	4
Subject 10	6
Subject 11	6
Subject 12	3
Subject 13	3

**Patient Information Sheet**

**Study Title:** An Investigation Into The Control Of The Knee Joint During Single Leg Balancing And Stepping Tasks With Knee Pain Sufferers

**Researchers:** Prof. Jim Richards ([JRichards@uclan.ac.uk](mailto:JRichards@uclan.ac.uk))

Prof. James Selfe ([JSelfe1@uclan.ac.uk](mailto:JSelfe1@uclan.ac.uk))

**Research Student:** Steven Lindley ([SLindley@uclan.ac.uk](mailto:SLindley@uclan.ac.uk))

We would like to invite you to take part in our research study as you are currently suffering with knee pain. Before you decide we would like you to understand why the research is being done and what it would involve for you. The following information is designed to provide you with answers to questions that you may have regarding participating in this study. Please take your time to read the following information carefully. If you have any other queries please do not hesitate in asking one of the research team so that you feel happy to consent. This study is being undertaken as part of a PhD for Steven Lindley.

**Background of the Study**

Control of the knee joint is considered an important aspect in knee pain treatment and management, however there is limited research investigating this. A common technique used in clinical practice is the application of tape across the knee cap. Tape and other similar treatments, such as bracing and Tubigrip, have been shown to improve the control, pain and function of the knee joint. However, the mechanisms behind these benefits are not well understood.

**What is the purpose of the study?**

The aim is to contribute to the knowledge gap within knee pain research, enhancing the treatment and management. The study aims to accomplish this by investigating the differences in muscular activity and joint mechanics of the lower limbs during simple movement tasks.

**Why have I been chosen?**

You have been invited to participate in this research study as you are currently suffering with knee pain for more than 3 months and have reported pain on at least 2 of the following activities: Prolonged sitting, ascending or descending stairs, squatting, kneeling, running and hopping/jumping. By participating you will add valuable information to the knowledge gap in knee pain.

**What will I have to do in the testing session?**

You will be required to attend one testing session at the University of Central Lancashire (UCLan, Preston), lasting approximately 2 hours.

- Questionnaire

You will be asked to complete 10 short questions about your thoughts on your movement patterns followed by rating your knee pain on a scale. No names will be associated with this or any of the data, thus is totally anonymous.

- What intervention will be used?

A trained clinician shall apply small strips of medical non allergic tape. This taping technique is a commonly used intervention within clinical practice. You will be asked to perform two tasks both with and without the tape applied.

- What tasks will I have to perform?

The testing session will require you to participate in two tasks; stepping down from a 20cm step and a single leg balancing task (Figure 1). These tasks are within your normal daily activities and capabilities, such as walking up and down stairs.



Figure 1. The two tasks you shall be asked to participate in a) Stepping down from a 20cm step b) single leg balancing

The picture below shows the application of the taping technique (Figure 2).



Figure 2. The taping technique applied across the knee cap.

- What data will be recorded?

During the testing session your movements will be recorded using infrared cameras, these cameras capture sensory information with no visual recordings being taken (the data captured appears as dots on a computer screen). In order for the cameras to capture accurate and measurable data, small reflective markers will be placed on your lower limbs with tape (Figure 4).

To assess the control of your muscles during the two tasks up to five discrete EMG sensors (Figure 3) shall be placed on the surface of the skin being secured with tape. EMG (Electromyography) is a common non-invasive technique used for recording the electrical activity produced by muscles, a similar method to measuring ECG (heart signals).



Figure 3. The EMG sensors being placed on the surface of the skin.



Figure 4. The reflective markers being placed on the surface of the skin

- Where are the markers and sensors being placed?

The EMG sensors and reflective markers shall be placed upon the skin of the lower limbs, as shown in the diagram below (Figure 5). A small amount of hair shall be removed from the knee area for two of the EMG sensors.

