School of Physiotherapy and Exercise Science

An investigation into the influence of changes in static single leg standing posture on hip and thigh muscle activation in a pain free population

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature

Simon Prior

Date: 7 April 2013

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Abstract

Study Design:

Normative data collection, descriptive, single-group study.

Objectives:

Determine the influence of changes in trunk and pelvic posture during static single leg standing, on hip and thigh muscle activation in pain-free adults.

Background:

Lower limb injuries are common and often relate to patterns of single leg loading, which are a focus of clinical practice. For example, much of the research into ACL injury identifies a position of knee valgus angle to be a contributing factor. It is therefore considered that patterns of motor activation during single leg stance may be a factor related to injury risk, such as the role of the gluteus medius muscle to control valgus knee position. Trunk and pelvis posture, in a sagittal plane, are known to influence trunk muscle activation patterns while in double legged standing, the influence that trunk and pelvis posture has on lower limb muscle activation in single leg stance is yet largely unknown. There also exists evidence that pelvic posture, in a frontal plane, can influence hip muscle activation patterns in single leg standing. There is currently no study that looks at trunk and pelvis position in both sagittal and frontal plane in single leg stance. Therefore, the purpose of this study aims to investigate the influence of changes in trunk and pelvic posture during static single leg on hip and thigh muscle activation in a pain free population.

Specific objectives of this study include:

- Develop reliable protocol for positioning subjects and evaluating hip and thigh muscle activity.
- Record EMG data of 8 different hip and thigh muscles in 9 different adopted static single leg trunk and pelvis positions.
- Determine whether trunk and pelvis position can predict hip and thigh muscle activity in single leg stance.

The hypotheses for this study are that there will be differences in hip and thigh muscle activity levels between the reference Upright single leg standing posture and:

1. Anterior and Posterior Trunk Sway in single leg stance (sagittal plane)
2. Left and Right Trunk Shift in single leg stance (frontal plane)
3. Anterior and Posterior Pelvic Rotation in single leg stance (sagittal plane)
4. Lateral Pelvic Raise and Drop of the pelvis in single leg stance (frontal plane)

Methods:

As the methods in this study are novel the reliability of both EMG and kinematics were tested and analysed over 6 trials. A Sub-MVIC method of normalising EMG was chosen as it has been shown to be reliable and best represented the specific test postures. For the main study, hip and thigh muscle activation patterns were compared in 22 asymptomatic, male subjects (20-45 years old) in paired clinically relevant test postures: Anterior Trunk Sway vs. Posterior Trunk Sway; Anterior Pelvic Rotation vs. Posterior Pelvic Rotation; Left Trunk Shift vs. Right Trunk Shift; and Lateral Pelvic Drop vs. Lateral Pelvis Raise. Surface EMG was collected from eight hip and thigh muscles which included gluteus maximus, gluteus medius, semitendinosus**,** biceps femoris (long head), vastus lateralis, rectus femoris, adductor longus and tensor fascia lata. Kinematic data was collected with a 14 camera 3-dimensional motion analysis system (Vicon). The Vicon Full Body Plug-in Gait model (excluding upper limb and head markers) was used to monitor the test postures. Six trials of each test posture were conducted with 30 seconds rest between each trial.

Statistical Analysis:

All data were coded and analysed using the SPSS statistical software v19.0. Intraclass correlation coefficient ($ICC_{2,1}$) was computed to establish the reliability of the test posture angles and reliability of muscle activation in the reference upright posture and the eight test postures. Repeated measures ANOVA was performed along with associated F-tests to determine if there were significant differences in muscle activation between each measurement. An alpha level of $p<0.05$ was set to determine significance.

Results:

Kinematic reliability of the defining Vicon angles in the Upright Standing (reference) posture showed ICC values of 0.54-0.93 and in each of the pair-wise test postures was 0.70-0.89. Mean ICC values for each of the 8 muscles across each of the nine test postures (i.e. 72 variables) using six trials were greater than 0.75, with 16 exceptions.

The main results of this study considered muscle activation patterns and showed Anterior Trunk Sway (compared to Posterior) increased posterior sagittal plane muscle activity with a concurrent deactivation of anterior sagittal plane muscles (p 0.016 - <0.001). Lateral hip abductor muscles increased activation during Left Trunk Shift (compared to Right) ($p \leq$ 0.001). Lateral Pelvic Drop (compared to Raise) decreased activity in hip abductors and

increased hamstring, adductor longus and vastus lateralis activity (p 0.037 - <0.001). Whilst there was group consistency seen in some muscles (e.g. gluteus maximus in Anterior and Posterior Trunk Sway) there was however variability displayed in others, particularly adductor longus and semitendinosus which had the lowest ICC values in most positions.

Conclusion:

In general, kinematic and EMG values showed good reliability across most muscles and test positions. Normative kinematic and EMG data (hip and thigh) is established in asymptomatic young males. This study has shown hip and thigh muscle activity patterns in single leg stance are affected by trunk and pelvis posture. Changes in trunk position in the sagittal plane and pelvis position in the frontal plane had the greatest effect on muscle activation. Patterns of change in muscle activation are broadly explicable through activation of muscles that function in the same plane as the positional change. Although these results broadly suggest a group effect there is evidence in some muscles, such as adductor longus, to suggest that the response to changes in both trunk and pelvic posture is variable for different individuals.

Publications

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List of Abbreviations

EMG	Electromyography
BMI	Body Mass Index
Gmax	Gluteus Maximus
Gmed	Gluteus Medius
ST	Semitendinosus
BF	Biceps Femoris
VL	Vastus Lateralis
RF	Rectus Femoris
AL	Adductor Longus
TFL	Tensor Fascia Lata
ITBS	Iliotibial Band Syndrome
ACL	Anterior Cruciate Ligament
ICC	Intraclass Correlation Coefficient
MVIC	Maximal Voluntary Isometric Contraction
Sub-MVIC	Sub-Maximal Voluntary Isometric Contraction

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Chapter 1 – Literature review

1.1 Introduction

Lower limb injuries account for over 50% of injuries in athletic populations (Dick et al., 2007), making the understanding of possible mechanisms underlying lower limb injuries an important research priority. Many lower limb injuries result from overuse or cumulative stress during repetitive single leg loading tasks such as running or sports that involve changing direction (Brukner and Khan, 2007). Altered patterns of muscle activation around the hip and thigh are one proposed mechanism behind a number of different lower limb injuries (Fredericson et al., 2000, Cowan et al., 2009). Training lower limb motor control and conditioning has also been shown to reduce lower limb injuries, suggesting that a deficit in lower limb motor control may predispose to lower limb injury (Olsen et al., 2005). It is logical to hypothesize that postures adopted by athletes when loading on one leg may contribute to these altered hip and thigh muscle activation patterns, and therefore injury. This hypothesis is supported by research considering the influence of hip and knee posture on lower limb muscle activation patterns (Hewett et al., 2005, Alentorn-Geli et al., 2009). Another possible postural mechanism contributing to altered lower limb muscle activation patterns during single leg loading is the influence of trunk and pelvic postures.

To date, there is limited evidence that trunk and hip muscle activity is influenced by changes in trunk position in the sagittal direction, but this has only been shown in double leg standing (O'Sullivan et al., 2002, Wang et al., 2006). Earlier research identified changes in hip abductor muscle activity occurred with a change in frontal plane pelvic movement in single leg stance (Inman, 1947, Hardcastle and Nade, 1985). However, there is a lack of knowledge regarding the influence of changes in sagittal and frontal plane trunk or pelvic position during single leg stance in healthy controls.

Therefore, the purpose of this study was to investigate whether different sagittal and frontal plane trunk and pelvic postures during single leg stance are associated with consistent differences in hip and thigh muscle activation patterns in healthy young male controls.

1.2 Different types of Lower Limb injury

Broadly speaking sports injuries can be divided into traumatic and overuse. Traumatic injuries may include sprains, joint injuries, strains, contusions, fractures or dislocations and are usually a result of a single incident (Olsen et al., 2004) or foul play. Overuse injuries may be the result of altered muscle activation or patterns (Fredericson et al., 2000) which may result in repeated tissue strain leading to pain (Cowan et al., 2009), chronic problems (Friel et al., 2006) and tissue failure (Hewett et al., 2006) and are therefore of interest to treating therapists. Sports which are predominately lower limb orientated are of particular focus with respect to overuse injuries and may also relate to altered technique (Noehren et al., 2007), training volumes (Hamill et al., 2008) as well as poor motor control (Cowan et al., 2009). During the 2001-2002 UEFA Champions League (soccer) season Walden and colleagues (2005) found that overuse injuries accounted for nearly 30% of all injuries. Achilles tendinopathy, adductor related groin pain and patellar tendinopathy were three of the top four overuse injuries. The exact reason for these injuries is largely unknown; though considering some of the evidence above relating overuse injuries to altered muscle activation, further research into the relevant muscles vulnerable to injury such as the adductors and quadriceps is warranted.

Athletic injuries involving the hip and pelvis are reported to vary in incidence from 5% to 21% (Lloyd-Smith et al., 1995, Geraci, 1994). In one study, overuse mechanisms accounted for 82% of the injuries to the hip and pelvis that presented to a general sports medicine clinic (Lloyd-Smith et al., 1995). Orchard and colleagues (2002) reported hamstring injuries to be the most common lower limb injury amongst Australian Rules Football players, making up 15% of all injuries, which is similar to the 12% reported with football (soccer) in England (Hawkins and Fuller, 1999, Hawkins et al., 2001). The highest injury recurrence rate in Australian Rules Football and football was found in the hamstrings with incidence between 12% (Woods et al., 2004) and 34% (Orchard and Seward, 2002). Therefore, identification of factors predisposing footballers to hamstring injury or re-injury is an important research priority. Similarly, knee pain due to overuse is also very common. Anterior knee pain contributed some 20-40% of knee complaints presenting to general practice (Orchard et al., 1996) while lateral knee pain including iliotibial band syndrome (ITBS) is seen as the leading cause of lateral knee pain in runners (Taunton et al., 2002). As there appears high prevalence of overuse injuries to the pelvis and hip and the hamstring muscles that attach to this area, research into the influence that pelvic posture has on muscle activation patterns in the lower limb seems warranted.

1.3 Kinematics, muscle function, and the influence of prevention rehabilitation programs on lower limb injury

The causes of lower limb injuries are thought to be multifactorial (Brukner and Khan, 2007). Based on the above injury data, research into the causes and prevention of lower limb injury has considered various aspects of trunk and lower limb kinematics and muscle function.

1.3.1 Kinematics

Changes in kinematics are seen to be associated with lower limb injury. Noehren and colleagues in (2007) found that compared with age matched controls, in female runners the symptomatic group with ITBS had significantly greater hip adduction and knee internal rotation during the stance phase of running. Myer and colleagues (2010) investigated 240 middle and high school female basketball players observing that athletes who developed patellofemoral pain syndrome during the season demonstrated increased knee abduction moment at initial foot contact on the most-symptomatic limb compared to their teammates without patellofemoral pain syndrome whist running.

More evidence to suggest that differences in the kinematics of body positioning are associated with injury has come from Hewett and colleagues (2009). They observed via video analysis that female athletes, who sustained an anterior cruciate ligament (ACL) injury, had greater lateral trunk motion and knee adduction compared to male athletes or control females. Some of Hewett’s (Hewett et al., 2005) earlier work prospectively assessed 205 female athletes for kinematics and kinetics during a jump-landing task and monitored them over two seasons of soccer and one of basketball. They reported that the 9 athletes who sustained a confirmed ACL injury had, during landing, 8° more knee adduction and 2.5 times higher knee abduction moment. They also had 20% greater ground reaction force and 16% shorter stance times, which indicates that the increased force, moments and range of motion happened more quickly. This research supports the link between body positioning (knee abduction particularly) and injury, though there remains a lack of information regarding lower limb muscle activation patterns and its relation to body position.

Most investigations into single leg loading have focused on knee position and hip muscle activation. Russell and colleagues (2006) investigated the difference between men and women performing a single leg drop off movement from a height of 60cm. This attempted to simulate the deceleration experienced in athletic movement. They found women have greater valgus knee position on landing and proposed this as an explanation for the higher female incidence of ACL injury (Arendt and Dick, 1995, Hewett et al., 2005). However they found no difference in gluteus medius (Gmed) activity between the sexes, suggesting the level of muscle activation was the same though there may have been a difference in the muscle's length tension relationship. McLean and colleagues (2005) also found that during a side step cutting task, females had significantly larger normalised knee valgus moments than males. A greater peak valgus moment was associated with larger initial hip flexion and internal rotation, and with larger initial knee valgus angle. Previous researchers (Olsen et al., 2004) described ACL injury mechanism in female team handball as appearing to be a forceful valgus collapse with the knee close to full extension combined with external or internal rotation of the tibia during cutting or single leg jump shot landing. Their description of the injury was concluded via within game video footage combined with interviews of ACL injured players to compare injury characteristics between player recall and the video analysis.

While the above kinematic research suggests limb position is related to injury mechanism, both traumatic and overuse, there is little research into the muscle activation patterns in response to differences in trunk and pelvic positioning and how this relates to injury.

1.3.2 Muscle function

One intrinsic factor widely explored in recent research is the link between different patterns of muscle activation and the relationship to some lower limb injuries. For example, in ACL ruptures one of the risk factors has been reported to be weakness or deactivation of the hamstrings during dynamic movement, when co-activation is needed with the quadriceps. It has been postulated that this may lead to excessive tibial anterior translation. This is particularly important as in the first 30° to 40° of knee flexion during weight acceptance quadriceps contraction increases ACL strain (Alentorn-Geli et al., 2009, Hewett et al., 2006).

In the presence of patellofemoral pain syndrome, Cowan et al (2009) studied a small mixed gender cohort (7 females and 3 males) and found there was a delay of muscle activity in vastus medialis relative to vastus lateralis (VL), as well as both the anterior and posterior portions of gluteus medius during a stair stepping task. There was also a reduction in side trunk flexion strength. Whilst they also reported no difference in hip abduction strength when compared to the control group, the study was under powered to perform a gender specific analysis. The results of this study suggest that retraining of the activation of vastus medialis and the gluteus medius should be a focus of rehabilitation, as the activation of these muscles appears to be affected in individuals with patellofemoral pain.

Morrissey and colleagues (2012) found a decrease of 20-40% in gluteus medius to adductor longus (AL) activity ratio in footballers with adductor related groin pain. They observed a main difference in initial frontal plane EMG (comparing activity matched uninjured players) to be a reduction in the activity of gluteus medius in the injured leg during movement or stance phase of gait. Sagittal plane muscles and associated kinematics were not reported. Whilst this research does not prove a cause or effect relationship, it does demonstrate that lower limb muscle function, gluteus medius in this case, is affected in leg injuries.

When considering altered muscle strength and its relationship to lower limb injury, Fredericson and colleagues (2000) investigated the relationship between isometric side lying hip abduction strength and ITBS. They found that in a cohort of long distance runners, in the presence of having ITBS, both male and females displayed significantly weaker abductor torque (normalised to body weight and height) on the injured side. This was compared to their uninjured side as well as a control group without ITBS. Croisier et al (2008) reported the incidence of hamstring muscle strains were 4 times higher in soccer players who went untreated after preseason isokinetic strength testing discovered a decrease in hamstring to quadriceps ratio.

It is reported to be common to find, in patellofemoral pain syndrome, hip abductor weakness present on the affected side that may result in poor control of femoral adduction and internal rotation leading to patellar maltracking (Fredericson and Yoon, 2006, Cichanowski et al., 2007). Interestingly the same decreased strength in the hip abductors is present in patients with chronic ankle instability (Friel et al., 2006). This finding does not assign causality in chronic ankle stability though it does suggest the importance of screening and addressing the muscle weakness in at risk populations.

A prospective study carried out by Leetun and colleagues (2004) found a link between preseason hip muscle strength and lower limb injuries. They studied 140 college athletes (80 female and 60 males) and found that athletes that experienced injuries during a season had statistically significant weaker hip abduction strength (measured in an isometric sideling position) and hip external rotation strength (measured in an isometric seated position) scores.

1.3.3 Injury prevention rehabilitation programs

While the majority of traumatic injuries are thought to be unavoidable, there is evidence that traumatic ACL injuries may be the result of poor body position and control (Olsen et al., 2004), and therefore have the potential to be prevented with the implementation of rehabilitation aimed at correcting body position. Olsen and colleagues (2005) implemented a 15-20 minute warm-up program with 958 (808 female and 150 male) young handball players aged between 15-17 years old. The exercises focused on the alignment of the hip, and particularly the knee over toe position and were performed at the start of each training session for 15 consecutive sessions and then one time each week through the rest of the season. This group found that over the season there were only 48 injuries in the intervention group compared with 81 in the control group.

Junge et al (2011) implemented an injury prevention program called “The 11”, countrywide across amateur male football teams in Switzerland during 2008 aimed at reducing injuries such as sprains to the ankle and knee ligaments as well as hamstring and groin strains. “The 11” is a simple 10 exercise program developed in cooperation with national and international experts under the leadership of F-MARC (FIFA–Medical Assessment and Research Centre). It takes 10-15 minutes each training session and is incorporated into the warm-up paying particular focus to body alignment of the hips and trunk and keeping the knees-over-toes on the weight bearing foot. Their reported results of a reduction in total match injuries by 11.5% and a reduction in total training injuries of 25.3% seems very positive in the teams that used the program compared to the teams who did not. However, the figures of injuries per 1000 hours look less impressive. That is, total match injuries were 14.18 per 1000 hours (in those who did not use "The 11") compared to 12.55 (did use "The 11"), and total training injuries were 2.65 per 1000 hours (did not use "The 11") to 1.98 (did use "The 11"). Non-contact injuries were the largest group of preventable injuries seen in this study with the motor training aspects of this program tentatively implicated.

Subsequently the programme was modified to include more comprehensive warm-up exercises to be used for training and matches as well as providing more variation and progression in order to attract higher compliance to the program, terming this the "11+". The utility of this program was investigated by Soligard et al (2008) who documented a non-significant reduction in injury incidence of 29% in a cohort of adolescent female football players. Again their focus was on neuromuscular control and to facilitate body awareness during all foot contact situations such as landing, running and cutting. These findings support that training motor control of the lower limb has a positive impact on lower limb injury prevention.

1.4 Rehabilitation approaches aimed at changing lower limb muscle function

Rehabilitation for lower limb overuse injuries commonly involves elements of muscle retraining and strengthening. While this approach is widely accepted (Witvrouw et al., 2000, Fredericson et al., 2000), there is a lack of consensus regarding which exercise parameters are most effective. Two broad types of exercise rehabilitation commonly used include weight bearing strengthening to target specific functional deficits and non-weight bearing strengthening targeting isolated muscle groups.

1.4.1 Weight bearing v non-weight bearing

There is a significant body of research demonstrating that increases in thigh muscle strength occurs whether a weight bearing or non-weight bearing program is applied to elderly individuals (Rhodes et al., 2000, Olivetti et al., 2007), those suffering from osteoarthritis (Jan et al., 2009) or post ACL surgery (Mikkelsen et al., 2000, Fukuda et al., 2013). This is not that surprising considering all subjects in these studies was in a de-conditioned state, and any strength program targeting these muscles will lead to a gain in strength. Augustsson and colleagues (1998), examined healthy young, generally active, asymptomatic subjects and compared the effects of a weight bearing (barbell squat) and non-weight bearing (weight machine knee extension, weight machine hip adduction) exercise program. They found that over six weeks significant general strength improvements were seen in both groups but no significant improvement was observed in the isokinetic knee extension 1-repetition maximum test. With a barbell squat, the weight bearing group improved 23 kg (31%), which was significantly more than the 12 kg (13%) seen in the non-weight bearing group. In the vertical jump test, the weight bearing group improved significantly, 5cm (10%), while no significant changes were seen in the non-weight bearing group. The results of this study suggest that program specificity is important and therefore to improve performance of a weight bearing task, a weight bearing exercise should be used. Therefore, to investigate muscle activation patterns in the lower limb and how this may relate to weight bearing tasks, the test position or positions chosen should be one of a weight bearing nature.

1.4.2 Weight bearing exercises

Weight bearing exercises are thought to promote muscle strengthening in postures more relevant to physical function with a greater potential carry over to real life functional activities. Whilst there is a lack of current literature in this area one study that showed weight bearing exercises can result in functional changes in a specific task was by Snyder and colleagues (2009), who used “closed chain” hip rotation exercises. They demonstrated that a six-week strengthening program in females could alter running kinematics (analysed by high speed camera). Hip abduction and external rotation strength increased by 13% and 23%, respectively. Eversion range of motion decreased and a trend for decreased hip internal rotation range of motion was observed. Rear foot inversion moment and knee abduction moment decreased by 57% and 10%, respectively. This weight bearing exercise program produced strength changes as expected, but the carryover of altered kinematics during a functional activity such as running supports the functional exercise benefits of weight bearing exercises.

1.4.3 Non-weight bearing exercises

The use of non-weight bearing exercises had less success for altering lower limb function in a study conducted by Herman et al (2008). They found that knee and hip kinematics and kinetics did not change in a stop-jump double leg task in female recreational athletes following a nine week "non-weight bearing/open chain" strength program for the quadriceps, hamstrings, gluteus maximus (Gmax) and Gmed, whilst strength in these muscles did significantly improve. Morriss and colleagues (2001) investigated the effects of a six week open chain isokinetic program targeting the quadriceps and hamstrings. They found that whilst peak torque improved for the quadriceps on average by 10.5%, the standing long jump performance didn't change. Although there is an absence of literature in this topic, the results of these studies may be interpreted to suggest that muscles need to be trained using a more functional task specific positions in order to gain functional transfer.

1.4.4 Muscle activation and functional carryover

There is a large body of research into muscle activation patterns during common rehabilitation exercises. One objective of this research is to identify which exercise "best" activates certain muscles, rather than examining which exercise programs result in improvements in function and/or physical performance. This raises the question as to whether the aim should be to identify the "best exercise" that elicits the highest activation of the desired muscle in the hope it translates to better function or performance, rather than aim for optimal task specific positioning to recruit the target muscle.

To summarise what has been studied previously, Boren and colleagues (2011), compared the "best" Gmax and Gmed exercises from the studies of Distefano (2009), Ayotte (2007) and Bolgla and Uhl (2005) and ranked them against each other based on the electromyography (EMG) recorded normalised to maximal voluntary isometric contraction (MVIC). Single limb squat ranked third for Gmed (89% MVIC) and fifth for Gmax (71%

MVIC). The other top five exercises for each muscle were non-functional and were performed in non-weight bearing positions. That is, they tested individual muscles rather than muscle synergies, which are thought to represent normal function. In addition, none of the exercises were used to try and improve a specific task or test whether it had functional carryover. Therefore the clinical utility of exercises that are simply targeted at activating or strengthening muscles without correlation to improvements in function or physical performance remains to be demonstrated.

Recent research has looked at the relationship between static muscle strength and muscle function in a dynamic task. Popovich and Kulig (2012) found that during a single leg landing task, female subjects with diminished static hip muscle strength had greater hip muscle EMG activation, greater lumbo-pelvic angular displacement, and demonstrated higher velocity of their lumbopelvic sagittal plane movement and right lateral bend movement during landing. This highlights the important relationship between hip muscle strength and lumbo-pelvic motor control (both kinematic and muscle activation patterns). Further research directions from this study could look at whether the same kinematic parameters could be changed by increasing functional hip muscle strength.

Interestingly some evidence that rehabilitation via a non-strengthening approach can have a positive effect on functional improvement came from a study by Mizner and colleagues (2008). They demonstrated that improved landing biomechanics when performing a double leg drop vertical jump task could be achieved after a single training session of verbal instruction on how to decrease knee valgus position and angles. The improvement was independent of muscle strength. Such a finding suggests that addressing motor control impairments by focusing on movement patterns appears to be beneficial to functional performance and is a worthwhile approach to rehabilitation especially considering the immediate effect it can have.

1.5 Influence of body position on muscle activation

After reviewing the literature regarding rehabilitation exercises, there is emerging evidence to support that functional, weight-bearing exercises are more beneficial in terms of their effect on changing function or physical performance. One proposed mechanism for the effect of functional exercises in lower limb injury prevention and rehabilitation is retraining kinematics which results in improved lower limb muscular performance and therefore may have a protective effect against injury (Olsen et al., 2005). While this approach appears logical and is becoming more widely accepted, what are not well documented are the specific alterations in body mechanics that produce the required change in functional and muscular performance. For example, while there is some evidence that weight bearing approaches in single leg stance can be beneficial in changing functional performance (Snyder et al., 2009), there is a lack of normative data into what effect different trunk and pelvis postures have on hip and thigh muscle activation patterns. By obtaining normative data we may be able to better explain and predict muscle activation patterns in various functional positions.

1.5.1 Double leg positioning

The majority of existing research into lower limb muscle activation patterns has been conducted in double leg standing (Wang et al., 2006). In the sagittal plane, while these findings may correlate to a degree with single leg standing, frontal plane forces are likely to differ significantly between double and single leg stance.

Weight bearing position

In a study that investigated lower limb muscle activation during two common resistance training exercises, McCurdy et al (2010) compared single leg vs. double leg squat. They found a modified single leg squat produced higher biceps femoris (BF) and gluteus medius activity, and the double legged squat produced higher rectus femoris (RF) activity in elite female athletes. Whilst this research investigated double versus single leg tasks, there was no consideration of the influence changes in trunk and pelvis position within each task had on muscle activation patterns. Troubridge (2000) also investigated double leg squat and found there was a difference of activation with thigh muscles with a change in lower limb position. The study showed that VL activity was greater in a more narrow foot position when compared with internally and externally rotated femur positions. Semimembranosus and semitendinosus (ST) (medial hamstring muscles) activity was greater in the internally rotated foot position when compared with the externally rotated position. All muscles except vastus medialis showed greater activity during the ascent phase. No foot position was found superior to others for all muscles. In this study, there was no consideration of the influence that trunk or pelvis position had on the muscle activation patterns.

A few studies do suggest that different trunk positions activate or inhibit specific muscles or groups of muscles in double leg standing tasks. For example, there is some literature to suggest that changing posture in a sagittal plane whilst in double leg stance will change the activation of muscles around the trunk. O'Sullivan and co-workers (2002) demonstrated differences in abdominal and back muscle activity levels when comparing active upright standing to sway standing. Hip and thigh muscle activity was not recorded in this study. Wang and co-workers (2006) measured leg, hip and trunk muscle activation during sagittal plane standing postures, where the change in movement was hip flexion and hip extension. Their results showed that with anterior trunk sway (hip flexion), there was an increase in hamstring and erector spinae activation (dorsal muscles), accompanied by a decrease in RF and rectus abdominus activation (ventral muscles). The opposite was found when the subject adopted a posterior trunk sway posture (hip extension).

The response to a moving platform requiring balance reactions has also been investigated. Henry et al (1998) investigated double leg stance and response to single platform movements in multiple directions (9cm in 200ms). The direction of maximal activity for the thigh and pelvis muscles was generally in response to diagonal translations, except for the Tensor Fascia Lata (TFL) and RF, which were maximally active in response to lateral translations. Although the response to perturbation could occur at multiple sites (such as ankle, hip and trunk), this study further supports that muscle activity around the hip and thigh is responsive to postural and balance demands.

Non-weight bearing positions

Lovell and colleagues (2012) showed a relationship between sagittal plane hip position and EMG activation in the muscles of AL, adductor magnus, gracilis and pectineus. They took six clinical hip adduction examination positions in either side lying or supine. The positions were hip flexion at 0°, 45°, 70° and 90° (squeeze from the knees, squeeze from the feet, or squeeze in a side lying position). EMG activation was highest in Hips 0° or Hips 45° for adductor magnus, AL and gracilis. EMG activation for pectineus was highest in Hips 90°. While not in a functional weight bearing posture, this study does suggest that joint position will have an influence on some muscle activation patterns even without the added balance demands of weight bearing postures. This is an area that needs further research as there is currently a lack of literature to draw from.

1.5.2 Single leg positioning

Weight bearing position

In relation to posture and muscle activation, there is a gap in the literature regarding investigation of single leg stance, a position more commonly associated with lower limb injury than double leg stance. In particular, there is a lack of knowledge regarding what effect pelvic and/or trunk postures have on lower limb (hip and thigh) muscle activation. One of the few studies investigating aspects of this relationship was Inman (1947) who reported that when considering frontal plane muscle activity during single leg stance, the weight bearing hip abductor muscles (Gmed, gluteus minimus, TFL) showed increased activity as the non-weight bearing pelvic side would move from a “sagging” position (pelvic drop), to pelvis level, to a 20° elevated position (pelvic raise). He also reported that with a pelvic “sag” angle between 10-20°, palpation of TFL in this sag position was found to be “tense” with little muscle activation, possibly reflecting passive tension in the muscle. Interpretation of this paper was hampered somewhat by an incomplete explanation of the methodology: the authors did not explain how they recorded pelvic kinematics or what statistical calculations were performed. This paper investigated one hip muscle in one plane of hip movement, which highlights the need for research that investigates and compares frontal and sagittal plane positions of multiple muscles of the hip and thigh.

Hardcastle and Nade (1985) obtained EMG from 3 "normal" subjects as part of a larger study investigating the significance of the "Trendelenburg" test to try to define "normal" muscle activity of the frontal plane hip muscles. They reported in single leg stance with the pelvis dropped on the non-stance side (a classical Trendelenburg position); there was no activity in Gmax, Gmed, gluteus minimus or adductor magnus, though there was activity in TFL. They also reported that "if the subject, on command, voluntarily raised the pelvis on the non-stance side", hip abductor muscle activity increased gradually, in agreement with Inman (1947), and there was no activity in Gmax or adductor magnus. Unfortunately interpretation of this paper was also hampered by a limited description of methods, such that the finding of "no activity" in some muscles is difficult to interpret as there is no documentation of EMG methods nor statistics performed.

Earl (2004) investigated three variations of a single-leg-stance exercise (hip abduction only, abduction-internal rotation (ABD-IR), and abduction-external rotation) with a pulley system applying force 45° vertically and recorded EMG activity of three parts of Gmed (anterior, middle, and posterior). Their results showed ABD-IR produced the most activity in the anterior and middle sections of the Gmed muscle. Their results support the notion that alterations in hip position influence activation of the Gmed muscle. In these studies, the influence of altering trunk and pelvis position was not investigated.

While there is some limited evidence supporting the notion that trunk, hip, and thigh muscle activity is influenced by changes in trunk and pelvis position in the sagittal and frontal plane in either double leg and single leg standing, to date no research has investigated the effects of analysing the relationship between both kinematics and muscle activation patterns during single leg stance when varying trunk and pelvic position.

Computer Modeling

Changes in pelvic and hip loading and the resultant influence on muscle activation patterns are potentially influenced by a large number of variables. An alternate strategy is to conduct experimental modeling through computer simulation allowing manipulation of individual joint positions and muscle activations. Lewis and colleagues (2007, 2010) employed a musculoskeletal model to estimate hip joint forces during simulated prone hip extension, supine hip flexion and also simulated gait. They predicted that decreasing gluteal muscle activation during hip extension and decreasing iliopsoas muscle activation during hip flexion resulted in increased anterior hip joint force. The model also indicated that increasing the maximum end range hip extension increased anterior hip joint force. Despite the limitations of computer simulation, which is the direct application of the findings to "real life" assuming that all intrinsic and extrinsic forces and variables are equal both on and off a computer, this research further supports the concept that alterations in both muscle activation and joint position during muscle activation can have an influence on hip joint forces.

1.6 Static assessment and the relationship to dynamic function

1.6.1 Static posture

There is literature to support the idea that static posture can predict dynamic posture. This is of particular interest to the treating therapist as the majority of clinical assessment is carried out initially in the clinic usually in a confined space. There is evidence for this with regards to the trunk, where habitual sitting and standing postures strongly correlate with complex landing and other functional postures. Wade et al (2012) found that in elite female gymnasts their landing lower lumbar spine position correlated highly to their static lower lumbar spine position in sitting and standing. Similarly, Mitchell et al (2008) showed that in a group of nursing students with and without lower back pain static lower lumbar spine sitting posture strongly correlated with lower lumbar spine posture in functional tasks including squatting, transferring a pillow and picking up a box. Normative data for trunk and pelvic postures and muscle activation patterns are not available to allow such clinical inferences to be made for this body region.

1.6.2 Static strength and its relation to kinematic function?

Recent research has investigated the relationship between static muscle strength and joint kinematics in static and dynamic tasks. Kendall et al (2010) studied a population of subjects with non specific lower back pain compared to pain free individuals. They found no relationship between isometric strength of the hip abductors and the magnitude of pelvic drop during a statically performed Trendelenburg posture as well as during walking in either population. Although it was not measured it is worth considering that lack of pelvic drop may also be due to other factors including available range of motion at the hip and lumbar spine, not just strength. Similarly, Burnet and Pidcoe (2009) found no relationship between isometric hip abduction strength and the degree of pelvic drop during running in a cohort of nine males and 12 females. These studies did not investigate the hip abductor muscle activation whilst performing the test conditions.

Thijs and colleagues (2007) examined knee valgus and varus angles in healthy tennis players as they performed a forward lunge and found no relationship between hip muscle strength and knee position. There was a moderate positive correlation found between the external rotation/internal rotation force ratio and the amount of knee varus during the forward lunge movement. Sigward and colleagues (2008) also found that hip muscle strength was not predictive of lower limb kinematics in a group of female high school students performing a double leg drop-land task.

Lawrence and colleagues (2008) investigated whether hip external rotator muscles, quadriceps or hamstring strength had a relation to single-legged 40 cm drop landing. They found hip external rotation strength had no relationship with sagittal or frontal plane angular motion throughout the landing cycle at the hip and knee. However the weak group produced a greater external knee adduction (valgus) moment, net knee anterior shear joint reaction force, and a greater hip adduction moment.

Whilst the link between hip muscle strength and kinematic function is not clear, there is evidence that some aspects of muscular performance influence lower limb kinematics. Snyder at al (2009) showed that foot, hip and knee kinematics could be changed by an increase in hip abduction and external rotation strength. This improvement could be attributed to the learned effect from the program exercises. Bittencourt et al(2012) concluded that decreased isometric hip abductor torque together with a reduced passive hip internal range of motion predicted an increased valgus knee position during a single leg squat in a mixed cohort of male and female athletes. This suggests that strength does play some role in knee position. In the presence of patellar femoral pain syndrome, when compared to a control group, reduced kinematic performance was associated with diminished strength in hip abduction, hip external rotation and hip extension. The kinematic effects observed included increased ipsilateral trunk lean, contralateral pelvic drop, hip adduction, peak hip internal rotation and knee abduction during a mix of activities such as single leg squat, running, drop jump and a step down manoeuver (Nakagawa et al., 2012, Souza and Powers, 2009).

The effect of fatiguing the hip abductor muscles and it's relation to performance of some common activities has also been investigated. McMullen et al (2011) found that following a fatiguing protocol (side lying concentric and eccentric hip abduction), both postural control (static and dynamic) and quality of movement were affected negatively in both men and women. The tests they used were centre-of-pressure measurements performed on a force platform, the Star Excursion Balance Test, and lateral step-down test. Geiser et al (2010) used a similar "fatiguing" position (side lying concentric and eccentric hip abduction) and defined "fatigue" to be an inability of the muscle to produce 80% of maximal peak torque during an isometric contraction. They observed that the knee angle at initial ground contact was more adducted and there was a greater internal knee adductor moment as subjects performed either a cut, jump, or running task.

The above literature does not support a simple relationship between muscle strength and kinematic function. The research by Popovich and Kulig (2012) described earlier that considers the relationship between hip muscle strength, lumbo-pelvic motion and muscle activity supports that muscle activation and kinematic function is potentially influenced by a number of factors. These factors suggest that a weaker individual needs to use a relatively higher degree of muscle activation, compared to stronger subjects to achieve the same task, representing a less efficient strategy to control and stabilise the lumbo-pelvic region. There appears to be a clear gap in the current literature in this area around defining the muscle activation patterns and the influence of body kinematics whilst performing clinically relevant tasks.

1.7 Summary of key points

- Overuse injuries in the lower limb are common, with research identifying that both altered kinematics and altered muscle activation patterns are possible injury mechanisms.
- Rehabilitation strategies that target kinematic retraining and muscle strengthening are common. Investigations of weight bearing versus non-weight bearing exercises and functional versus non-functional exercises in relation to improved functional performance suggest that functional weight bearing exercises have more direct correlation with functional performance.
- Rehabilitation programs focusing on sports specific body alignment control have been shown to reduce injury rates.
- There is evidence that alterations in body kinematics can influence muscle activation patterns in the hip and thigh, but most evidence is for changes in foot, knee and hip position.
- There is some limited evidence that changes in the position of the trunk or pelvis in upright postures can influence lower limb muscle activation patterns.
- There is no normative data regarding variation in trunk and pelvic posture and how it affects muscle activation around hip and thigh in sagittal and frontal planes in the functional position of single leg stance.

1.8 Basis for current research

The commonly employed clinical strategy of examining a patient in a static single leg stance needs to be examined to determine the influences that changes in the trunk and pelvic posture have on normal muscle activation of the hip and thigh. This information will provide baseline normative data that can be further explored in clinical populations and during dynamic functional activities.

Therefore, the purpose of this study is to investigate whether different hip and thigh muscle activation patterns are associated with varying sagittal and frontal plane trunk and pelvic postures during single leg stance in healthy controls.

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Chapter 2 – Methods

2.1 Research Hypotheses

Based on a review of the literature, the following *a-priori* research hypotheses were developed;

H1 Alterations in *sagittal plane trunk position* in static single leg stance will result in changes in sagittal plane hip and thigh muscle activation patterns.

H2 Alterations in *sagittal plane pelvic position* in static single leg stance will result in changes in sagittal plane hip and thigh muscle activation patterns.

H3 Alterations in *frontal plane trunk position* in static single leg stance will result in changes in frontal plane hip and thigh muscle activation patterns.

H4 Alterations in *frontal plane pelvic position* in static single leg stance will result in changes in frontal plane hip and thigh muscle activation patterns.

2.2 Study design

This study was conducted using a within-subjects normative, descriptive design.

2.3 Ethical approval

Ethical approval for undertaking this research prior to its commencement was granted by the Human Research Ethics Committee of Curtin University of Technology, Perth, Australia (Appendix A, page 95) and Aspetar Hospital, Doha, Qatar (Appendix B, page 96).

2.4 Subjects

Subjects were offered the opportunity to participate in the study via personal invitation with no financial cost to them and no offer of reimbursement. Potential subjects were provided with an information sheet outlining the purpose of the study (Appendix C, page 97). Written informed consent was completed by all volunteers prior to participating in the study (

Appendix D, page 99). Subjects were given the opportunity not to participate in the study and withdraw from the study at any time without prejudice, none of them elected to do. There were 22 male subjects, aged between 20-45 years who participated in the study.

2.4.1 Inclusion criteria

Subjects needed to be asymptomatic healthy males aged between 18-45 years who were regularly engaged in physical exercise of at least 30 minutes duration three times per week. Male subjects were chosen for 2 reasons. Firstly, we were unable to test women due to the cultural and religious restrictions in Qatar where this research was conducted. Secondly, there are greater numbers of male athletes in Qatar making the application of our findings and furthering this research more specific.

2.4.2 Exclusion criteria

Subjects were excluded if they;

- Had a body mass index (BMI) greater than 30 due to the influence adipose tissue has on EMG signal (Nordander et al., 2003).
- Had a lower limb or back injury within the last three months that had restricted participation in their usual physical activities.
- Were unable to understand written and spoken English.
- Were unable to adopt and sustain the required test postures.

2.4.3 Calculation of sample size

We assumed that the difference in the EMG of the paired positions would be normally distributed with standard deviation 0.3. Accordingly, if the true difference in the mean response of matched pairs is 0.5, we would need to study 5 pairs of subjects to be able to reject the null hypothesis that this response difference is zero with probability (power) 0.8 (Dupont and Plummer, 1998). The Type I error probability associated with this test of this null hypothesis is 0.05 (Dupont and Plummer, 1998). Since these were speculative estimates of the effect size we arbitrarily chose a more conservative sample size of 20 subjects. Allowing for up to 10% dropout, we initially recruited for 22 subjects.

2.5 Variables

2.5.1 Independent variables

Commonly adopted static single leg standing positions were defined (See 2.6.3). These were a reference upright posture and four pairs of test positions that represented changes in trunk and pelvis position in both sagittal and frontal planes. The test positions were named as follows:

- Upright Standing (sagittal and frontal planes)
- Pair 1. Anterior Trunk Sway and Posterior Trunk Sway (sagittal plane)
- Pair 2. Anterior Pelvic Rotation and Posterior Pelvic Rotation (sagittal plane)
- Pair 3. Left Trunk Shift and Right Trunk Shift (frontal plane)
- Pair 4. Lateral Pelvic Raise and Lateral Pelvic Drop (frontal plane)

2.5.2 Dependent variables

- Muscle activation
    - Gluteus maximus (Gmax)
    - Gluteus medius (Gmed)
    - Tensor fascia lata (TFL)
    - Semitendinosus (ST)
    - Biceps femoris (long head) (BF)
    - Vastus lateralis (VL)
    - Rectus femoris (RF)
    - Adductor longus (AL)

2.6 Testing protocol

For the main study, subjects attended a single testing session. The testing session ran for approximately 90 minutes. On arrival, subjects were asked to review the Information Sheet (Appendix C, page 97) and sign the consent form. They were then asked questions to screen for exclusion criteria. Subjects were asked to disrobe to their underwear and were measured for body weight and height to establish their BMI (in kg/m^2).

2.6.1 Kinematic procedures

Three dimensional kinematic data was recorded using a 14 camera Vicon system (OMG, Oxford, England), with MX-13 cameras (OMG, Oxford, England) through Vicon Nexus software (v1.5, OMG, Oxford, England), at a sampling rate of 500 Hz. To monitor the necessary body positions, the Full Body Plug-in Gait model (v2.5, OMG, Oxford, England) (excluding upper limb and head markers), was used.