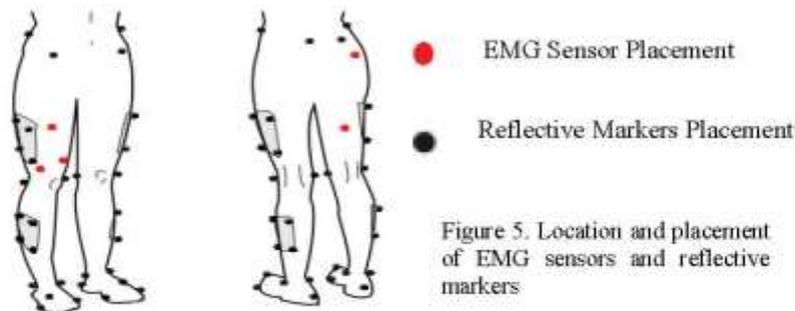


Figure 5. Location and placement of EMG sensors and reflective markers

#### What should I bring?

To allow accurate placement of the markers onto the skin you will be asked to bring shorts and t-shirt, private changing facilities are provided. If you do not have these then appropriate clothing will be provided.

#### Who will be involved?

The study will be conducted by a team of researchers made up of experts in the field of human movement sciences and physiotherapy.

#### Are there any risks in taking part?

The testing will not involve any movements that exceed the range of movement or loading that would normally occur during normal daily physical activity, therefore the risk of injury is minimal. A full risk assessment has been conducted to ensure the testing area, actions of the exercise and the equipment is safe for your participation.

**Do I have to take part?**

No, the study is entirely voluntary. You are free to withdraw from the study at any time with no explanation required. Your medical care will not be affected if you choose not to take part in the study.

**Confidentiality**

All data and information recorded will be safeguarded with anonymity, stored on password protected computer. A digital backup copy will be stored on the researchers password protected computer, with all files password protected.

**Ethical Review**

Ethical approval for the study has been obtained from the BuSH (Built, Sport, and Health) of the University of Central Lancashire (UCLan) as well as the National Research Ethics Committee and Lancashire Teaching Hospitals NHS Foundation Trust Research and Development Committee.

**Further Information**

If you would like further information or any clarification then please contact:

Steven Lindley

Doctoral Student

Brook Building (BB121)

University of Central Lancashire

[SLindley@uclan.ac.uk](mailto:SLindley@uclan.ac.uk)

01772 89 (5707)

**Complaints Procedure**

If you are unhappy with how you have been dealt with or have any other issues and would like to discuss matters then please contact:

John Minten

Head of School

School of Sports, Tourism and the Outdoors

Greenbank Building (GR 159)

University of Central Lancashire

[jhminten@uclan.ac.uk](mailto:jhminten@uclan.ac.uk)

01772 89 (4901)

5

Version 3  
19/06/2013

Patient Identification Number:

## CONSENT FORM

**Title of Project:** An Investigation Into The Control Of The Knee Joint During Single Leg Balancing And Stepping Tasks With Knee Pain Sufferers

**Researchers:** Prof. Jim Richards (JRichards@uclan.ac.uk)

Prof. James Selfe (JSelfe1@uclan.ac.uk)

**Research Student:** Steven Lindley (SLindley@uclan.ac.uk)

Please initial box

1. I confirm that I have read and understood the participant information sheet dated 19/06/2013 (version no. 3) for the above study. I have had the opportunity to consider the information and have had any questions answered satisfactorily.
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason, without my medical care or legal rights being affected.
3. I have fully completed the health screening questionnaire.
4. I consent to the use of the infra-red camera
5. I understand that data collected from the study may be looked at by regulatory authorities or by persons from the Trust where it is relevant to my taking part in this research. I consent to these persons having access to this data
6. I agree to take part in the above study.

\_\_\_\_\_  
Name of Participant

\_\_\_\_\_  
Date

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Name of Person taking consent  
(If different from researcher)

\_\_\_\_\_  
Date

\_\_\_\_\_  
Signature

\_\_\_\_\_  
Researcher

\_\_\_\_\_  
Date

\_\_\_\_\_  
Signature

When completed: 1 for participant; 1 for researcher site file;

1  
Version 3

19/06/2013

Patient Identification Number:

**Patellofemoral Pain Questionnaires**

**The Movement Specific Reinvestment Scale (Masters, Eves & Maxwell, 2005)**

Directions: Below are a number of statements about your movements. The possible answers go from 'strongly disagree' to 'strongly agree'. There are no right or wrong answers so circle the answer that best describes how you feel for each question.