Anthropometric measurements of bilateral joint widths (ankle, knee and wrist), and leg lengths were taken to calibrate the Vicon system. According to the Vicon Full Body Plug-in Gait model manual (Appendix E, page 100), 23 photo reflective markers were placed on the subject using double sided adhesive tape (Appendix F, page 101) and (Figure 1).

Figure 1: Photo-reflective marker placement on a subject

2.6.2 EMG procedures

Surface EMG of the following muscles were recorded:

- gluteus maximus
- gluteus medius
- tensor fascia lata
- semitendinosus
- biceps femoris (long head)
- vastus lateralis
- rectus femoris
- adductor longus

The location was marked for the EMG electrodes according to Perotto (2005) (Appendix G, page 102). EMG signals were recorded using integral dry reusable electrodes with an inter-electrode distance of 20 mm (Biometrics SX230, Gwent, UK). Low impedance between electrodes was optimized by abrading and cleaning the skin with emery paper and alcohol. The EMG electrodes were attached with specific double-sided tape suited for these electrodes. A common earth electrode was placed over the wrist. Signals were recorded at a sampling frequency of 1000 Hz using Biometrics hardware (Biometrics DataLOG, Gwent, UK) and dedicated software. EMG signals were amplified and filtered (band pass 30 Hz – 500 Hz, gain = 1000) and muscle electrical activity was determined by calculating the mean value of the root mean square (Basmajian and De Luca, 1985) (cited in) (Sims and Brauer, 2000).

The EMG signal quality for each electrode was then visually inspected. Manual resistance was applied to the right leg of the subject in standing to produce isometric muscle activation in the directions of hip adduction, hip flexion, hip abduction, hip extension and knee flexion. These isometric contractions were sufficient to observe for consistent activation of all muscles being tested. In the event of poor signal quality, electrode placement procure for the relevant muscle was repeated and then the same signal quality assessment was conducted until acceptable EMG quality was produced.

EMG was normalised to Upright Standing (a Sub-Maximal Voluntary Isometric Contraction (Sub-MVIC) normalisation method)(please refer to section 4.1.1 for detail on selection of

EMG normalisation procedure) EMG for each of the paired test postures was expressed as a percentage of the reference Upright Standing posture.

2.6.3 Test protocol

The subject was first positioned within the Vicon system frame of reference. The Vicon system was calibrated for each subject by visually checking all cameras were working and ensuring all markers on the subject were detected by the computerised system.

Once satisfied the Vicon and EMG systems were working, the testing procedure was explained in detail to the subject. The testing session followed the same order of procedures. The only component of the testing protocol that was randomized was the order of test positions. However, 'Upright Standing' was always the first position tested; as it was the reference posture from which all other test postures were guided. It also served as the familiarisation posture, which allowed the subject to understand the procedures and ask any questions if required. The order of measuring the eight test positions (other than Upright Standing) were selected randomly using a blinded envelope selection process.

Initially subjects were shown and then asked to perform the 'Upright Standing' position, which was the first position. Some consistent body positions were required for all test postures, and these were explained to the subject using consistent cues. The cues were:

- Stand on the right leg with the right knee in full extension (fully straight or locked), then just "unlock" the right knee and maintain this position. The aim was for the knee to be in approximately 10° flexion, although the subject was not made aware of the specific angle.
- The left knee was to be flexed enough so that the left foot was just off the ground behind the subject's body and the left thigh was to be in a neutral hip flexion/extension position. Between each test the subject was advised to put the left foot on the ground and place more weight on the left leg in order to rest the right leg.
- Arms were to be lightly folded in front of the abdomen, in order to avoid covering the photo reflective markers.
- Head and eyes were directed to a point on the wall in front of the subject that was approximately at eye level.

Once the subject was familiarised with the Upright Standing position, they were taught the remaining test positions. As described, Upright Standing was the first position, followed by the other eight randomly selected positions. Each test position was performed and recorded six times.

The test positions are shown in Figure 2, page 38, in Chapter 3, and were defined as follows:

Upright Standing

Upright Standing was defined as a position in which the subject stood on the right leg with the right acromion, right greater trochanter, and right lateral malleolus lining up to form an angle of approximately 180°(+/- 10°). The subject was instructed to unlock the right knee in slight (approximately 10°) flexion. Pelvic position was also visually monitored to ensure a neutral position in a sagittal plane and level with horizontal (i.e. no drop or raise) in the frontal plane.

Anterior Trunk Sway and Posterior Trunk Sway

The position of the trunk in the Upright Standing position for each subject was defined as the reference Thorax Angle. The Anterior Trunk Sway and Posterior Trunk Sway angles were measured by the Vicon system and defined as the trunk being at least 10° anterior and posterior (in the sagittal plane) to the Upright Standing Thorax Angle respectively. Sagittal plane knee and ankle angles remained constant, as did all frontal plane angles.

Anterior Pelvic Rotation and Posterior Pelvic Rotation

The position of the pelvis in the Upright Standing position for each subject was used as the reference Pelvic Angle. The Anterior Pelvic Rotation and Posterior Pelvic Rotation angles were defined as at least 5° anterior and posterior to the Upright Standing sagittal plane Pelvic Angle respectively. Sagittal plane trunk, knee and ankle angles remained constant, as did all frontal plane angles.

Trunk Shift Left and Trunk Shift Right

The position of the trunk in the Upright Standing position for each subject was defined as the reference Thorax Angle. The Trunk Shift Left and Trunk Shift Right angles were defined as at least 10° left and right of the Upright Standing frontal plane Thorax Angle respectively. Frontal plane Hip and pelvis angles remained constant, as did all sagittal plane angles.

Lateral Pelvic Raise and Lateral Pelvic Drop

The position of the pelvis in the Upright Standing position for each subject was used as the reference Pelvic Angle. The Lateral Pelvic Raise and Lateral Pelvic Drop angles were defined as at least 5° higher and lower of the Upright Standing posture frontal plane Pelvis Angle respectively. Frontal plane trunk angle remained constant, as did all sagittal plane angles.

EMG recording was started when the subject was judged to be holding a stable test position and was stopped after six seconds of recording. A rest period of 15 seconds was given between test positions to minimize the influence of fatigue. Position instructions with a short practice and feedback were given before each new test position, to ensure the subject was able to adopt and maintain the required position. Trials in which subjects lost their balance or deviated significantly from the required test position were stopped, the data discarded and the trial repeated.

2.6.4 Statistical Analysis

All data were coded and analyzed using the SPSS statistical software v19.0 (SPSS inc., Armonk, USA). Repeated measures ANOVA was performed along with associated F-tests to determine if there were significant differences in muscle activation between each measurement. An alpha level of $p<0.05$ was set to determine significance.

2.7 References

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Chapter 3 - Kinematic reliability

3.1 Introduction

In addition to the main research hypotheses, as some original research methods were employed, an evaluation of methodological reliability was necessary. Firstly reliability of subject positioning was considered. It was necessary to determine if subjects could be guided into the same test position across different trials, and to establish the absolute variability associated with doing so. It was also necessary to ensure the defined paired test positions were clearly different from each other. Therefore, the following research questions were developed:

- Can subjects be reliably positioned (in both the sagittal and frontal planes), in a variety of commonly observed single leg standing positions?
- Are the paired test positions significantly different from each other, as determined by the Vicon analysis?
- What is the minimum number of trials required to ensure data is collected in a consistent position?

3.2 Methods

As it was unknown how many trials would be required to achieve acceptable reliability and variance, six trials were arbitrarily chosen to be performed for each subject. The reliability was then examined post hoc considering 5 conditions (Upright Standing and the four paired test postures), as shown in (Figure 2). The kinematic examination considered: all 6 trials, the first 5 trials, the first 4 trials, the first 3 trials, and the first 2 trials. This analysis allows future research to conduct power analyses a priori given the variance data for each parameter for each number of examinations.

3.2.1 Kinematic measurement

In terms of measuring kinematics, a range of measurement options are available. These include photo reflective skin markers with angle analysis using two-dimensional digital photography (O'Sullivan et al., 2006), three dimensional electromagnetic analysis (Jordan et al., 2004), tri-axial accelerometers (Wong and Wong, 2008), pelvic goniometry (Sprigle et al., 2003) and bubble inclinometry (Piva, 2003). While all these methods have been shown to have acceptable reliability, three-dimensional multi-camera marker-based motion analysis, such as the Vicon 3D system, remains the most widely respected method of non-invasively examining kinematics (Balan et al., 2005, Russell et al., 2006). The Vicon 3D motion capture system is a widely accepted and valid measure of kinematics (Eve et al., 2006, Norcross et al., 2010). However, the inter-trial reliability and validity of a clinician positioning subjects in some of the novel test postures selected for this study has not been previously evaluated. To measure the consistency of the nine test positions, 3D kinematic data for each trial was collected using the methods described in section 2.6.1.

3.2.2 Test postures

The definitions of the test postures are explained in the above section 2.6.3.

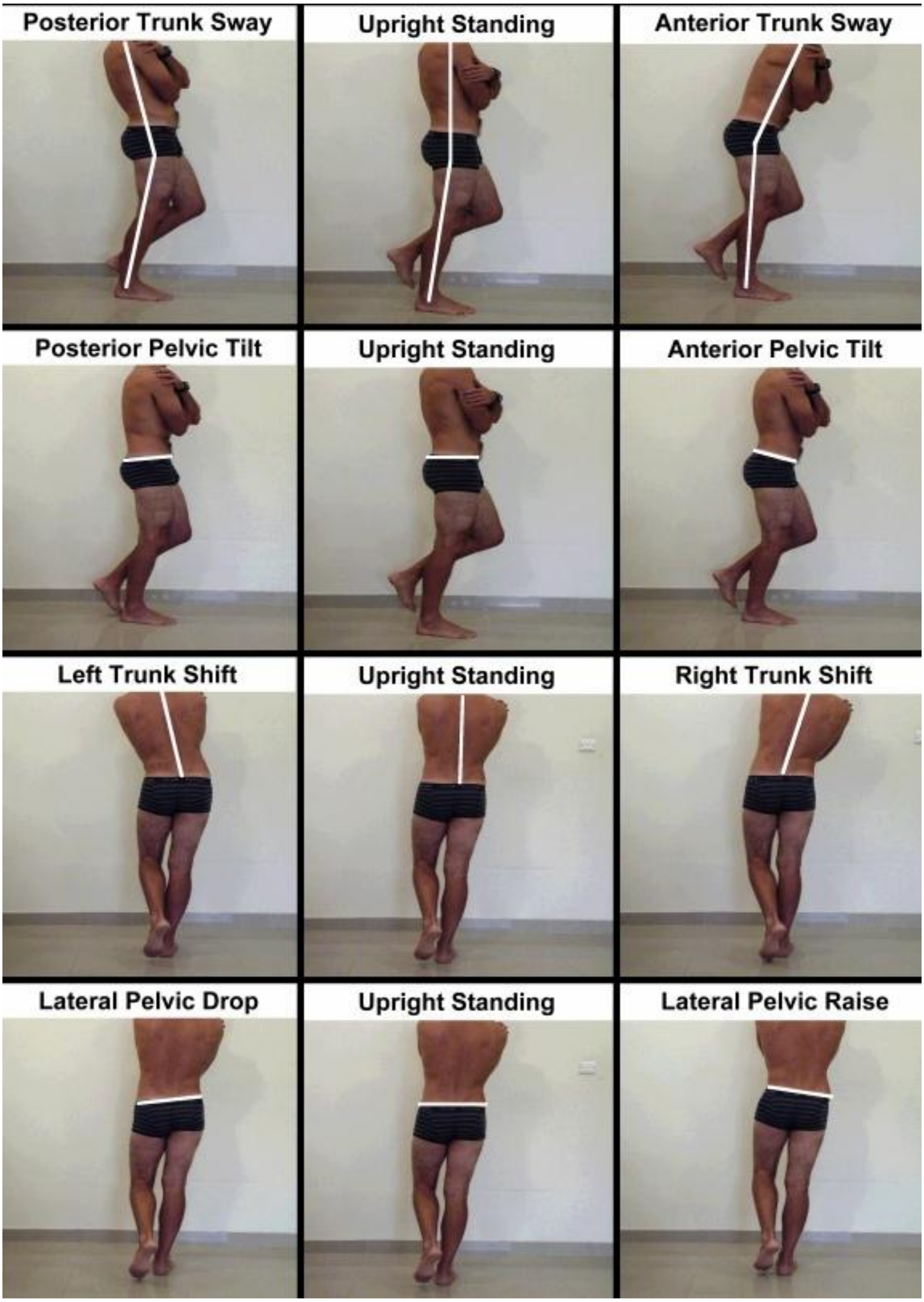

Figure 2: Test positions

3.3 Statistical Analysis

All data were coded and analysed using the SPSS statistical software v19.0 (SPSS inc., Armonk, USA). In order to establish both the inter-trial reliability and standard error of the angles in the reference Upright Standing posture and the 8 test postures, interclass correlation coefficient (ICC $_{(2,1)}$) was computed (Shrout and Fleiss, 1979). The angles monitored were the seven body position Vicon reference angles defined in Section 2.6.1. An $ICC_{(2,1)}$ value greater than 0.75 was considered good reliability (Cohen, 1988). An alpha level of $p<0.05$ was set a priori.

3.4 Results

3.4.1 Reliability of defining angles

Table 1 shows the reliability of the defining Vicon angle in each of the test postures.

Reliability of the defining angles over 6 trials				
Position	**Defining Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Anterior Trunk Sway	R Thorax X	17.4±6.7 (2.5)	0.89(0.80-0.95)	<0.001
Posterior Trunk Sway	R Thorax X	-13.9±4.2 (1.7)	0.84(0.74-0.92)	<0.001
Anterior Pelvic Rotation	R Pelvis X	18.9±3.2 (1.8)	0.76(0.62-0.87)	<0.001
Posterior Pelvic Rotation	R Pelvis X	3.8±4.4 (1.6)	0.87(0.78-0.93)	<0.001
Left Trunk Shift	R Thorax Y	10.3±3.3 (2.1)	0.71(0.56-0.85)	<0.001
Right Trunk Shift	R Thorax Y	-15.6±3.5 (2.2)	0.70(0.55-0.84)	<0.001
Lateral Pelvic Drop	R Pelvis Y	6.4±2.9 (1.1)	0.84(0.72-0.92)	<0.001
Lateral Pelvic Raise	R Pelvis Y	-7.6±2.7 (1.5)	0.75(0.61-0.87)	<0.001

Table 1: Reliability of the defining Vicon angle in each of the test postures

3.4.2 Reliability of Upright Standing

Over the six trials of Upright Standing, all of the seven body position reference angles were examined for reliability, and the results are shown in Table 2. Reliability of all seven angles was good, except for the Thorax Y angle. The absolute values of the standard deviation and SEM for this angle indicate very consistent subject positioning.

Upright Standing			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	12.2±5.8 (2.0)	0.89(0.81-0.95)	<0.001
R Knee X	9.0±5.5 (2.0)	0.88(0.8-0.94)	<0.001
R Pelvis X	12.0±3.9 (1.1)	0.91(0.85-0.96)	<0.001
R Pelvis Y	-1.1±2.8 (1.1)	0.87(0.79-0.94)	<0.001
R Spine X	-14.8±5.4 (1.5)	0.93(0.88-0.97)	<0.001
R Thorax X	-2.7±3.9 (1.1)	0.91(0.85-0.96	<0.001
R Thorax Y	-1.8±1.6 (1.4)	0.54(0.36-0.73)	<0.001

Table 2: Reliability of the seven Vicon reference angles in Upright Standing

3.4.3 Reliability of paired test positions

Pair wise comparisons of the four paired test postures demonstrated that the paired test postures were clearly different from each other (p>0.001) supporting the validity of the testing procedure for the defining trunk or pelvic angles over the six trials.

3.4.3.1 Anterior Trunk Sway vs. Posterior Trunk Sway

The mean change in angle Thorax X between Anterior Trunk Sway and Posterior Trunk Sway was 31.3°. The subjects necessarily accommodated this change in trunk position with small movements at their pelvis and hip. The reported magnitudes of those joints that experienced a statistically significant change in position are detailed in Table 3.

Pair wise position	**Angle**	**Mean change (95% CI)**	**p value**
Anterior Trunk Sway vs. Posterior Trunk Sway	R Hip X	15 (12 - 18)	<0.001
	R Knee X	2 (-1 - 4)	0.337
	R Pelvis X	9 (7 - 12)	<0.001
	R Pelvis Y	0 (-1 - 1)	1.000
	R Spine X	22 (19 - 26)	<0.001
	R Thorax X*	31 (28 - 34)	<0.001
	R Thorax Y	0 (-1 -1)	1.000

Table 3: Mean change in reference angles between Anterior Trunk Sway and Posterior Trunk Sway. The shaded/* angle highlights the defining angle for this pair wise position.

3.4.3.2 Anterior Pelvic Rotation vs. Posterior Pelvic Rotation

The mean change in angle Pelvis X between Anterior Pelvic Rotation and Posterior Pelvic Rotation was 15.1°. Sagittal plane angles (Hip X, Spine X, Thorax X) And Frontal plane angles (Pelvis Y) showed accommodative changes depicted in Table 4.

Pair wise position	Angle	Mean change (95% CI)	p value
Anterior Pelvic Rotation vs. Posterior Pelvic Rotation	R Hip X	16° (13° - 18°)	<0.001
	R Knee X	-1° (-4° - 2°)	1.000
	R Pelvis X*	15° (13° - 17°)	<0.001
	R Pelvis Y	1° (0° - 2°)	0.028
	R Spine X	-18° (-21° - -16°)	<0.001
	R Thorax X	-3° (-5° - -1°)	<0.001
	R Thorax Y	-1° (-2° - 0°)	0.087

Table 4: The mean change in reference angles between Anterior Pelvic Rotation and Posterior Pelvic Rotation. The shaded/* angle highlights the defining angle for this pair wise position.

3.4.3.3 Left Trunk Shift vs. Right Trunk Shift

The mean change in angle Thorax Y between Left Trunk Shift and Right Trunk Shift was 25.9°. The accommodative changes in frontal plane angles for are shown in Table 5.

Pair wise position	Angle	Mean change (95% CI)	p value
Left Trunk Shift vs. Right Trunk Shift	R Hip X	0° (-2° - 3°)	0.907
	R Knee X	1° (-1° - 3°)	0.826
	R Pelvis X	0° (-2° - 1°)	1.000
	R Pelvis Y	3° (1°- 4°)	<0.001
	R Spine X	0° (-2° - 2°)	1.000
	R Thorax X	-1° (-2° - 1°)	1.000
	R Thorax Y*	26° (24° - 28°)	<0.001

Table 5: The mean change in reference angles between Left Trunk Shift and Right Trunk Shift. The shaded/* angle highlights the defining angle for this pair wise position.

3.4.3.4 Lateral Pelvic Raise vs. Lateral Pelvic Drop

The mean change in angle Pelvis Y between Lateral Pelvic Drop and Lateral Pelvic Raise was 14.1°. All other angles experienced no significant change illustrated in Table 6.

Pair wise position	Angle	Mean change (95% CI)	p value
Lateral Pelvic Drop vs. Lateral Pelvic Raise	R Hip X	0° (-3° - 3°)	1.000
	R Knee X	1° (-2° - 4°)	1.000
	R Pelvis X	-1°(-3° - 1°)	0.581
	R Pelvis Y*	14° (12° - 16°)	<0.001
	R Spine X	1° (-1° - 4°)	0.521
	R Thorax X	0° (-3° - 2°)	1.000
	R Thorax Y	0° (-1° - 2°)	1.000

Table 6: The mean change in reference angles between Lateral Pelvic Drop and Lateral Pelvic Raise. The shaded/* angle highlights the defining angle for this pair wise position.

3.4.4 Determining the minimum number of trials required

Six Trials

Mean ICC values for each of the seven kinematic angles (defined in section 2.6.1) across each of the nine test postures (i.e. 63 variables) using six trials were greater than 0.75, with 8 exceptions. The means, SD, SEM, and ICC values for these 8 variables are shown in Table 7. Of these 8 variables which had ICC's <0.75, the SEM was ≤4° in all cases. The entire table showing these data for all 63 variables is included as Appendix H, page 103.

6 trials				
Position	**Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright Standing	R Thorax Y	-1.8±1.6 (1.4)	0.54(0.36-0.73)	<0.001
Posterior Trunk sway	R Thorax Y	-2.1±2.0 (1.1)	0.72(0.56-0.85)	<0.001
Left trunk shift	R Thorax Y	10.3±3.3 (2.1)	0.71(0.56-0.85)	<0.001
Right trunk shift	R Thorax Y	-15.6±3.5 (2.2)	0.70(0.55-0.84)	<0.001
Lateral Pelvic drop	R Thorax Y	-1.7±3.1 (2.8)	0.54(0.36-0.74)	<0.001
Lateral Pelvic raise	R Thorax Y	-2.1±2.7 (2.1)	0.63(0.45-0.79)	<0.001
Right trunk shift	R Pelvis Y	-2.2±3.1 (1.9)	0.73(0.58-0.85)	<0.001
Lateral Pelvic drop	R Spine X	-16.5±6.7 (4.0)	0.74(0.58-0.86)	<0.001

Table 7: The mean angle, SD, and SEM for positions and reference angles with ICC < 0.75 over 6 trials

Five Trials

Using the first 5 trials, the mean ICC values for each of the seven joint angles across each of the nine test postures over five trials ranged from 0.75 to 0.96, with 6 exceptions. These data are presented in Table 8 and the reliability data for all variables is presented in Appendix H, page 103.

5 trials				
Position	**Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright Standing	R Thorax Y	-1.9±1.5 (1.4)	0.51(0.32-0.72)	<0.001
Left Trunk Shift	R Thorax Y	10.4±3.3 (1.9)	0.73(0.58-0.86)	<0.001
Right Trunk Shift	R Thorax Y	-15.4±3.5 (2.2)	0.70(0.54-0.84)	<0.001
Lateral Pelvic Drop	R Thorax Y	-1.9±3.4 (2.8)	0.59(0.39-0.77)	<0.001
Lateral Pelvic Raise	R Thorax Y	-2.1±2.7 (2.1)	0.59(0.40-0.77)	<0.001
Lateral Pelvic Drop	R Spine X	-16.3±6.6 (4.2)	0.71(0.55-0.85)	<0.001

Table 8: The mean angle, SD, and SEM for positions and reference angles with ICC < 0.75 over 5 trials

Four Trials

When considering the first 4 trials, the mean ICC ranged from 0.75 to 0.96, with 6 exceptions (Table 9). The complete data for all variables using 4 trials is included in Appendix H, page 103.

4 trials				
Position	**Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright Standing	R Thorax Y	-1.9±1.6 (1.5)	0.48(0.27-0.70)	<0.001
Right Trunk Shift	R Thorax Y	-15.3±3.5 (2.3)	0.69(0.51-0.84)	<0.001
Lateral Pelvic Drop	R Thorax Y	-2.1±3.7 (2.8)	0.64(0.43-0.81)	<0.001
Lateral Pelvic Raise	R Thorax Y	-2.0±2.7 (2.1)	0.60(0.39-0.78)	<0.001
Right Trunk Shift	R Pelvis Y	-2.3±3.2 (1.8)	0.74(0.58-0.87)	<0.001
Lateral Pelvic Drop	R Spine X	-16.0±6.7 (4.4)	0.68(0.49-0.84)	<0.001

Table 9: The mean angle, SD, and SEM for positions and reference angles with ICC < 0.75 over 4 trials

Three Trials

For the first 3 trials, mean ICC was ≥ 0.75 for all variables, with 7 exceptions. These data are presented in Table 10 and Appendix H, page 103.

3 trials				
Position	**Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright Standing	R Thorax Y	-1.8±1.8 (1.4)	0.56(0.32-0.76)	<0.001
Anterior Trunk Sway	R Thorax Y	-1.5±2.2 (1.2)	0.74(0.54-0.87)	<0.001
Posterior Pelvic Rotation	R Thorax Y	-1.3±2.3 (1.3)	0.73(0.53-0.87)	<0.001
Right Trunk Shift	R Thorax Y	-15.1±3.9 (2.3)	0.71(0.51-0.86)	<0.001
Lateral Pelvic Drop	R Thorax Y	-2.0±3.5 (2.8)	0.57(0.31-0.78)	<0.001
Lateral Pelvic Raise	R Thorax Y	-1.9±3.0 (2.0)	0.66(0.44-0.83)	<0.001
Lateral Pelvic Drop	R Spine X	-15.9±7.0 (4.8)	0.65(0.42-0.83)	<0.001

Table 10: The mean angle, SD, and SEM for positions and reference angles with ICC < 0.75 over 3 trials

Two Trials

Finally, the mean ICC for the first two trials showed ICC ≥ 0.75 for 58 of the 63 variables. These data are shown in Table 11 and Appendix H, page 103.

2 trials				
Position	**Angle**	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright Standing	R Thorax Y	-2.0±1.8 (1.4)	.50(0.13-0.75)	0.005
Posterior Trunk Sway	R Thorax Y	-1.9±1.9 (1.3)	.64(0.29-0.84)	0.001
Lateral Pelvic Drop	R Thorax Y	-2.0±3.3 (3.3)	.36(-0.11-0.69)	0.061
Lateral Pelvic Raise	R Thorax Y	-1.8±3.2 (2.1)	.66(0.34-0.84)	<0.001
Lateral Pelvic Drop	R Spine X	-15.5±7.5 (5.5)	.58(0.21-0.81)	0.003

Table 11: The mean angle, SD, and SEM for positions and reference angles with ICC < 0.75 over 2 trials

3.5 Discussion

3.5.1 Reliability of defining angles, and pair-wise position comparisons

Acceptable reliability of positioning subjects in static single leg standing has been shown in previous research (Norcross et al., 2010). The results of our research support this finding and additionally showed that subjects can be reliably positioned in single leg standing postures that involve a variety of different trunk and pelvic positions. This has relevance for EMG measurement, as variation in joint position is linked with alterations in EMG activation patterns (De Luca, 1997).

This study has now established normative data in respect to defining the amount of movement that occurs in key body regions when adopting specific trunk and pelvic positions during single leg stance. The intra-rater reliability associated with this positioning is seen to vary according to the number of trials and the angle being examined. Clinically, it is important to keep in mind both the intra-rater reliability as well as the between-trial error effect size. Estimates of these are seen in both the SD and SEM and need to be considered in context of the total range of motion available, as well as the change in range of motion being examined (Hopkins, 2006). For example, a standard error of 1° would be clinically important in a joint displaying only a few degrees total range of motion (e.g. the Sacroiliac joint (Sturesson et al., 2000)), but clinically meaningless in, say, shoulder flexion where this is much less than 1% of the total range available. Conversely, if the change in range of motion being examined was considering two angles only separated by a few degrees (Whiteley et al., 2008) then such an error would be clinically important. For example, the intra-rater reliability during the test positions of Left Trunk Shift and Right Trunk Shift were <0.75. Specifically, Left Trunk Shift mean $ICC_{(2, 1)}$ was 0.71 and Right Trunk Shift was 0.70. The SD and SEM ranges were 3.3° – 3.5° and 2.1° – 2.2° respectively. The mean change in position however was 26.3°. Accordingly, the variability relative to these postural changes is likely clinically insignificant.

3.5.2 Reliability of Upright Standing

To validate the Upright Standing position as the position for EMG normalisation and therefore our reference posture, the reliability of subject positioning was required. The ICC's of the kinematic measures showed values ≥ 0.87. Thorax Y (frontal plane) was the only exception with a mean ICC of 0.54. Again, this needs to be considered in light of the SEM of this value which was 1.4°, which is likely, clinically insignificant.

3.5.3 Determining the minimum number of trials

With respect to future studies considering the findings of this research it was considered valuable to analyse the reliability of 2 trials, 3 trials, 4 trials, and 5 trials. This information can then be used *a-priori* in power calculations, as well as informing clinicians who may use this data to examine these positions. It is suggested that future researchers examine the intra-rater reliability data along with the error estimates when considering the appropriate number of trials to conduct when they are using the positioning methods outlined here. Taking this into consideration, our results support that 2 trials only will be adequate for future studies except for the angle Spine X in a Lateral Pelvic Drop position.

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Chapter 4 – EMG reliability

4.1 Introduction

Once reliability of subject positioning was established, the capacity to reliably record EMG signal in the different test postures across the different muscles also needed to be determined. Accordingly, the following research question was developed:

- Can EMG activity of hip and thigh muscles be reliably recorded in a variety of commonly observed single leg standing positions?

Norcross et al (2010) investigated static single leg stance in an upright posture. Surface EMG amplitudes of the Gmax, Gmed, RF, VL, adductors, and BF along with hip and knee kinematics were measured concomitantly during single leg stance. Their aim was to assess the reliability of this position as a sub-MVIC method of normalising EMG. They found this position could reproduce reliable normative data around single leg stance muscle activation patterns, but co-efficients of variation were higher in some muscles than others. While there is some existing evidence to support the proposed methodology, the EMG reliability in the novel test postures of this study required evaluation.

4.1.1 Normalisation of EMG signal

The method of normalising our EMG signal to a reference value also required consideration. Lehman and McGill (1999) stated; "EMG normalization is the process by which the activation of the muscle contraction is expressed as a percentage of that muscle's activity during a calibrated test contraction. Normalization is essential for physiologic interpretation and for comparison between the same muscle in different positions and between different subjects."

When choosing a method of normalising EMG there are two commonly described approaches: the MVIC or the sub-MVIC contraction method. While MVIC is the most commonly used method of normalisation (Bolgla and Uhl, 2007, Fernandez-Pena et al., 2009, Arokoski et al., 1999), Sub-MVIC has been shown to be reliable (Dankaerts et al., 2004) and is considered more meaningful in examination of sub-maximal activation situations as the motor strategies employed likely vary in sub-maximal and maximal activations (Dankaerts et al., 2004).

Some practical limitations have been documented for the MVIC method (Allison et al., 1998). There is increased time required to MVIC test each muscle and it has been suggested that subjects need training in MVIC to make the results more accurate. Without training, MVIC has been shown to be as much as 40% lower than when compared to trained subjects (Solomonow, 1999) cited in (Ankrum, 2000). Additionally, multiple maximal effort contractions during normalisation procedures could increase the likelihood of fatigue prior to the data collection and therefore influence data accuracy.

To ensure an accurate comparison, both the MVIC and Sub-MVIC must be established with the muscle and joint in similar positions as during the experimental methods. Otherwise, the muscle area under the electrode will change and may result in inaccurate data (Mirka, 1991, Enoka and Fuglevand, 1993). As the methods in our study involved performing the testing in a variety of positions, it was deemed impractical to conduct MVIC in each of these positions.

Performing an MVIC assumes the subject will produce their maximum contraction. This is difficult to ascertain in practice, and may be impossible when applying this method to symptomatic patients (Yang and Winter, 1984, Soderberg and Knutson, 2000, Bolgla and Uhl, 2007). The methods described here involved collecting EMG from muscles that were in close proximity, increasing potential for electrical cross-talk. This cross-talk is thought to be more problematic with increased muscle activation during a MVIC (De Luca and Merletti, 1988, Koh and Grabiner, 1993).

Given the above issues with MVIC, it was considered that Sub-MVIC would be the method best suited to our study. However, the Sub-MVIC method is not without limitations. Firstly, there can be difficulties in establishing equivalent sub-maximal load for different muscles (Allison et al., 1998, Dankaerts et al., 2004). With the proposed methodology, the potential issue with using the single leg stance position is that subjects are required to maintain their balance, such that large movements would likely result in non-uniform muscle activation patterns, violating the assumptions underlying the use of Sub-MVIC (Norcross et al., 2010).

It has been reported that Sub-MVIC are more reliable in a painful population (McGill, 1991, O'Sullivan et al., 2002) and are more sensitive when assessing low levels of muscle activity (O'Sullivan et al., 2002, Snijders et al., 1995, Allison et al., 1998).

Our chosen position of normalisation, single leg Upright Stance, has previously been shown to be have good to excellent reliability with ICC's ranging from 0.8 to 0.94 (Norcross et al., 2010). This position also allows for application to any future research aimed at investigating symptomatic subjects, where performing MVICs could be problematic.

4.2 Methods

An outline of the methodology of surface EMG measurement of the hip and thigh muscles was provided in Chapter 2. The landmarks for electrode placement as defined by Perotto (2005) are provided in Appendix G, page 102. Figure 3 shows the electrode placement on a subject.

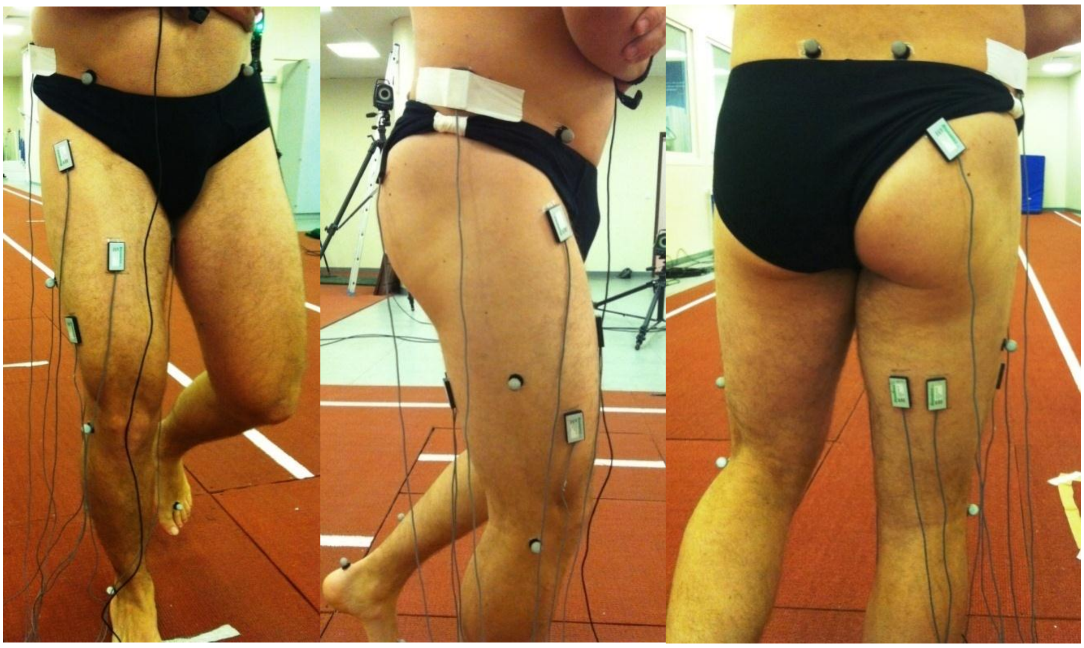

Figure 3: Surface EMG electrode placement

EMG data was first collected in Upright Standing, and then the other positions were tested in random order, as described in Chapter 2. Each test position was held for six seconds to allow for collection of a stable four seconds of data. EMG muscle activation patterns in each of the paired test positions were expressed as a percentage of the muscle activation in the reference Upright Standing position.

4.3 Statistical Analysis

All data were coded and analysed using the SPSS statistical software v19.0 (SPSS inc., USA). In order to establish the reliability of the muscle activation in the reference upright standing posture and the 8 test postures, interclass correlation coefficient ($ICC_{(2,1)}$) was computed (Shrout and Fleiss, 1979). Repeated measures ANOVA was performed along with associated F tests to determine if there were significant differences in muscle activation between each measurement. An ICC value greater than 0.75 was considered a good intra-rater reliability (Cohen, 1988). An alpha level of $p<0.05$ was set a priori as determining statistical significance. The reliability of the EMG measurements was considered for five different conditions from all six trials down to the first two trials.

4.4 Results

4.4.1 Upright Standing (reference posture)

The EMG ICC's, mean, (SD) and SEM for 8 muscles across all subjects over 6 trials during the Upright Standing position is presented in Table 12 below.

Upright Standing			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.87 ± 1.80 (2.46)	0.29 (011-0.52)	<0.001
BF	18.76 ± 22.77 (7.93)	0.90 (0.82-0.95)	<0.001
Gmax	9.25 ± 7.12 (2.65)	0.87 (0.77-0.93)	<0.001
Gmed	25.08 ± 18.34 (3.15)	0.97 (0.94-0.98)	<0.001
RF	26.28 ± 27.93 (10.03)	0.88 (0.79-0.94)	<0.001
ST	17.71 ± 12.68 (9.41)	0.64 (0.47-0.80)	<0.001
TFL	47.96 ± 31.09 (11.78)	0.89 (0.80-0.94)	<0.001
VL	42.71 ± 21.39 (10.24)	0.80 (0.68-0.90)	<0.001

Table 12: Reliability of EMG activity in Upright Standing

4.4.2 Reliability of the test positions

Intra-subject reliability for all test positions over all muscle groups are presented in Table 13 through to Table 20.

Anterior Trunk Sway			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.40 ± 4.62(0.84)	0.97(0.95-0.99)	<0.001
BF	50.19 ± 30.29(12.34)	0.87(0.77-0.93)	<0.001
Gmax	20.52 ± 12.08(3.29)	0.93(0.88-0.97)	<0.001
Gmed	29.99 ± 18.40(4.63)	0.96(0.93-0.98)	<0.001
RF	12.71 ± 12.93(4.48)	0.94(0.88-0.97)	<0.001
ST	45.88 ± 22.37(7.95)	0.88(0.80-0.94)	<0.001
TFL	26.62 ± 15.79(5.48)	0.87(0.78-0.94)	<0.001
VL	47.19 ± 21.45(10.07)	0.84(0.74-0.92)	<0.001

Table 13: Reliability of EMG activity in Anterior Trunk Sway

Posterior Trunk Sway			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	6.93 ± 4.26(1.04)	0.94(0.89-0.97)	<0.001
BF	10.76 ± 6.07(6.14)	0.51(0.32-0.71)	<0.001
Gmax	6.87 ± 5.44(1.50)	0.92(0.86-0.96)	<0.001
Gmed	22.43 ± 17.42(5.23)	0.96(0.93-0.98)	<0.001
RF	49.59 ± 44.66(15.79)	0.90(0.83-0.95)	<0.001
ST	9.04 ± 7.36(8.13)	0.36(0.18-0.59)	<0.001
TFL	71.80 ± 57.65(23.25)	0.85(0.75-0.92)	<0.001
VL	56.65 ± 29.79(13.30)	0.83(0.72-0.92)	<0.001

Table 14: Reliability of EMG activity in Posterior Trunk Sway

Anterior Pelvic Rotation			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.36 ± 2.09(1.44)	0.74(0.60-0.87)	<0.001
BF	17.01 ± 16.37(7.57)	0.83(0.71-0.91)	<0.001
Gmax	11.12 ± 5.60(2.15)	0.88(0.80-0.94)	<0.001
Gmed	26.84 ± 25.66(3.79)	0.98(0.96-0.99)	<0.001
RF	29.22 ± 26.59(11.16)	0.84(0.73-0.92)	<0.001
ST	13.87 ± 10.61(4.87)	0.82(0.70-0.91)	<0.001
TFL	47.50 ± 29.32(12.03)	0.84(0.74-0.92)	<0.001
VL	51.15 ± 28.21(7.39)	0.93(0.87-0.97)	<0.001

Table 15: Reliability of EMG activity in Anterior Pelvic Rotation

Posterior Pelvic Rotation			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.10 ± 1.37(0.94)	0.63(0.46-0.80)	<0.001
BF	33.66 ± 37.26(13.75)	0.86(0.77-0.93)	<0.001
Gmax	13.58 ± 13.49(3.37)	0.93(0.88-0.97)	<0.001
Gmed	31.01 ± 24.37(10.69)	0.88(0.79-0.94)	<0.001
RF	21.82 ± 16.22(8.16)	0.82(0.71-0.91)	<0.001
ST	28.41 ± 21.47(14.37)	0.69(0.53-0.83)	<0.001
TFL	41.30 ± 30.19(14.68)	0.79(0.66-0.89)	<0.001
VL	66.16 ± 30.07(12.54)	0.86(0.76-0.93)	<0.001

Table 16: Reliability of EMG activity in Posterior Pelvic Rotation

Left Trunk Shift			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.01 ± 1.49(1.42)	0.51(0.32-0.71)	<0.001
BF	17.38 ± 16.93(8.58)	0.76(0.62-0.88)	<0.001
Gmax	11.74 ± 9.20(2.86)	0.91(0.83-0.95)	<0.001
Gmed	32.95 ± 23.73(4.75)	0.96(0.93-0.98)	<0.001
RF	38.81 ± 31.72(14.42)	0.83(0.72-0.92)	<0.001
ST	16.35 ± 14.26(12.46)	0.53(0.34-0.73)	<0.001
TFL	67.12 ± 39.60(19.63)	0.80(0.67-0.90)	<0.001
VL	43.82 ± 20.23(13.64)	0.66(0.49-0.81)	<0.001

Table 17: Reliability of EMG activity in Left Trunk Shift

Right Trunk Shift			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.67 ± 4.41(2.09)	0.90(0.82-0.95)	<0.001
BF	16.68 ± 17.60(10.13)	0.73(0.57-0.85)	<0.001
Gmax	8.87 ± 7.35(2.35)	0.94(0.90-0.97)	<0.001
Gmed	21.73 ± 16.52(4.26)	0.94(0.89-0.97)	<0.001
RF	28.04 ± 20.93(7.69)	0.86(0.77-0.93)	<0.001
ST	12.95 ± 9.00(8.07)	0.47(0.28-0.68)	<0.001
TFL	41.70 ± 25.84(13.81)	0.74(0.59-0.87)	<0.001
VL	42.64 ± 20.76(8.82)	0.86(0.77-0.93)	<0.001

Table 18: Reliability of EMG activity in Right Trunk Shift

Lateral Pelvic Drop			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	6.79 ± 4.66(3.21)	0.67(0.49-0.83)	<0.001
BF	34.48 ± 28.88(11.57)	0.84(0.72-0.92)	<0.001
Gmax	8.64 ± 4.91(2.51)	0.82(0.69-0.91)	<0.001
Gmed	12.70 ± 6.87(3.19)	0.83(0.70-0.92)	<0.001
RF	17.85 ± 14.87(6.89)	0.80(0.67-0.90)	<0.001
ST	20.86 ± 15.04(7.94)	0.76(0.60-0.88)	<0.001
TFL	24.08 ± 12.63(6.07)	0.80(0.66-0.90)	<0.001
VL	52.40 ± 37.57(13.24)	0.87(0.77-0.94)	<0.001

Table 19: Reliability of EMG activity in Lateral Pelvic Drop

Lateral Pelvic Raise			
Muscle	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.55 ± 1.13(0.79)	0.61(0.42-0.78)	<0.001
BF	12.45 ± 12.57(6.62)	0.81(0.69-0.90)	<0.001
Gmax	14.61 ± 14.62(3.54)	0.95(0.90-0.97)	<0.001
Gmed	37.12 ± 35.23(4.41)	0.99(0.98-0.99)	<0.001
RF	34.54 ± 27.19(12.82)	0.78(0.65-0.89)	<0.001
ST	10.10 ± 8.22(5.78)	0.63(0.45-0.79)	<0.001
TFL	82.17 ± 48.92(24.29)	0.82(0.70-0.91)	<0.001
VL	41.77 ± 20.64(10.03)	0.79(0.66-0.89)	<0.001

Table 20: Reliability of EMG activity in Lateral Pelvic Raise

4.3.4 Determining the minimum number of trials required

Six Trials

Mean ICC values for each of the 8 muscles (defined in section 4.2) across each of the nine test postures (i.e. 72 variables) using six trials were greater than 0.75, with 16 exceptions. The means, (SD), SEM, and ICC values for these 16 variables are shown in Table 21. The entire table showing this data for all 72 variables is included as Appendix I, page 108.