**1. I remember the times when my movements have failed me.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**2. If I see my reflection in a shop window, I will examine my movements.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**3. I reflect about my movement a lot.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**4. I try to think about my movements when I carry them out.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**5. I am self-conscious about the way I look when I am moving.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**6. I sometimes have the feeling that I am watching myself move.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**7. I am aware of the way my body works when I am carrying out a movement.**

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

8. I am concerned about my style of moving.

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

9. I try to figure out why my actions failed.

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

10. I am concerned about what people think about me when I am moving.

strongly disagree    moderately disagree    weakly disagree    weakly agree    moderately agree    strongly agree

**Numeric Pain Rating Scale (NPRS)**

What has been your usual or average level of pain in your knee in the past week?

Please put an X through a number

No Pain

Worst pain imaginable

0	1	2	3	4	5	6	7	8	9	10
---	---	---	---	---	---	---	---	---	---	----

12.5 Appendix E – Ethical Approval

12.5.1 University of Central Lancashire – Non-symptomatic Subjects



2<sup>nd</sup> September 2011

Jim Richards/James Selfe/Steven Lindley  
School of Sports Tourism & the Outdoors  
University of Central Lancashire

Dear Jim, James & Steven

**Re: Faculty of Health & Social Care Ethics Committee (FHEC)  
Application - (Proposal No.522)**

The FHEC has granted approval of your proposal application 'An investigation into the control of the knee joint during simple stepping, squatting and walking tasks' on the basis described in its 'Notes for Applicants'.

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 Research Office.

Yours sincerely

Denise Forshaw  
Chair  
**Faculty of Health Ethics Committee**

## 12.5.2 University of Central Lancashire – Symptomatic Subject



21<sup>st</sup> March 2013

Jim Richards & Steven Lindley  
School of Sports Tourism & the Outdoors  
University of Central Lancashire

Dear Jim & Steven

**Re: BuSH Ethics Committee Application**  
**Unique Reference Number: BuSH 149**

The BuSH ethics committee has granted approval of your proposal application 'An Investigation Into The Control Of The Knee Joint During Single Leg Balancing And Stepping Tasks With Knee Pain Sufferers'.

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](mailto:roffice@uclan.ac.uk) quoting your unique reference number.

Yours sincerely

Denise Forshaw  
Chair  
**BuSH Ethics Committee**



**Health Research Authority**  
National Research Ethics Service

**NRES Committee North West - Lancaster**

HRA NRES Centre - Manchester  
Barlow House  
3rd Floor  
4 Minshull Street  
Manchester  
M1 3DZ

Telephone: 0161 625 7818  
Facsimile: 0161 625 7299

19 June 2013

Mr Steven Lindley  
University of Central Lancashire  
School of Sport, Tourism and the Outdoors  
Brook Building, Room 121  
PR1 2HE

Dear Mr Lindley

**Study title:** **An Investigation Into The Control Of The Knee Joint During Single Leg Balancing And Stepping Tasks With Knee Pain Sufferers**  
**REC reference:** **13/NW/0405**  
**IRAS project ID:** **116145**

Thank you for your email of 19 June. I can confirm the REC has received the documents listed below and that these comply with the approval conditions detailed in our letter dated 17 June 2013

**Documents received**

The documents received were as follows:

<i>Document</i>	<i>Version</i>	<i>Date</i>
Covering Email		19 June 2013
Participant Consent Form	3	19 June 2013
Participant Information Sheet	3	19 June 2013
Questionnaire: Healthscreening	3	19 June 2013
Questionnaire: Patellofemoral pain questionnaires	3	19 June 2013

**Approved documents**

The final list of approved documentation for the study is therefore as follows:

<i>Document</i>	<i>Version</i>	<i>Date</i>
Covering Letter		19 June 2013
Evidence of insurance or indemnity		01 August 2012
Investigator CV	James Selfe	