6 trials				
Position	**Muscle**	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright	AL	4.87 ± 1.80(2.46)	0.29(011-0.52)	<0.001
Upright	ST	17.71 ± 12.68(9.41)	0.64(0.47-0.80)	<0.001
Posterior Trunk Sway	BF	10.76 ± 6.07(6.14)	0.51(0.32-0.71)	<0.001
Posterior Trunk Sway	ST	9.04 ± 7.36(8.13)	0.36(0.18-0.59)	<0.001
Anterior Pelvic Rotation	AL	5.36 ± 2.09(1.44)	0.74(0.60-0.87)	<0.001
Posterior Pelvic Rotation	AL	5.10 ± 1.37(0.94)	0.63(0.46-0.80)	<0.001
Posterior Pelvic Rotation	ST	28.41 ± 21.47(14.37)	0.69(0.53-0.83)	<0.001
Left Trunk Shift	AL	5.01 ± 1.49(1.42)	0.51(0.32-0.71)	<0.001
Left Trunk Shift	ST	16.35 ± 14.26(12.46)	0.53(0.34-0.73)	<0.001
Left Trunk Shift	VL	43.82 ± 20.23(13.64)	0.66(0.49-0.81)	<0.001
Right Trunk Shift	BF	16.68 ± 17.60(10.13)	0.73(0.57-0.85)	<0.001
Right Trunk Shift	ST	12.95 ± 9.00(8.07)	0.47(0.28-0.68)	<0.001
Right Trunk Shift	TFL	41.70 ± 25.84(13.81)	0.74(0.59-0.87)	<0.001
Lateral Pelvic Drop	AL	6.79 ± 4.66(3.21)	0.67(0.49-0.83)	<0.001
Lateral Pelvic Raise	AL	4.55 ± 1.13(0.79)	0.61(0.42-0.78)	<0.001
Lateral Pelvic Raise	ST	10.10 ± 8.22(5.78)	0.63(0.45-0.79)	<0.001

Table 21: Reliability of EMG across six trials: Muscles in postures with $ICC_{(2,1)} < 0.75$

Five Trials

Using the first 5 trials, the mean ICC values for each of the 8 muscles across each of the nine test postures over five trials ranged from 0.75 to 0.99 with 16 exceptions. These data are presented in Table 22 and the reliability data for all variables is presented in Appendix I, page 108.

5 trials				
Position	**Muscle**	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright	AL	4.88 ± 1.99(2.57)	0.23(0.03-0.48)	0.009
Upright	ST	18.35 ± 13.34(9.46)	0.63(0.44-0.80)	<0.001
Posterior Trunk Sway	BF	10.47 ± 5.81(5.18)	0.51(0.30-0.72)	<0.001
Posterior Trunk Sway	ST	9.01 ± 7.61(8.68)	0.34(0.13-0.59)	<0.001
Posterior Pelvic Rotation	AL	5.09 ± 1.40(1.01)	0.60(0.40-0.78)	<0.001
Posterior Pelvic Rotation	ST	28.83 ± 22.53(14.62)	0.64(0.45-0.81)	<0.001
Left Trunk Shift	AL	5.08 ± 1.63(1.46)	0.49(0.28-0.71)	<0.001
Left Trunk Shift	ST	16.27 ± 14.44(12.51)	0.68(0.49-0.83)	<0.001
Left Trunk Shift	VL	43.70 ± 19.26(13.21)	0.65(0.46-0.81)	<0.001
Right Trunk Shift	BF	16.96 ± 17.30(10.26)	0.71(0.54-0.85)	<0.001
Right Trunk Shift	ST	13.21 ± 8.98(8.57)	0.49(0.28-0.70)	<0.001
Right Trunk Shift	TFL	42.13 ± 25.78(14.66)	0.67(0.49-0.83)	<0.001
Lateral Pelvic Drop	AL	6.97 ± 4.91(3.28)	0.73(0.56-0.87)	<0.001
Lateral Pelvic Drop	ST	20.73 ± 15.14(8.33)	0.73(0.56-0.87)	<0.001
Lateral Pelvic Raise	AL	4.55 ± 1.10(0.84)	0.54(0.33-0.74)	<0.001
Lateral Pelvic Raise	ST	10.18 ± 8.31(6.06)	0.60(0.40-0.78)	<0.001

Table 22: Reliability of EMG across five trials: Muscles in postures with $ICC_{(2,1)} < 0.75$

Four Trials

When considering the first four trials, the mean ICC ranged from 0.75 to 0.99, with 15 exceptions Table 23. The complete data for all variables using four trials is included in Appendix I, page 108.

4 trials				
Position	**Muscle**	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright	AL	4.89 ± 1.99(2.70)	0.27(0.02-0.56)	0.018
Upright	ST	18.90 ± 13.80(9.84)	0.67(0.45-0.83)	<0.001
Posterior Trunk Sway	BF	10.76 ± 6.27(5.54)	0.53(0.28-0.75)	<0.001
Posterior Trunk Sway	ST	9.15 ± 8.33(9.54)	0.33(0.07-0.60)	0.006
Posterior Pelvic Rotation	AL	5.11 ± 1.45(1.09)	0.56(0.31-0.77)	<0.001
Posterior Pelvic Rotation	ST	28.89 ± 23.12(16.26)	0.74(0.56-0.87)	<0.001
Posterior Pelvic Rotation	TFL	42.55 ± 30.23(15.75)	0.74(0.55-0.87)	<0.001
Left Trunk Shift	AL	5.12 ± 1.63(1.47)	0.51(0.26-0.74)	<0.001
Left Trunk Shift	ST	15.55 ± 14.70(9.61)	0.68(0.46-0.84)	<0.001
Left Trunk Shift	VL	43.71 ± 18.57(12.85)	0.62(0.39-0.80)	<0.001
Right Trunk Shift	BF	17.23 ± 17.69(10.79)	0.68(0.46-0.84)	<0.001
Right Trunk Shift	ST	13.67 ± 9.85(8.96)	0.61(0.38-0.80)	<0.001
Right Trunk Shift	TFL	42.21 ± 24.49(16.08)	0.64(0.41-0.81)	<0.001
Lateral Pelvic Drop	ST	21.02 ± 14.87(8.61)	0.71(0.50-0.86)	<0.001
Lateral Pelvic Raise	ST	9.78 ± 7.58(5.69)	0.74(0.55-0.87)	<0.001

Table 23: Reliability of EMG across four trials: Muscles in postures with less $ICC_{(2,1)} < 0.75$

Three Trials

For the first 3 trials, mean ICC was ≥ 0.75 for all variables with 13 exceptions. This data is presented in Table 24 and Appendix I, page 108.

3 trials				
Position	**Muscle**	**Mean(mV)) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright	AL	4.82±2.11 (2.51)	0.28(0.02-0.56)	<0.001
Upright	ST	19.22±14.87 (9.74)	0.67(0.45-0.83)	<0.001
Posterior Trunk Sway	BF	10.71±6.50 (5.36)	0.54(0.29-0.75)	<0.001
Posterior Trunk Sway	ST	9.04±9.58 (10.54)	0.33(0.07-0.60)	<0.001
Posterior Pelvic Rotation	AL	5.10±1.51 (1.19)	0.56(0.32-0.77)	<0.001
Posterior Pelvic Rotation	TFL	43.69±31.15 (17.49)	0.74(0.55-0.87)	<0.001
Left Trunk Shift	AL	5.19±1.85 (1.57)	0.52(0.26-0.74)	<0.001
Left Trunk Shift	ST	16.00±15.45 (9.92)	0.68(0.47-0.84)	<0.001
Left Trunk Shift	VL	44.28±18.11 (12.93)	0.63(0.40-0.81)	<0.001
Right Trunk Shift	BF	17.67±18.84 (12.08)	0.68(0.47-0.84)	<0.001
Right Trunk Shift	ST	13.23±9.92 (7.19)	0.62(0.39-0.80)	<0.001
Right Trunk Shift	TFL	41.55±23.78 (16.36)	0.64(0.42-0.82)	<0.001
Lateral Pelvic Drop	ST	21.27±15.09 (8.97)	0.72(0.51-0.86)	<0.001

Table 24: Reliability of EMG across three trials: Muscles in postures with $ICC_{(2,1)} < 0.75$

Two Trials

Finally, the mean ICC for the first two trials showed ICC ≥ 0.75 in 58 of the 72 variables. This data is shown in Table 25 and Appendix I, page 108.

2 Trials				
Position	**Muscle**	**Mean(mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
Upright	AL	5.02±2.93 (4.14)	0.38(-0.04-0.68)	0.039
Upright	ST	19.69±15.98 (22.60)	0.69(0.39-0.86)	0.000
Upright	VL	41.80±21.17 (29.93)	0.74(0.48-0.88)	<0.001
Posterior Trunk Sway	BF	11.03±7.27 (10.29)	0.60(0.25-0.81)	0.001
Posterior Trunk Sway	ST	9.73±12.20 (17.25)	0.30(-0.13-0.63)	0.087
Anterior Pelvic Rotation	AL	4.90±1.47 (2.08)	0.73(0.46-0.88)	<0.001
Anterior Pelvic Rotation	RF	27.60±26.59 (37.60)	0.72(0.44-0.87)	<0.001
Posterior Pelvic Rotation	AL	5.25±1.73 (2.45)	0.53(0.14-0.77)	0.006
Left Trunk Shift	AL	5.27±2.13 (3.02)	0.39(-0.02-0.69)	0.032
Left Trunk Shift	VL	44.22±19.28 (27.26)	0.72(0.43-0.87)	<0.001
Right Trunk Shift	BF	18.12±20.10 (28.42)	0.63(0.30-0.83)	0.001
Right Trunk Shift	ST	13.55±9.81 (13.88)	0.65(0.31-0.84)	0.001
Right Trunk Shift	TFL	42.42±23.96 (33.88)	0.57(0.20-0.79)	0.003
Lateral Pelvic Drop	ST	20.49±15.86 (22.44)	0.70(0.39-0.87)	0.000

Table 25: Reliability of EMG across two trials: Muscles in postures with $ICC_{(2,1)} < 0.75$

4.4 Discussion

4.4.1 EMG reliability

It is widely accepted that measurement of EMG has the potential to be highly variable. Factors such as subcutaneous fat thickness and slight variation in task execution (McGill, 1991), electrode application and placement (Jensen et al., 1993), muscle fatigue (Hansson et al., 1992), contraction velocity and muscle length (McGill and Norman, 1986), and cross talk from nearby muscles (Koh and Grabiner, 1993) may affect the quality of the signal.

While standardised testing protocols are followed to minimize influence of these factors, the variation in task execution needs to be considered in studies involving novel testing procedures. The likely influence of variability in task execution during the single leg standing positions in this study could be considered quite low given the kinematic reliability results. This is further supported by the large correlations shown in the EMG reliability results.

In general, there was good reliability of EMG muscle activation across multiple trials of most muscles in all of the test positions, supporting the notion that the EMG activation in the different test postures can be reliably measured. Consideration of the lower ICC values (as well as the associated SEM's and means) for AL and ST in the reference posture of Upright Standing is required.

There were two muscles in particular that displayed lower reliability than the others: AL and ST. AL displayed its lowest $ICC_{(2,1)}$ (mean 0.29) during Upright Standing and mean ICC scores range of 0.51-0.74 during all pelvic positions, and left trunk shift. These results contrast with the reliability of EMG recording of AL during Anterior Trunk Sway, Posterior Trunk Sway and Right Trunk Shift, (0.97, 0.94 and 0.90 respectively). We postulate that the lower reliability values seen in Upright Standing are likely attributable to variable motor strategies employed by individuals in this position (in comparison to more stable strategies in the others) in contrast to a technical error such as cross talk or skin resistance which would be present in all positions for this muscle. We speculate that this variability may be an interesting avenue for future research given the relatively high injury rate associated with the AL muscle.

The ST muscle also displayed less reliability with mean ICC's of 0.36-0.69 during the positions of Upright Standing, Lateral Pelvic Raise, Posterior Pelvic Rotation, Left and Right Trunk Shift, and Posterior Trunk Sway. There were higher mean ICC's observed in Anterior Trunk Sway, Anterior Pelvic Rotation and Lateral Pelvic Drop (0.88, 0.82, and 0.76 respectively). As is the case with AL, the positions with lower ICC's suggest the existence of large variability in the muscle activation patterns used in our study sample. Again, these results suggest future research into ST may be of interest.

The data obtained here from measuring EMG reliability should assist future research in conducting power analyses a priori for each number of examinations, as well as informing clinical practice by describing the variance associated with the testing.

4.4.2 Minimum number of trials required

Considering the reliability results of the EMG data across different numbers of trials, it can be suggested that, in general, only two trials are required. As was the case for the kinematic analyses, researchers need to examine the intra-rater reliability data along with the error estimates specifically for the muscle and position of interest, in planning power analyses for future investigations (particularly for the AL and ST muscles).

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Chapter 5 - Main Study Results

The influence of changes in trunk and pelvic position during single leg standing posture on hip and thigh muscle activation in a pain free population.

Paper Submitted to BMC Musculoskeletal Disorders (Appendix J, page113).

5.1 Introduction

This main study investigated hip and thigh muscle activation patterns across common trunk and pelvis positions in right single leg stance in 22 asymptomatic, male subjects. Lower limb injuries are common and often relate to single leg loading. Patterns of single leg loading are a focus of clinical practice. However, the influence that trunk and pelvis posture has on lower limb muscle activation in single leg stance is largely unknown. Surface EMG was collected from eight hip and thigh muscles and 3-dimensional kinematic data was collected to monitor test postures.

5.2 Results

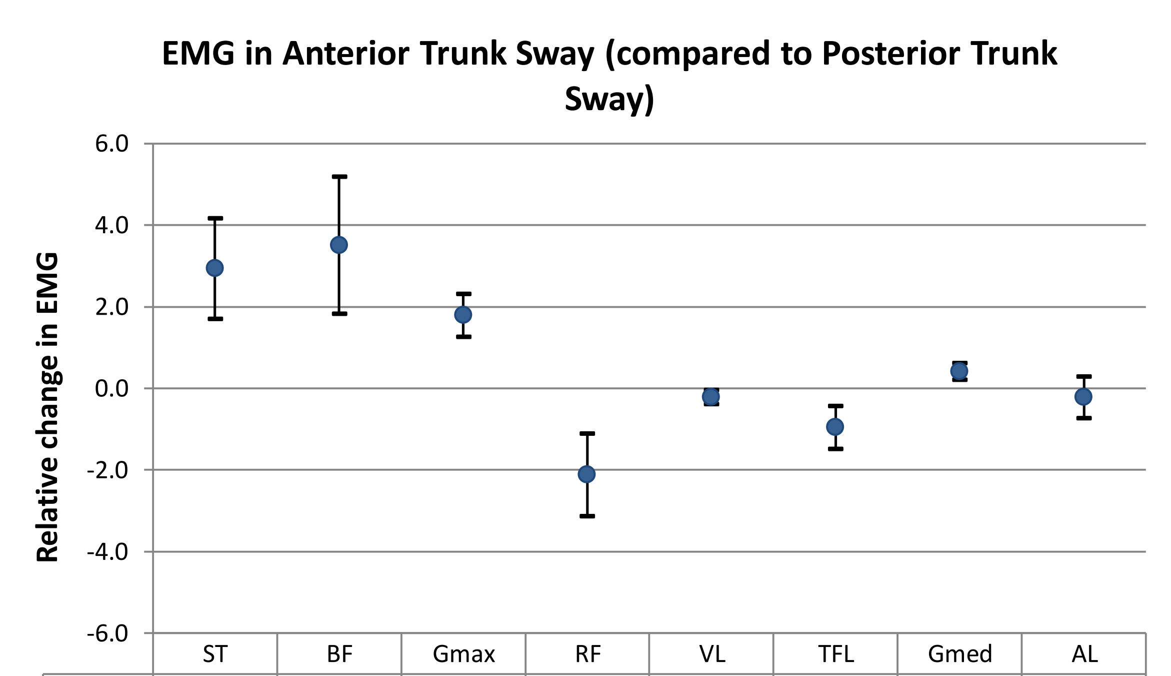
5.2.1 Subjects

Twenty-two subjects completed the data collection. Of these, two subjects were unable to adopt or maintain a stable Pelvic Drop position. Therefore, their data were not included in the analyses of the Lateral Pelvic Drop vs. Lateral Pelvic Raise positions, meaning this analysis included 20 subjects. For all other test positions, stable EMG data was collected for all 22 subjects.

5.2.2 Mean differences in muscle activation between paired test postures

5.2.2.1 Anterior Trunk Sway vs. Posterior Trunk Sway

When comparing muscle activation in the sagittal plane movements of Anterior Trunk Sway with Posterior Trunk Sway, the posterior sagittal plane muscles all showed increased activation, while the anterior sagittal plane muscles showed decreased activation levels in Anterior Trunk Sway. AL showed no change (Figure 4).

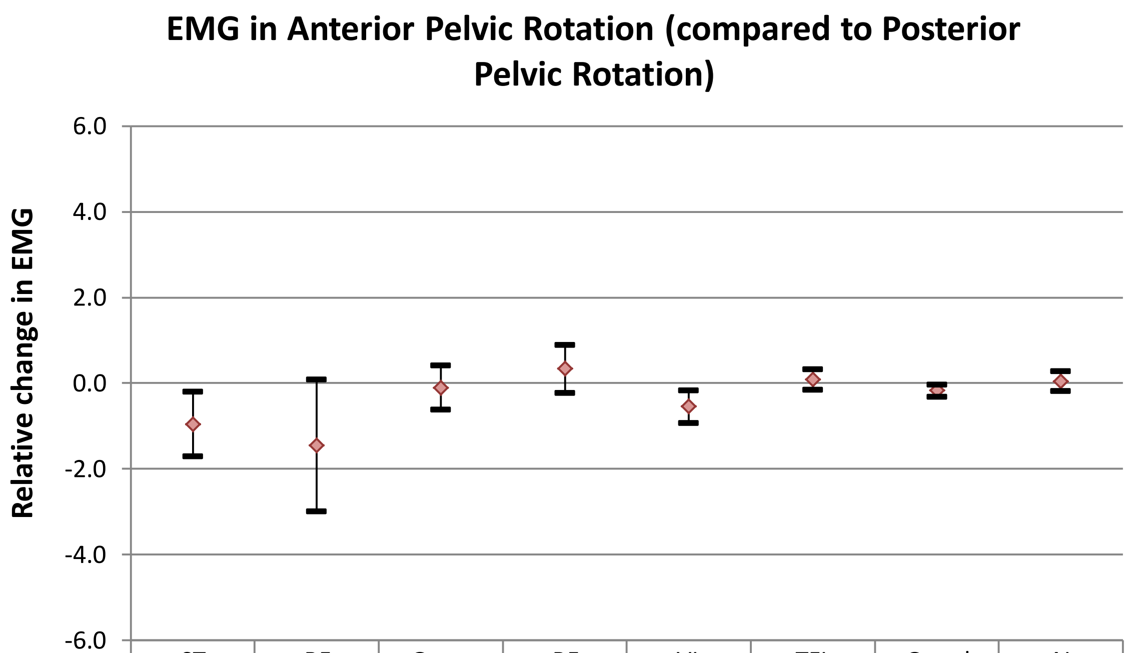


	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
95 upper	4.16110	5.18095	2.31385	-1.10937	-.04543	-.43381	.61527	.28669
95 lower	1.70072	1.81905	1.26160	-3.13791	-.39366	-1.49437	.20018	-.73760
Mean	2.93091	3.50000	1.78773	-2.12364	-.21955	-.96409	.40773	-.22545

Figure 4: Mean muscle activation levels in Anterior Trunk Sway compared to Posterior Trunk Sway. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, semitendinosus activation is approximately 2.9 times higher in Anterior Trunk Sway compared to Posterior Trunk Sway, whereas rectus femoris is activated at 1/2.1 (approximately 47%) Posterior Sway compared to Anterior Sway. The 95% CI are represented by the values seen in the Lower and Upper bounds.

5.2.2.2 Anterior Pelvic Rotation vs. Posterior Pelvic Rotation

When comparing muscle activation in the sagittal plane movements of Anterior Pelvic Rotation with Posterior Pelvic Rotation, the muscles of ST, Gmed and VL all showed lower muscle activation in Anterior Pelvic Rotation. All other muscles displayed no change (Figure 5).

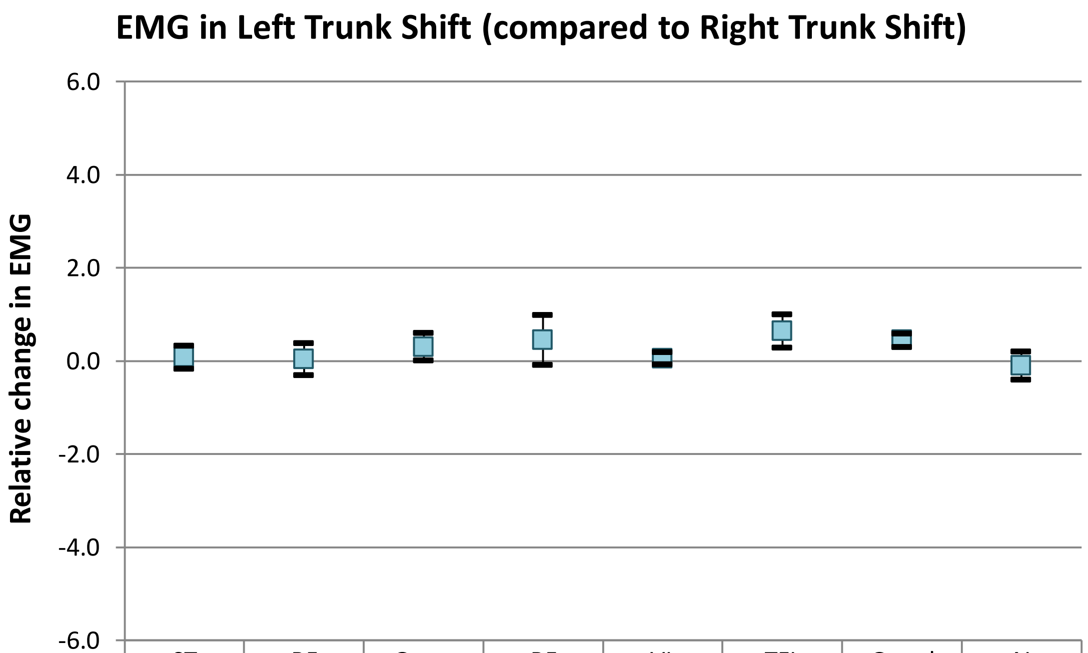


	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
95 upper	-.95955	-1.45500	-.10909	.32864	-.54773	.07591	-.17864	.04182
95 lower	-1.70976	-2.99103	-.62506	-.23124	-.92853	-.16410	-.31846	-.19207
Mean	-.20933	.08103	.40688	.88851	-.16692	.31592	-.03881	.27571
P value	.015	.062	.665	.236	.007	.518	.015	.714

Figure 5: Mean muscle activation levels in Anterior Pelvic Rotation compared to Posterior Pelvic Rotation. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, vastus lateralis and gluteus medius activation is lower in Anterior Pelvic Rotation compared to Posterior Pelvic Rotation. The 95% CI are represented by the values seen in the Lower and Upper bounds.

5.2.2.3 Left Trunk Shift vs. Right Trunk Shift

When comparing muscle activation in the frontal plane movements of Left Trunk Shift with Right Trunk Shift, the lateral hip abductors (Gmax, Gmed and TFL), showed increased activation in Left Trunk Shift. There was no difference found in the other muscles (Figure 6).

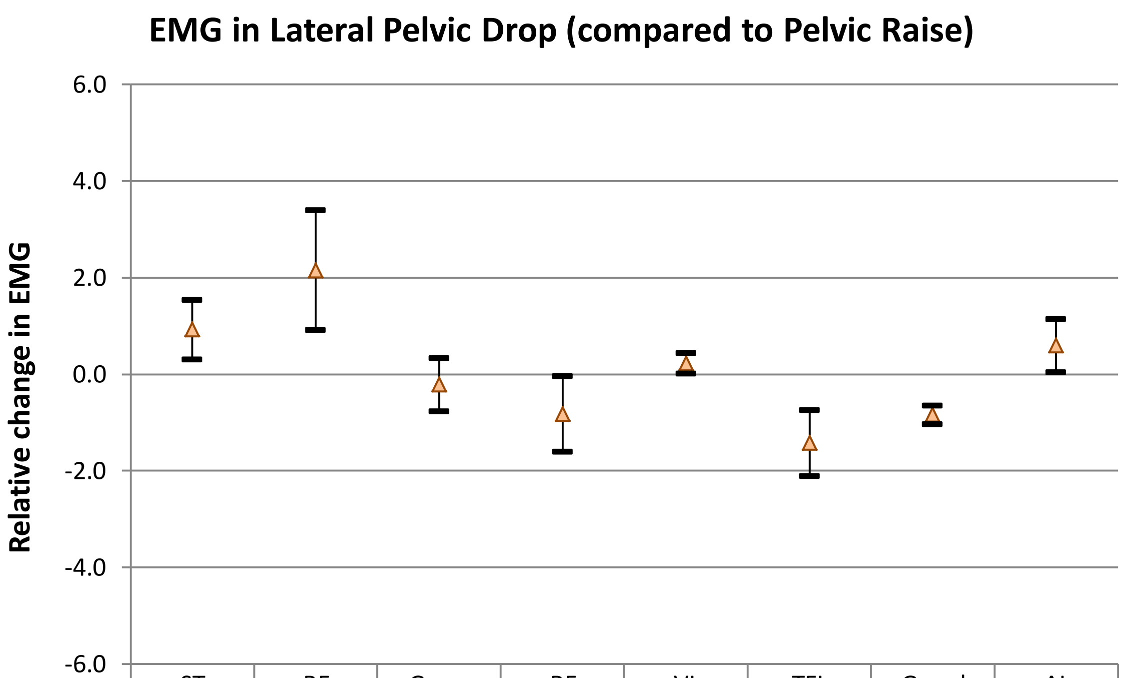


	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
95 upper	.08136	.03636	.30500	.45409	.05864	.64045	.44591	-.10000
95 lower	-.17030	-.30744	.01114	-.08477	-.06909	.28119	.29695	-.39889
Mean	.33303	.38017	.59886	.99296	.18637	.99972	.59487	.19889
P value	.509	.828	.043	.094	.351	.001	<.001	.494

Figure 6: Mean muscle activation levels in Left Trunk Shift compared to Right Trunk Shift. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, gluteus maximus and tensor fascia lata activation is higher in Left Trunk Shift compared to Right Trunk Shift. The 95% CI are represented by the values seen in the Lower and Upper bounds.

5.2.2.4 Lateral Pelvic Drop vs. Lateral Pelvic raise

When comparing muscle activation in the frontal plane movements of Lateral Pelvic Drop with Lateral Pelvic Raise, the lateral hip abductors (Gmed and TFL) showed decreased activation, as did rectus femoris in Lateral Pelvic Drop. The hamstring group (ST and BF) increased their activation along with AL and VL in Lateral Pelvic Drop. Gmax displayed no change (Figure 7).



	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
95 upper	.92000	2.14800	-.21950	-.82400	.22400	-1.42900	-.84200	.58750
95 lower	.30074	.90805	-.77034	-1.60468	.01553	-2.11663	-1.03297	.04170
Mean	1.53926	3.38795	.33134	-.04332	.43247	-.74137	-.65103	1.13330

Figure 7: Mean muscle activation levels in Lateral Pelvic Drop compared to Lateral Pelvic Raise. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, semitendinosis and adductor longus activation is higher in Lateral Pelvic Drop compared to Lateral Pelvic Raise. The 95% CI are represented by the values seen in the Lower and Upper bounds.

5.2.3 Individual subject changes in muscle activation

The results above demonstrate the group mean change (plus standard deviation and confidence intervals), in muscle activation for each muscle between two paired test positions. However, it is also important to consider the change in muscle activation of individual subjects, as the group mean change may not necessarily represent that the direction and magnitude of change in muscle activation was consistent across all subjects. Individual subject changes in muscle activation for some muscles in some paired test positions of interest are provided below.

With regards to the graphs below (Figures 8-15), a definition and explanation is needed for the y-axis in terms of the use for Log_e. The choice of a base for log transformation is always arbitrary, and typically either base 10, or *e*. The decision to use a log transformation of base *e* in this case was arbitrary, and relates to ease of performance of further calculus-related analysis which are not presented here. The scale of the Y-axis represents the activation level that was calculated relative to the activation level for upright standing for the same muscle. Accordingly 1 indicates equality (of activation with the upright standing condition) 2 equals double the activation whereas 0.5 would equal half the activation.

5.2.3.1 Gluteus Maximus in Anterior Trunk Sway v Posterior Trunk Sway

In Anterior Trunk Sway, for the group and for every individual, the muscle activation is higher than when positioned in Posterior Trunk Sway (Figure 4). Of interest is that for two subjects, their activity of Gmax in both Anterior and Posterior Trunk Sway is higher (greater than 1), than when in upright standing. Whereas for all other subjects, muscle activation in Anterior Trunk Sway is higher than in Upright Standing and muscle activation in Posterior Trunk Sway is lower than in Upright Standing (Figure 8).

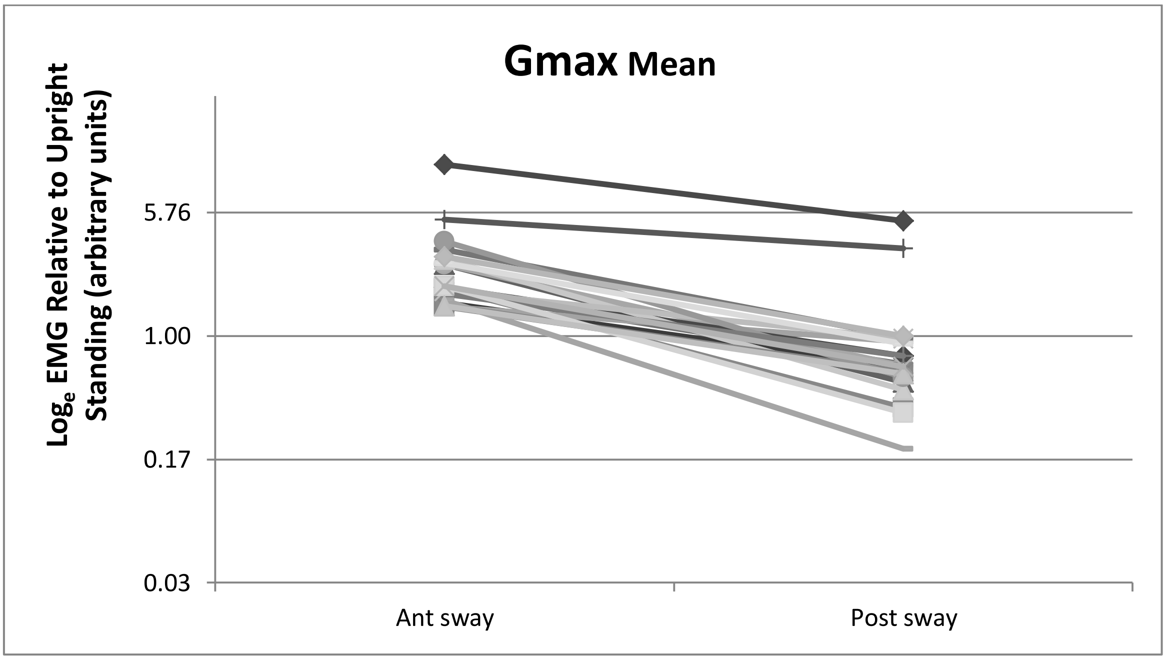


Figure 8: Individual subject changes in gluteus maximus activation: Anterior (Ant sway) vs. Posterior (Post sway) Trunk Sway

5.2.3.2 Tensor Fascia Lata in Anterior Trunk Sway v Posterior Trunk Sway

The group trend for TFL is opposite to that of Gmax, with activity being higher in Posterior Trunk Sway compared with Anterior Trunk Sway (Figure 4). Similar to the findings of Gmax, some subjects showed lower levels of TFL muscle activation in both Anterior and Posterior Trunk Sway compared to Upright Standing. In this instance, for some individuals, the activity for TFL was greatest in Upright Standing than the two variations of sagittal plane trunk position (Figure 9).

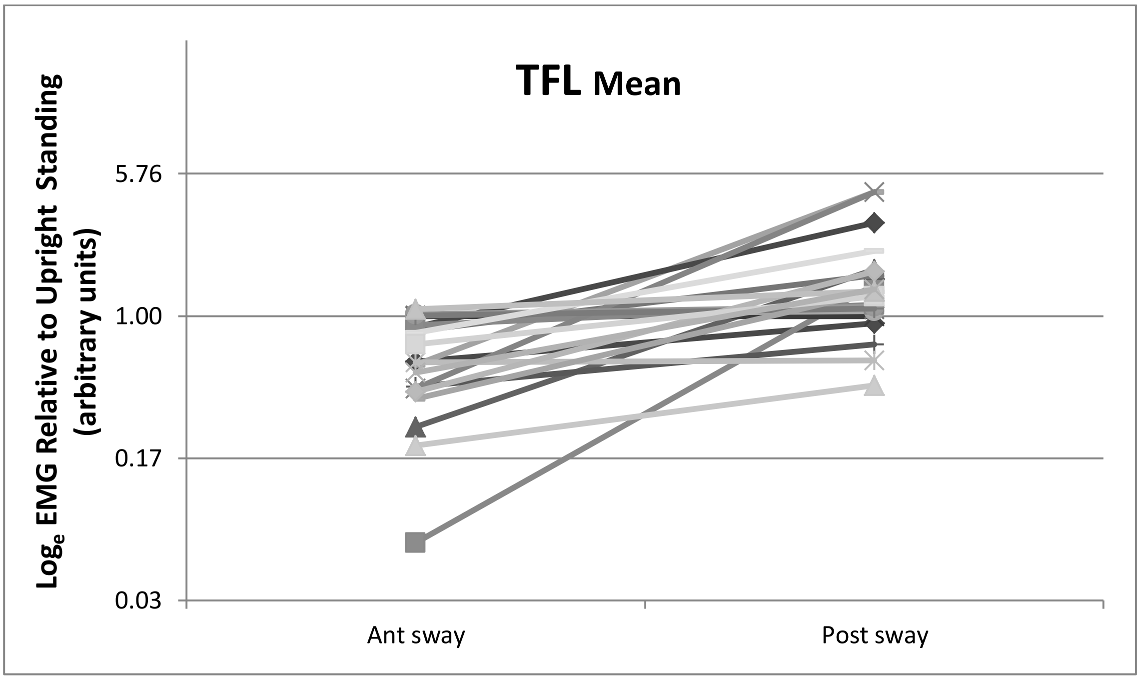


Figure 9: Individual subject changes in tensor fascia lata activation: Anterior (Ant sway) vs. Posterior (Post sway) Trunk Sway

5.2.3.3 Adductor longus in Anterior Trunk Sway v Posterior Trunk Sway

Marked variability of motor strategies are evident in the graph of individual subjects for the AL muscle (Figure 10). Interestingly good kinematic and EMG reliability was seen in the previous respective chapters although the group trend showed no statistical change in muscle activity.

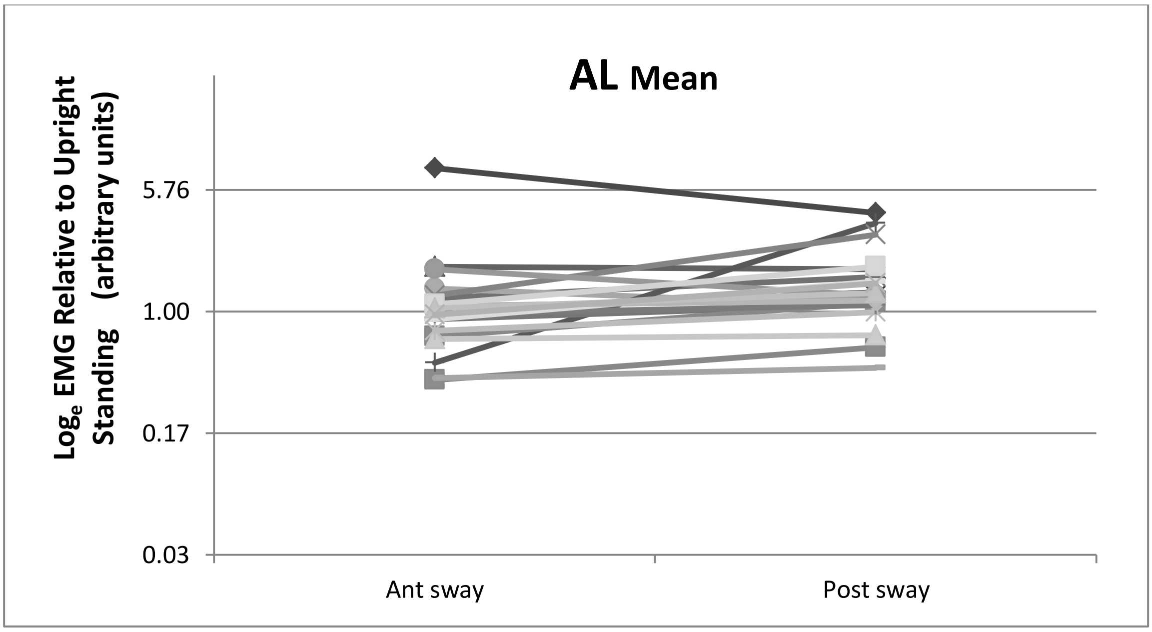


Figure 10: Individual subject changes in adductor longus activation: Anterior (Ant sway) vs. Posterior (Post sway) Trunk Sway

5.2.3.4 Adductor Longus in Lateral Pelvic Drop v Lateral Pelvic Raise

The group trend during Lateral Pelvic Drop was a slight increase in activation (*Error! Reference source not found.*). The interesting finding here is from visual inspection, five individuals are using very different activation strategies to the rest of the group (Figure 11). Specifically, two individuals showed very little activity during Lateral Pelvic Drop, and three individuals showed a large increase in activity during Lateral Pelvic Drop.

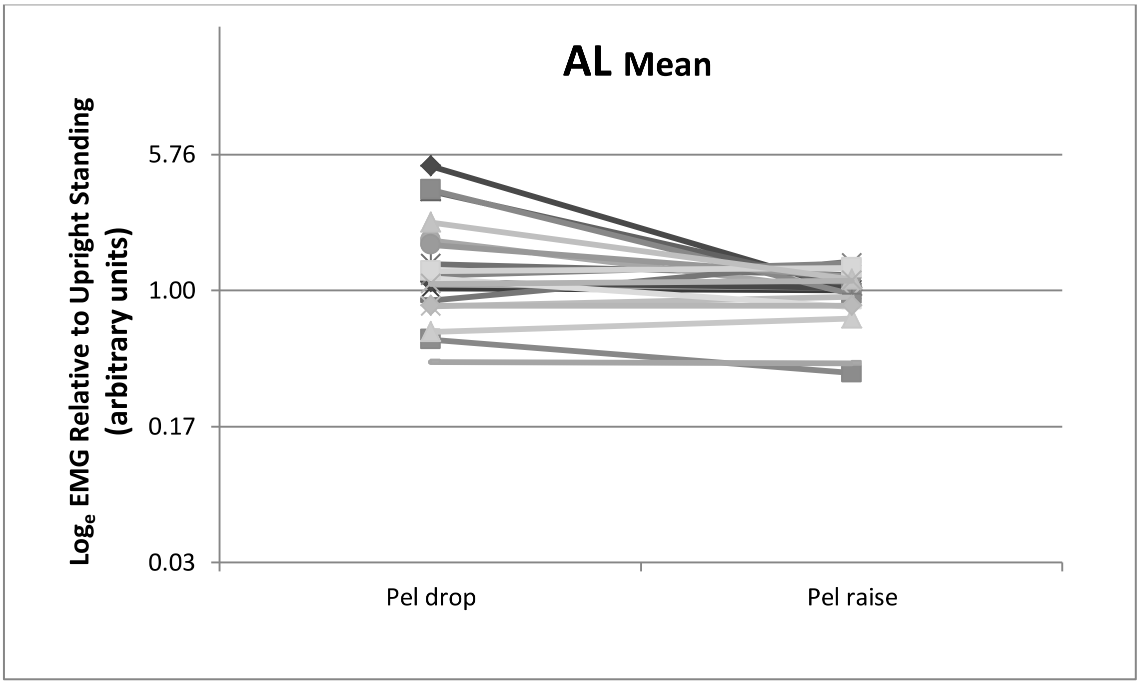


Figure 11: Individual subject changes in adductor longus activation: Lateral Pelvic Drop (Pel drop) vs. Raise (Pel raise)

5.2.3.5 Gluteus Medius in Anterior Pelvic Rotation v Posterior Pelvic Rotation

The group EMG activity of Gmed during sagittal plane hip movements showed a very small decrease in activation during Anterior Pelvic Rotation. If we consider Gmed to be a frontal plane mover or stabiliser, the observed relatively small changes in activity levels during Anterior and Posterior Pelvic Rotation are consistent given these sagittal plane movements (Figure 12).