Investigator CV	Jim Richards	
Investigator CV	Steven Lindley	
Other: Apendix A - Inclusion/exclusion Criteria	2	01 March 2013
Participant Consent Form	3	19 June 2013
Participant Information Sheet	3	19 June 2013
Protocol	2	01 March 2013
Questionnaire: Healthscreening	3	19 June 2013
Questionnaire: Patellofemoral pain questionnaires	3	19 June 2013
REC application	3.5	07 May 2013

You should ensure that the sponsor has a copy of the final documentation for the study. It is the sponsor's responsibility to ensure that the documentation is made available to R&D offices at all participating sites.

**13/NW/0405** **Please quote this number on all correspondence**

Yours sincerely



**Mrs Carol Ebenezer**  
**Committee Co-ordinator**

E-mail: [nrescommittee.northwest-lancaster@nhs.net](mailto:nrescommittee.northwest-lancaster@nhs.net)

Copy to: *Professor. James Selfe,*  
*Robert Walsh*

## 12.5.4 NHS Research & Development Permission

The Centre for Health Research and Innovation:  
Royal Preston Hospital  
Sharoe Green Lane  
Fulwood  
PRESTON  
PR2 9HT

Tel. 01772 52(8268)  
Fax. 01772 52(3184)

### CENTRE FOR HEALTH RESEARCH AND INNOVATION

Our Ref: GW/HAA

23 July 2013

Mr Steven Lindley  
University of Central Lancashire  
School of Sport, Tourism and the Outdoors  
Brook Building, Room 121  
PR1 2HE

Email: [s.lindley@uclan.ac.uk](mailto:s.lindley@uclan.ac.uk)

Dear Mr Lindley

**PIC Ref: 017**

**Study title: An Investigation Into The Control Of The Knee Joint During Single Leg Balancing And Stepping Tasks With Knee Pain Sufferers**

**REC reference: 13/NW/0405**

**IRAS project ID: 116145**

Lancashire Teaching Hospitals NHS Foundation Trust has reviewed the above project and agrees to act as a Participant Identification Centre (PIC) for this study.

As a PIC, the co-collaborator will be invited to identify potential study participants and inform them that they may take part in the above study by contacting the study team.

The following documents were received and reviewed:

Document	Version	Date
Covering Letter		19 June 2013
Evidence of insurance or indemnity		01 August 2012
Investigator CV		James Selfe
Investigator CV		Jim Richards
Investigator CV		Steven Lindley
Other: Appendix A - Inclusion/exclusion Criteria	2	01 March 2013
Participant Consent Form	3	19 June 2013
Participant Information Sheet	3	19 June 2013
Protocol	2	01 March 2013
Questionnaire: Healthscreening	3	19 June 2013
Questionnaire: Patellofemoral pain questionnaires	3	19 June 2013
REC application	3.5	07 May 2013
NRES letter – with conditions		17 June 2013
NRES favourable opinion letter – conditions met		19 June 2013

This letter acts as proof of NHS Permission to conduct the research project described in the Protocol submitted for review. You must inform the Trust of any amendments submitted to Ethics Committee and new approval sought. Identification of patients must be compliant with Data Protection Act 1998, Caldicott Principles and Research Governance Framework for Health and Social Care (2005). Any failure to comply with these requirements will result in action being taken under the Lancashire Teaching Hospitals NHS Trust Policy for Fraud and Misconduct in Research. You may also be requested to supply a progress reports and/or a final summary when the study concludes.

Please don't hesitate to contact me if you require clarification or further information. We wish you every success in your research.

Yours sincerely



Mrs Gemma Whiteley  
Research and Development Manager

Cc

Ms Ruth Squire  
Chartered Physiotherapist  
Lancashire Teaching Hospital NHS Trust  
Chorley Hospital  
Preston Rd  
Chorley

[ruth.squire@lthtr.nhs.uk](mailto:ruth.squire@lthtr.nhs.uk)

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[Lee.shimwell@lthtr.nhs.uk](mailto:Lee.shimwell@lthtr.nhs.uk)

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