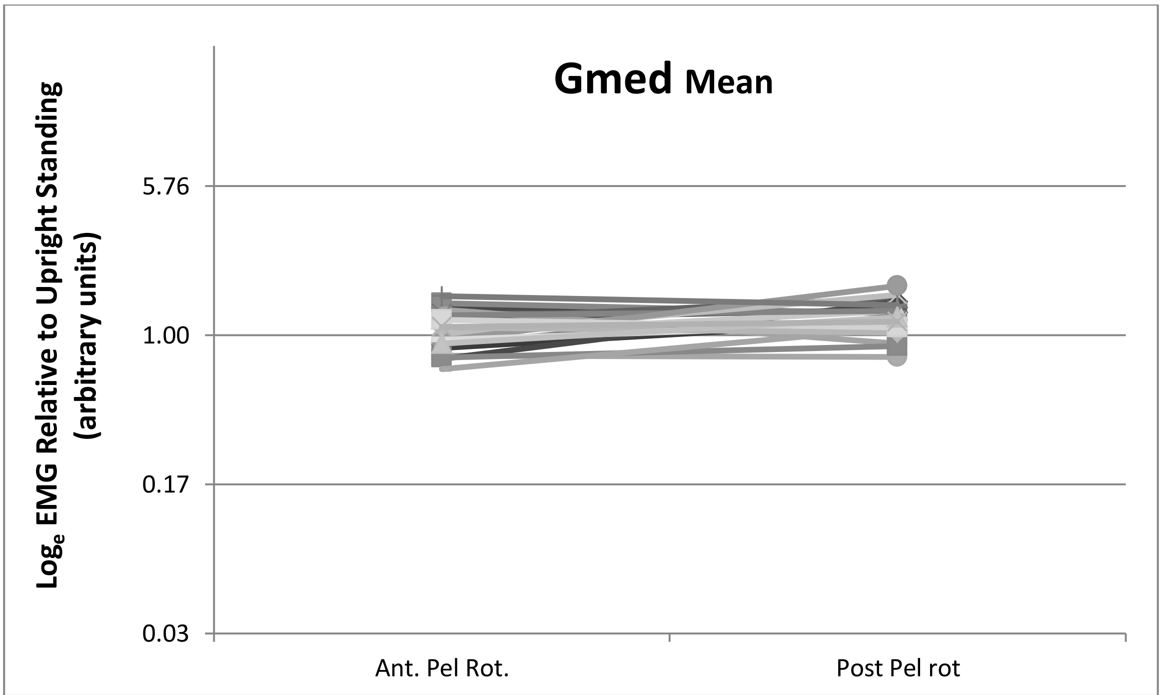


Figure 12: Individual subject changes in gluteus medius activation: Anterior (Ant. Pel Rot) vs. Posterior (Post Pel rot) Pelvic Rotation

5.2.3.6 Semitendinosus and biceps femoris in Anterior Trunk Sway v Posterior Trunk Sway

During Anterior Trunk Sway, EMG activity increased in both hamstring muscles recorded, for all subjects compared to the activity in Posterior Trunk Sway. The interesting observation is that while the trend is common for most subjects (Figure 14), two subjects displayed the complete opposite strategy using BF and one subject displayed the complete opposite strategy using ST compared to the entire group.

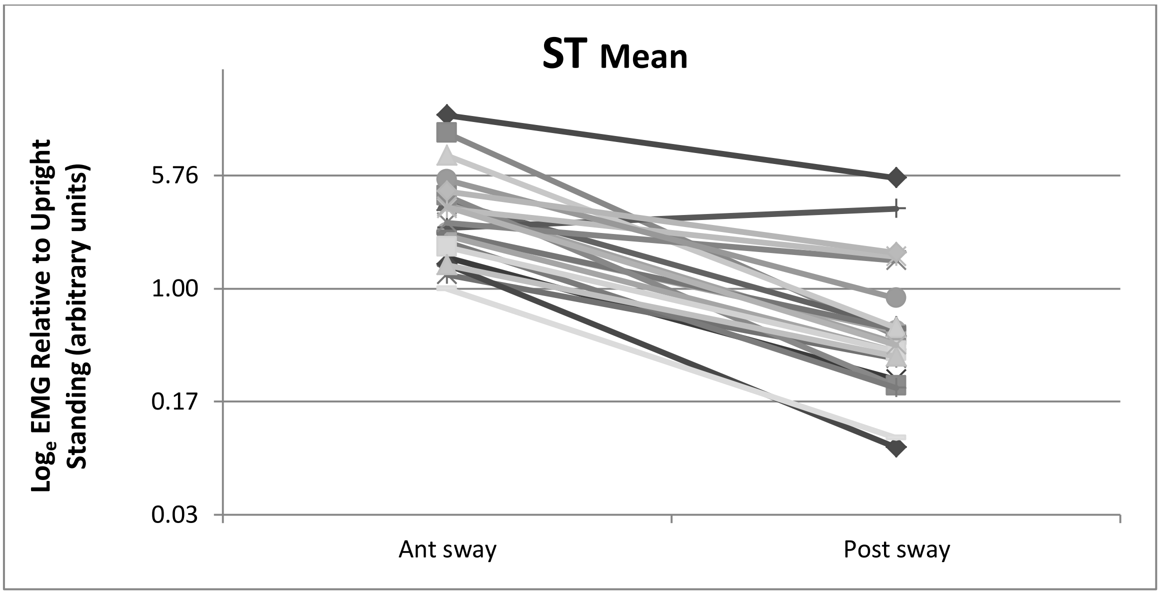


Figure 13: Individual subject changes in medial hamstring activation: Anterior (Ant sway) vs. Posterior (Post sway) Trunk Sway

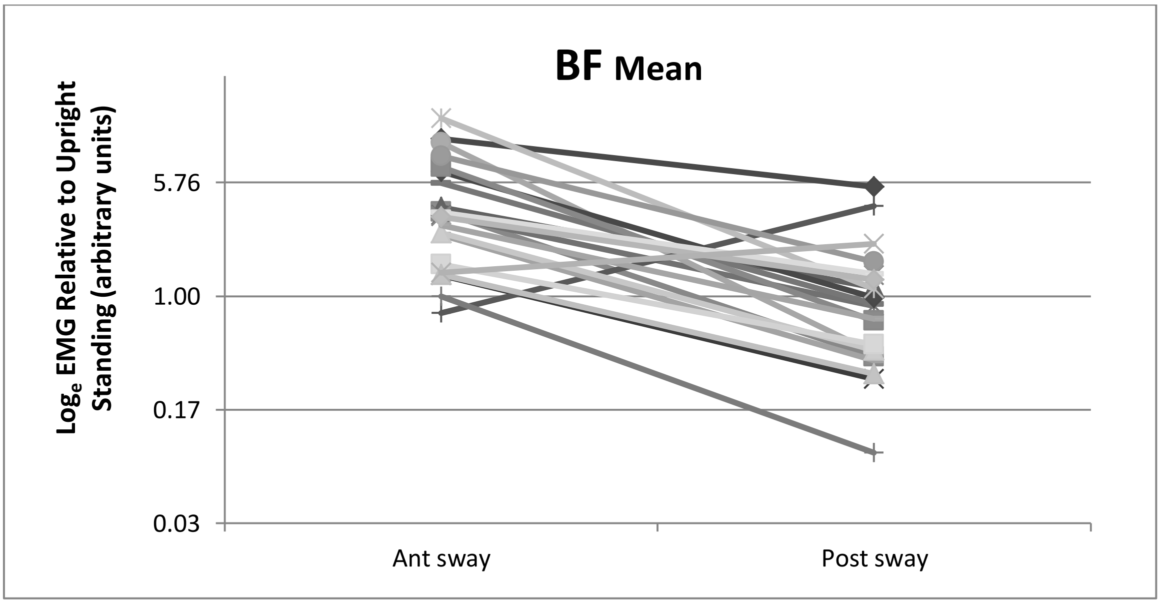


Figure 14: Individual subject changes in lateral hamstring activation: Anterior (Ant sway) vs. Posterior (Post sway) Trunk Sway

5.2.3.7 Gluteus Medius in Lateral Pelvic Drop v Lateral Pelvic Raise

Movement from Lateral Pelvic Drop to Lateral Pelvic Raise increased the activity of Gmed. Of interest here is the large variation of activation observed during the Lateral Pelvic Drop position whilst there was convergence of the activation level in adopting Lateral Pelvic Raise (Figure 15)

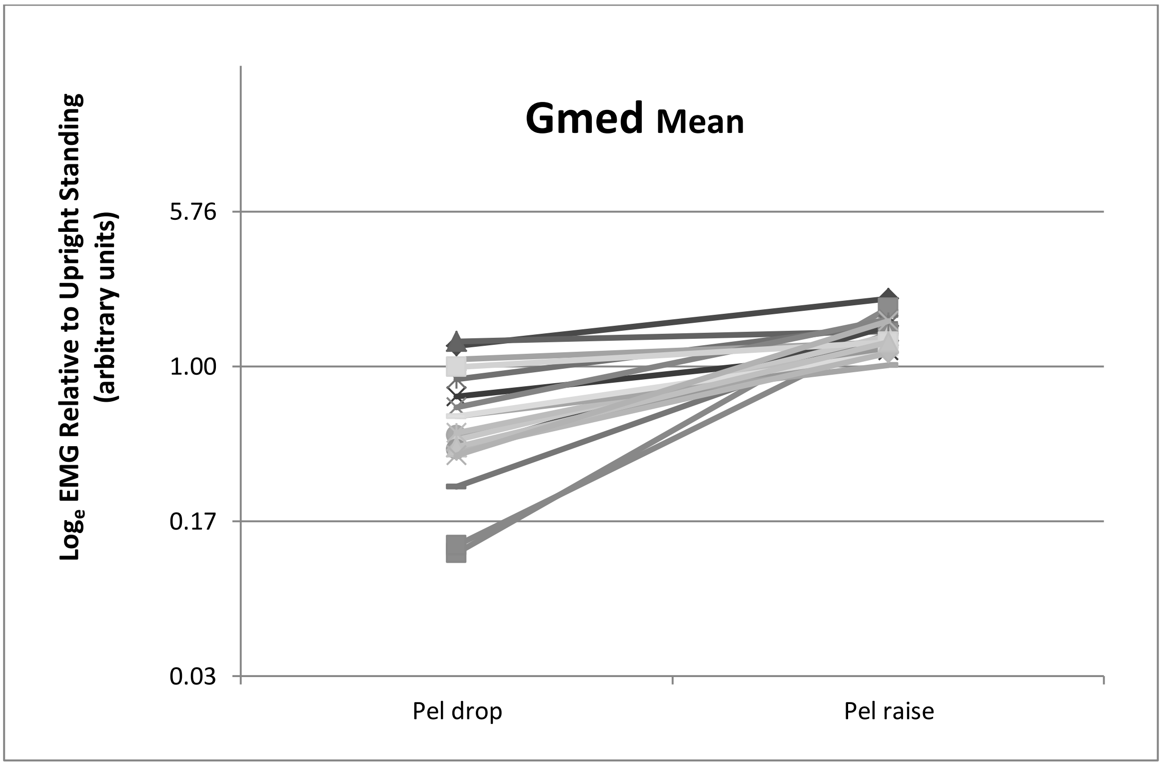


Figure 15: Individual subject changes in gluteus medius activation: Lateral Pelvic Drop (Pel drop) vs. Raise (Pel raise)

Chapter 6 - Discussion

6.1 Introduction

This study investigated the influences of changes in trunk and pelvis position in single leg standing on activation patterns of muscles around the hip and thigh. The preliminary evaluation of the reliability of both subject positioning and EMG muscle activity recordings, support that the hypothesised findings of changes in muscle activation in different test positions were for reasons other than measurement error. In addition, the interpretation of EMG muscle activity levels relative to a reference clinically relevant sub-MVIC value was considered. The results of this study demonstrate that changes in trunk and pelvis position clearly influence the levels of activation of different muscles of the hip and thigh, and that these interactions are complex in nature. Our a-priori hypotheses that changes in both trunk and pelvic posture during single leg stance would result in predictable changes in lower limb muscle activation are largely supported by the results. The results of this study and their implications are discussed below.

6.2 Kinematics and validation of the positioning

Our research was designed to have direct clinical application and therefore the test positions were selected on the basis that they represented common clinically observed variations in body posture. For example the Lateral Pelvic Drop was chosen as it represents the Trendelenburg position, a commonly reported habitual pelvic posture in individuals with hip pain (Bird et al., 2001). While this habitual posture has been investigated and defined in clinical populations, the influence of this posture on hip and thigh muscle activation patterns remains somewhat unclear (Hardcastle and Nade, 1985, Youdas et al., 2010). Paired test positions were defined to provide a comparison to the common clinical positions selected. For example, the opposite of the Trendelenburg position, Lateral Pelvic Raise, was compared to the Lateral Pelvic Drop in order to further inform the effect of changes in frontal plan pelvic position on muscle activation patterns.

Left and Right Trunk Shift were positions of clinical interest as these have been observed positions relating to ACL injury (Hewett et al., 2009). Anterior and Posterior Pelvic Rotation represent variations in natural body posture that have not been investigated previously during single leg stance. Anterior and Posterior Trunk Sway are common body postures (Smith et al., 2008), that have been investigated previously though only during double leg standing and sitting (O'Sullivan et al., 2002, Wang et al., 2006).

In terms of kinematic reliability, subjects could be reliably positioned in each of the test positions as defined by the relevant Vicon angle for each test position. Together with the large differences in defining angle between each of the paired test positions, these results showed that these test positions are clearly different from each other, supporting that observed changes in muscle activation could be attributed to changes in body position. This has direct clinical utility, where common clinically observed positions can be accurately visually assessed and interpretations regarding the influence body position has on certain muscles can be applied. Although some of the ICC's are not considered good correlations, the standard deviations and SEM's for these measures are still very low. These measures indicate a low level of positioning error and support the notion of clinical utility of these test positions. Reliable subject positioning has relevance for the measurement of EMG muscle activity, as variation in joint position is linked with alterations in EMG activation patterns (De Luca, 1997).

The kinematic results also demonstrated that for some of the paired test postures, angles other than the defining angle changed when subjects moved from one test posture to the other. For example, sagittal plane pelvis and hip angles changed, along with thorax angle when moving from Anterior Trunk Sway to Posterior Trunk Sway. These changes were expected, as in order to change position of the thorax in single leg standing and still maintain balance, movement at the pelvis and hip is also necessary. These results are consistent with studies into functional movement tasks, where changes in body position require adaptations at multiple body segments to maintain balance (Kuo et al., 2010, Janssen et al., 2002). This concept highlights the need to consider the influence of movement at proximal and distal body segments during functional tasks rather than considering just a single joint (Janssen et al., 2002). While some angles other than the defining angle changed in a consistent manner to adapt to changing balance demands in some of the test positions, in all instances stable joint angles were observed apart from those central to maintaining balance in single leg standing. Therefore, consistent positioning of different subjects in the same test positions can be considered an outcome of this study. This again supports that our test postures should be able to produce stable EMG data and therefore interpretation of the findings of this study regarding changes in body position and their influence on muscle activation patterns.

6.3 Reference posture of single leg Upright Standing is optimal for clinical research

To our knowledge, the only other study that previously investigated Upright Standing (on a single leg) as a position of normalisation was Norcross and colleagues (2010). The purpose of the Norcross study was to establish the reliability of single leg stance as a sub-MVIC EMG method of normalisation as it is thought to be a more "functional" position that considers the lower limb muscles working in synergy. In general our findings agree with Norcross and therefore both studies provide preliminary support for the use of this position as a reference posture for examining muscle activation patterns in single leg stance.

The more widely used MVIC EMG normalisation involves maximal contractions of muscles in generally non-functional test positions whereby each individual muscle is tested separately. Sub-MVIC normalisation has benefits over performing individual MVIC as it is a more "functional" position that is time efficient in assessing an increased number of kinematic angles and muscles in the presence of good reliability. The issues of comparing MVIC normalisation to functional activities that involve only relatively low levels of muscle activity are recognised as a limitation in clinical samples, particularly in subjects with pain disorders that impact on their capacity to perform pain free maximal muscle contractions (Dankaerts et al., 2004).

Norcross defined single leg stance as "standing on the dominant leg with the hands on the hips and the non-dominant knee flexed to 90°. Subjects were instructed not to allow the non-dominant leg to contact the dominant leg and to remain as still as possible" (Norcross et al., 2010). This definition is unclear regarding whether they controlled the thorax, pelvis, hip or knee positions, which may suggest there was some variability in these joint positions between subjects. In our study, we defined the thorax, pelvis, hip and knee positions to promote kinematic (and thus EMG) consistency and investigate whether in a clinical setting, subjects could be reliably positioned from visual assessment.

There were some differences between the studies regarding the recommendations for the use of Upright Standing to reliably assess EMG activity of some muscles. In the Norcross study, the ICC's for all muscles were 0.8 – 0.94 and they concluded RF, VL and BF should not be used due to a lack of measurement precision. They reported inter-subject and intra-subject coefficients of variation of EMG amplitude and due to the fact we did not, we cannot make a direct comparison to their values. We did, however, have similar ICC's for these muscles which were RF (0.88), VL (0.80), BF (0.90), but our results support that muscle activity of these muscles can be reliably measured with a well defined Upright Standing position. The other muscles Norcross investigated were Gmax, Gmed, and "Adductors", which they concluded can be reliably measured with their single leg stance method. The only discrepancy between our findings here concerns the "Adductors". Norcross reported a high ICC of 0.94 whereas we found a much lower ICC of 0.29. This is a difficult point to comment on partly due to the fact they did not state which specific adductor muscle/s they measured. Hence a direct comparison of our findings cannot be drawn.

The final differences between the studies are that our study also measured muscle activity in TFL and ST and we also monitored an additional four kinematic angles. The addition of the extra muscles were decided as ST is a medial hamstring muscle and therefore provides a balance and comparison to assessing BF, the lateral hamstring muscle. We measured TFL activity as it is an important muscle involved in controlling pelvic position in the frontal plane, and is thought to have a role in abnormal hip kinematics in some clinical populations . Norcross considered three kinematic angles (hip extension, hip abduction and knee flexion). Whilst we did not monitor hip abduction specifically we did include frontal plane pelvis position which can provide an indication of hip abduction/adduction if the pelvis moves on a fixed femur, as the consistent position of the lower limb was monitored and addressed if visually considered to be out of vertical alignment. Our study monitored an additional four angles of the thorax both in sagittal and frontal planes, which allowed for investigation of the influence of change in trunk position of the hip joints on hip and thigh muscle activity.

While Norcross did not report ICC's or SEM's for kinematics, they did report low kinematic standard deviations in line with our findings. The findings of these two studies when considered together do support the use of Upright Standing as a reliable and valid reference posture for EMG normalization in studies investigating muscle activation patterns around the hip and thigh during single leg stance. The advantage of having a functional, sub-maximal reference posture is of particular importance when comparing other functional tasks that involve only low levels of muscle activation, as well as in clinical populations where pain may limit maximal muscle contractions.

6.4 Body position influences on lower limb motor patterns during single leg stance

6.4.1 Consistent patterns

The results of the main part of this research broadly support our hypotheses that sagittal and frontal plane position in single leg stance can be easily and consistently changed, resulting in predictable changes in activation patterns of muscles around the hip and thigh. Further, the largest and most consistent changes in muscle activation occur in the muscles that function in the same plane of movement as the positional change.

It is common in clinical practice to focus on assessment and training lower limb alignment especially concerning knee valgus and hip adduction posture (Selkowitz et al., 2013, Reiman et al., 2012). However, there has been less focus on the interplay between the trunk and pelvis on hip and thigh muscle activation with regards to body alignment and postural sway. Our data demonstrates that specific trunk and pelvic positions are linked to predicable motor patterns in most muscles measured (such as Gmax and TFL), although variability does exist for other muscles (such as AL). Our finding of predictable changes in muscle activation patterns supports that trunk and pelvis position must be taken into account along with lower limb kinematics when considering influences of hip and thigh muscle activation patterns.

These findings have important clinical implications. For example, if the objective is to enhance the activation of Gmax and Gmed in single leg stance, then positioning the subject with either (or combined) increased anterior trunk sway, or contralateral (compared to the weight bearing stance leg) trunk shift in the frontal plane, or contralateral (compared to the weight bearing stance leg) pelvic elevation could help achieve this goal. These findings are in line with those of O'Sullivan et al (2002) who reported a consistent pattern of activation of the posterior trunk muscles and de-activation of the upper anterior abdominal wall with the same body position change of anterior trunk sway. This same pattern in the sagittal plane was also reported by Wang et al (2006) for the hip muscles.

While a number of authors including Distefano (2009), Ayotte (2007) and Bolgla and Uhl (2005) have investigated the activation of the Gmax and Gmed in commonly used rehabilitation exercises, there has been no consideration of the influence of trunk and pelvic position on these findings during weight bearing tasks. The results of the current study support the concept that rehabilitation of hip abductor muscle strength could be highly effective in a more functional single leg stance position if positioning of the trunk and pelvis are considered in these exercises. Although speculative, it may also be that people, who habitually adopt posterior sway postures during activities of daily living, may have associated deficits in their hip abductor muscles rendering them vulnerable to lower limb injuries associated with this deficit. This concept requires further investigation in clinical populations with specific muscle weakness such as in the hip abductors. Further, if on the other hand the clinical objective is to reduce the activation of a specific muscle such as TFL, then directing the subject to adopt an anterior trunk sway posture in single leg stance may help deactivate the muscle. These findings add a more functional alternative to recent research suggesting such a change in motor patterning is best achieved in primarily non-weight bearing positions (Selkowitz et al., 2013).

Comparing Lateral Pelvic Drop to Lateral Pelvic Raise positions, there was a clear pattern of reduced activation of the hip abductor muscles (TFL and GM) and RF and an increased activation of the hamstrings, AL and VL. These findings suggest a shift in activation away from the short hip abductors to some of the long hip/thigh muscles in the Trendelenberg posture. The Trendelenburg posture can be related with a number of clinical presentations (Hardcastle and Nade, 1985) and is thought to be a passive position requiring little muscle activation. While our results support this clinical interpretation for the hip abductor muscles (Gmed and TFL), the finding of increased activation on other muscles suggest it may be important to more broadly consider the influence of frontal plane single leg loading position on muscular activation patterns in clinical populations that are associated with Trendelenberg postures. For example, in individuals with osteoarthritic hips, both the hip adductors and abductors were found to be weak (Arokoski et al., 2002) when compared to a control group. Conversely, females with patellofemoral pain have been shown to have reduced hip abduction and external rotation strength, with no change in other muscles such as adductors or hip extensors (Prins and Van der Wurff, 2009) Additionally, our findings are also supported by the recognised role the adductors have in controlling frontal plain motion by producing adduction torque with respect to the femur-on-pelvis and pelvis-on-femur (Neumann, 2010). This role can be largely explain by the orientation of the muscle (Ward et al., 2010). Other research found a lack of correlation between hip abduction strength and lateral pelvic drop in a low back pain population (Kendall et al., 2010). It is possible that the presence of pain may lead to altered frontal plane lumbo-pelvic control. Lateral Pelvic Drop or Raise requires a certain amount of frontal plane lumbar motion which in some subjects may be compromised in the presence of pain. If the range of motion is not available then strength may not be necessary to control it (Bittencourt et al., 2012) The current research suggests that these relationships are complex and that again, the importance of considering the impact of more distal rather than just local changes in body position on muscle activation patterns.

Contrary to the Trendelenburg position, Lateral Pelvic Raise required greater activity in the hip abductor muscles to maintain the contra-lateral pelvis in an elevated position. This result is consistent with previous research (Bolgla and Uhl, 2005). Considering Di Mattia and colleagues (2005) found a weak relationship between isometric hip abduction strength and the Trendelenburg position (single leg squat also), our findings may have implications for functional retraining of frontal plane muscles by simple changes to frontal plane pelvic posture during functional tasks. This is an area for future research.

For the lateral trunk shift condition the pattern demonstrated was the activation of the hip abductor muscles (Gmax, Gmed and TFL) in the Left Trunk Shift position relative to the Right Trunk Shift during right single leg stance. These findings are consistent with the lateral shift of the upper body relative to the hip resulting in a greater demand on hip abductor system in order to maintain balance on the right leg. This observation may also fit with the findings of Popovich and colleagues (Popovich and Kulig, 2012) who found subjects with weak Gmax and Gmed landed with increased frontal plane trunk bend during a single leg step down landing task compared to a group of subjects who were found to have strong muscles.

The differences in muscle activation when the postural adjustment was initiated via the pelvis in a sagittal plane are more difficult to interpret however there were some consistent findings. There were significant reductions in activation of ST, Gmed and VL, when changing from Posterior to Anterior Pelvic Rotation. Considering their pelvic and femur attachments, this finding suggests that ST and Gmed, although speculative, are potentially placed in a more optimal length tension relationship to facilitate Posterior Pelvic Rotation. The implications for this may be directly applied to a clinical setting where by the goal of increasing ST and/or Gmed activation would be achieved by adopting a Posterior Pelvic Rotation and conversely, to decrease the load or inhibit either of these muscles, an Anterior Pelvic Rotation position could be encouraged. The decreased activation of VL during Anterior Pelvic Rotation may potentially be explained by a slight shift in body weight over the base of support decreasing the work required of VL to maintain balance, though without ground reaction force data and an absence in current literature to refer to, there is a lack evidence to support this suggestion and possibly an area for future research. Finally, it was surprising that Gmax didn’t show a greater or consistent change in activation considering its primary plane of action is in a sagittal direction. The reason for this could be that there were a range of responses between individuals, supporting the complex and variable nature of motor control for this region.

6.4.2 Variable patterns

While the results of our study broadly supported that changes in trunk and pelvis position result in predictable changes in muscle activation patterns around the hip and thigh, not every muscle responded predictably in all paired test positions. AL was the muscle that demonstrated the least predictable changes in activation. This may be partly explained by the lower EMG reliability of AL, which suggests the findings in relation to this muscle may need to be interpreted with caution.

Lateral Pelvic Drop, compared to Lateral Pelvic Raise, was the only position that proved to have a statistically significant group effect, which was to increase the activity levels of AL. This was particularly surprising considering a large mean change in the Thorax Y angle between Left and Right Trunk Shift of 26°. All other monitored angles experienced no change, with the exception of Pelvis Y (frontal plane), with a small mean change of three degrees, which could be considered unlikely to influence the muscle activation. The lack of change in other measured angles to counteract the large change in Thorax Y angle may be another explanation for the lack of change in adductor muscle activity, as perhaps there needs to be concurrent and larger change in the joint angles that these muscle cross (for example the hip joint) in order to influence the muscle control of the region.

Being a frontal plane orientated muscle, we expected to see more consistency and a larger effect on AL activity with frontal plane positions of the pelvis and particularly the trunk, but as a general trend this was not the case. Adductor injury is common (Ekstrand and Hilding, 1999, Hägglund et al., 2009, Werner et al., 2009) in sports such as football (soccer) that require repetitive dynamic movements (cutting, side stepping and kicking) that involve some degree of sagittal frontal plane movements at the hip and trunk. Therefore an enhanced understanding of the function of the adductor complex during such single leg movements may be important to gain insight into the vulnerability of the muscle group to strain. Our findings, shown in Anterior Trunk Sway and Posterior Trunk Sway (Figure 10), had good levels of AL EMG reliability with the existence of different motor strategies used by different individuals. This was also the case during Left and Right Trunk Shift (see Appendix K, page 138), though reliability was not as good. In addition to this we also found in half the subjects the activation levels were always above or below that of the neutral position "Upright Stance". The clinical implications for this may lie in prospective research identifying individuals that have increased muscle activation levels with anterior trunk sway as anterior trunk sway occurs with a cutting movement and monitor them for injuries.

Whilst there is a lack of direct research comparison, our findings may relate to the findings of Morrissey et al (2012), who reported that an increased adductor to abductor activity ratio (a relative over-activity of adductors) was observed in the presence of groin pain whilst performing a standing hip flexion movement. Tyler et al (2001) found a decreased adductor strength ratio with abductors was a predictive factor of groin pain. This highlights that the concept of over or under activity of AL needs further prospective investigation to assess if a subject could be predisposed to adductor strain based on their pattern of activation, and to further investigate the existence of variable motor strategies in relation to muscle injury.

Henry at al (1998) investigated double leg stance posture on a fast moving platform (9cm in 200ms) that the subject stood on. They found that AL was most active in two directions. Anterior translation of the platform caused what they termed "back sway" increased AL activation most, followed by an anterolateral direction of the moving platform. Similar to our hypothesis of AL being most influenced by frontal plane movements, one might have expected pure lateral platform translation would cause the greatest activation levels. In light of Henry's study (1998) and our current findings, it appears that AL does not act to control pure frontal plane movements, but possibly multi-planar movements such as in an antero-lateral direction (Hiti et al., 2011), which our study did not investigate. It may be that more challenging functional tasks in combination with a larger change to the hip joint position, such as a cutting movement may produce more consistency and activation of the adductor muscles. Our study has shed some light on the behavior of this muscle as it relates to single leg stance, but further research is required.

6.4.3 Individual Variation

Whilst we have found consistent motor patterns across subjects, observing the individual results must not be ignored. As shown in Figures 8 to 14 in Chapter 5, not every individual subject demonstrated the same direction and magnitude of change in muscle activation for every muscle in the different paired test postures. For example, for some muscles (Gmax, BF, ST, and AL) a small number of subjects, unlike the majority of the group, displayed muscle activity levels that did not cross the Upright Standing value in either Anterior or Posterior Trunk Sway. For the few subjects that had muscle activity always above the Upright Standing value even in Posterior Trunk Sway, this may represent a lack of relaxation of muscles not usually required in that specific posture in some individuals (meaning it was an unfamiliar position whereby the subject was unable to relax). Although speculative, the inability of a muscle to relax when altering body posture may have clinical implications in terms of a possible muscle overload mechanisms for some individuals. The concept of individuals developing their own “neurosignature” in response to pain that results in individual motor responses is accepted in pain literature (Melzack, 2001), and this has recognised implications for the individual management of patients with pain disorders (O'Sullivan, 2012). It may also be relevant to individual motor control patterns that are associated with the development of pain as suggested by Nelson-Wong and colleagues (2008). They found that a group of previously asymptomatic subjects, developed lower back pain during prolonged standing , used bilateral co-activation Gmed strategies which differed from the control group who demonstrated synergistic and reciprocal activation of these muscles.

There was a divergence in the pattern of activation in ST during Lateral Pelvic Drop condition (Appendix L, page 139). This suggests that when moving from Lateral Pelvic Raise, subjects again displayed a variety of motor control strategies to adopt the Lateral Pelvic Drop position, as some increased and others decreased their activation levels. Although this data broadly suggests a group effect in these findings, there is evidence in some muscles to suggest that the response to changes in both trunk and hip/pelvic posture is variable for different individuals. We hypothesise that these findings suggest the motor control strategies for controlling the pelvic and trunk posture in single leg stance are broadly consistent, but not always predictable, with some individual variance in muscle responses to the postural changes.

There were significant reductions in activation of ST when changing from Posterior to Anterior Pelvic Rotation (Appendix M, page 142), and a trend in the same direction for BF. Greater hamstring muscle activation would be logically expected to control Posterior Pelvic Rotation than Anterior Pelvic Rotation. The non-significant result of BF may be explained via visual graphical inspection of the hamstring muscles. There were a small number of subjects that displayed a clear opposing activation pattern, again suggesting there exists different motor control strategies for the same task in different individuals.

These findings support that individuals can utilise different motor control strategies to achieve the same functional outcome. This concept is not new, and has been shown in research involving simple motor tasks such as lifting a leg in supine lying (Beales et al., 2010), as well as in more complex single leg loading tasks in individuals recovering from injury such as ACL reconstruction (Phillips and van Deursen, 2008).

From a clinical perspective, where muscle loading and activation patterns are being examined during single leg stance, assessment in a range of functional trunk and pelvic postures may be important. Clearly these concepts need further investigation to test their significance. It is proposed that when considering individual variation in muscle activation in single leg stance in the clinical setting, muscle palpation and EMG biofeedback as well as analysis of body position may be important to use in combination.

6.7 Implications for clinical practice

The majority of clinical implications described in this section are somewhat speculative, as this study has been conducted on healthy individuals. Clearly further research into these concepts on clinical populations is required. However this data provides a basis upon which these studies can be conducted.

From the findings of this research, a number of implications for clinical practice have emerged. These include:

- The establishment of normative data in respect to defining the amount of movement that occurs in key body regions when adopting commonly observed trunk and pelvic positions during single leg stance.
- The confirmation that subjects can be easily and reliably positioned in different single leg stance positions without the use of complex equipment. This has implications both for the assessment of patients as well as retraining of body position during single leg stance. For example, screening tasks for injury prediction could be readily developed around these different single leg loading positions.
- Patterns of change in muscle activation are broadly predictable and the greatest changes are seen in the muscles that function in the same plane as the positional change. This may have utility for examining and retraining patients where there is a

deficit or an excess of activation in certain muscle groups during single leg standing tasks.

- Not all subjects showed variability in muscle activation across paired test positions. As variability is considered protective for injury, this could have implications regarding possible predisposition to injury in such individuals.
- The establishment of a reliable, functional position (upright single leg standing), to make assessment levels of muscle activity, which could be further validated with the use of clinical EMG biofeedback. This position has clinical utility where static assessment in various single leg postures highlight differences in muscle activation patterns of relevance to the individual with a clinical problem.
- An increased understanding of what could be considered "normal" muscle activation during single leg stance when observing different trunk and pelvis position. In healthy males, these results support that observing body position during single leg stance will give a good indication of the relative muscle activity of some hip and thigh muscles. Consistency can be found in Anterior Trunk Sway where there will be an increase in hamstring, Gmax and Gmed activation and a decreased activation in Posterior Trunk Sway. TFL had increased activation in Posterior Trunk Sway (relative to Anterior Trunk Sway), Lateral Pelvic Raise (relative to Lateral Pelvic Drop) and Left Trunk Shift (relative to Right Trunk Shift). Left Trunk Shift also increased Gmax and Gmed activity compared to Right Trunk Shift. Lateral Pelvic Raise increased activation in Gmed, compared to Lateral Pelvic Drop. Lateral Pelvic Drop increased hamstring and AL activation, relative to Lateral Pelvic Raise. Anterior Pelvic Rotation (relative to Posterior Pelvic Rotation) decreased the activation of ST, Gmed and VL. Portable EMG biofeedback would be the recommended clinical method of observing this.
- Our single leg standing position has good utility for injured patients to provide quick reliable assessment without undue patient demands. The utility of this assessment may become more relevant if future prospective research and research into symptomatic subjects have been completed thereby highlighting problem levels of muscle activity.
- While results are generalised across the group, even in a pain free population there are some individuals who display variable muscle responses to these changes in body position. Therefore body position changes cannot be directly extrapolated to

interpret muscle activation patterns, however simple clinical skills such as muscle palpation may assist individual interpretations.

- The AL muscle is frequently involved in pathology, which highlights the clinical importance in awareness of the variability seen in activation strategies whilst adopting our clinically relevant test postures. This finding warrants further investigation to establishing any association with symptomatology.
- Changing posture of the trunk results in consistent changes in posture around the hip. These regions clearly do not act in isolation during functional tasks, supporting the concept of looking broadly at body movement patterns rather than focusing on a single joint or region.
- The need to monitor hip and knee angles during single leg stance. It appears that with sagittal plane movements there is a relationship (statistical and clinical) between hip and knee angles and changes in pelvis/spine/thorax angles. This is likely a reflection of the need to change body position in order to maintain balance.
- Changing posture of the pelvis in the frontal plane resulted in consistent changes in activation of the hip abductors and a compensatory change in hamstring muscle activity. This may have implications for muscle retraining during injury rehabilitation.

6.8 Limitations of the study

As with any research, there are limitations to the study that need to be considered when interpreting the results. Some relevant limitations of this study include:

- Our choice of using Upright Standing in single leg stance as a Sub-MVIC method to normalise EMG to, was found to be reliable with the exception of AL and ST.
- All positions are limited by the individual's ability to maintain balance. As a result two subject's data had to be deleted as EMG recordings were judged to be too variable.
- The inability to quantify the amount of muscle activity needed for all sub-maximal positions.
- Sample size. While the findings of this study are clearly supported by strong results, larger numbers could reveal more consistent patterns in the variable muscle activation patterns that were observed in a small number of subjects.
- This study was conducted on males aged 18-45, therefore the results cannot be generalised to females nor very young or elderly male populations.
- This study was conducted on a pain free population. While essential for establishing normative data, the results cannot be generalised to specific injury or pain populations.
- Superficial muscles above the knee were investigated only. This was due to equipment availability and also practicality of the study to be readily transferred to the clinical setting. Therefore the response of other deeper hip and thigh muscles to changes in single leg stance position cannot be inferred from these results. Future research into the muscles below the knee and influencing the foot should also be included.
- This study only investigated uni-planar movements, as there was no previous data available. Uni-planar changes may not reflect reality of movement and function. It is more likely that individuals will adjust body position in multiple planes in response to task demand.
- Testing was performed in static postures as few people stand on one foot for long periods of time.

- This study did not look at habitual patterns of movement, as all positions were predefined. Therefore, it is not known whether subjects who are adopting habitual patterns of movement would show different muscle activation patterns in the same position as subjects who have be directed to adopt that position.

6.9 Recommendations for future research

While the findings of this research answer some important questions regarding muscle activation patterns during single leg stance, these results also produce more questions. The following recommendations for future research can be made:

- Further investigation of Sub-MVIC method of normalisation during single leg stance for AL and ST is required.
- The reliability trials support that in most instances, future studies could run two trials to sufficiently collect reliable data. It is suggested that researchers must review our data for the specific muscle and position intended for certainty.
- Bi-planar movements should be investigated, to determine the effect on muscle activation of changes in body position across multiple planes.
- Investigate specific injury populations. Subjects with pain in the lower limb region may display different patterns of muscle activation.
- Prospective research could investigate the influence of habitual trunk and pelvic posture on injury risk for the lower limb and pelvis.
- Previous studies have demonstrated that static postures represent a body signature that translates into functional tasks. Future studies should investigate whether patterns of muscle activation during static single leg stance translates to dynamic tasks.
- An intervention study to determine the effect of rehabilitating lower limb muscle activation patterns by changing single leg stance position compared with non-functional specific muscle strengthening exercises.

6.10 Summary

The study supports that changes in trunk and pelvic posture influence the levels of activation of different muscles of the hip and thigh in healthy males and that these interactions are complex in nature. Patterns of change in muscle activation are broadly predictable and the greatest changes are seen in the muscles that function in the same plane as the positional change. Anterior Trunk Sway increase posterior sagittal plane muscles activity concurrently with a deactivation of anterior sagittal plane muscles. Lateral hip abductor muscles increased activation during Left Trunk Shift. Lateral Pelvic Drop decreased activity in hip abductors and increased hamstring, AL and VL activity. Anterior Pelvic Rotation decreased the activation of ST, Gmed and VL.

For some muscles such as AL, large variability in patterns of muscle activation for some pair wise test postures was observed, supporting some individual variation in motor control strategies. Clinically the AL muscle is frequently involved in pathology, and this variability in activation strategies warrants further investigation to establish any association with symptomatology.

The results also highlight the need to look at the whole kinetic chain (Trunk and Pelvis) when examining the lower limb, hip and pelvis. Even in a pain free population and pain free postures there are, at times, variable responses to muscle activation within a group. Research into the relationship between trunk and pelvic posture and muscle activation patterns of the hip and thigh in specific injury populations is required. Further, prospective research could investigate the influence of habitual trunk and pelvic posture on injury risk for the lower limb and pelvis.

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Appendix A. Ethics approval letter from Curtin University

Curtin University

Memorandum

To	Professor Peter O'Sullivan, Physiotherapy
From	A/Prof Stephan Millett, Chair, Human Research Ethics Committee
Subject	Protocol Approval **HR 25/2011**
Date	13 May 2011
Copy	Mr Simon Prior, Physiotherapy Dr Tim Mitchell, Physiotherapy Graduate Studies Officer, Faculty of Health Sciences

Office of Research and Development

Human Research Ethics Committee

TELEPHONE 9266 2784
FACSIMILE 9266 3793
EMAIL hrec@curtin.edu.au

Thank you for your application submitted to the Human Research Ethics Committee (HREC) for the project titled "*An investigation into the influence of changes in static single leg standing posture on hip and thigh muscle activation in a pain free population*". Your application has been reviewed by the HREC and is **approved**.

- You have ethics clearance to undertake the research as stated in your proposal.
- The approval number for your project is **HR 25/2011.** *Please quote this number in any future correspondence.*
- Approval of this project is for a period of twelve months **10-05-2011** to **10-05-2012**. To renew this approval a completed Form B (attached) must be submitted before the expiry date **10-05-2012**.
- If you are a Higher Degree by Research student, data collection must not begin before your Application for Candidacy is approved by your Faculty Graduate Studies Committee.
- The following standard statement **must be** included in the information sheet to participants:
  This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number HR 25/2011). The Committee is comprised of members of the public, academics, lawyers, doctors and pastoral carers. Its main role is to protect participants. If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784 or by emailing hrec@curtin.edu.au.

Applicants should note the following:

It is the policy of the HREC to conduct random audits on a percentage of approved projects. These audits may be conducted at any time after the project starts. In cases where the HREC considers that there may be a risk of adverse events, or where participants may be especially vulnerable, the HREC may request the chief investigator to provide an outcomes report, including information on follow-up of participants.

The attached **FORM B** should be completed and returned to the Secretary, HREC, C/- Office of Research & Development:
When the project has finished, or

- If at any time during the twelve months changes/amendments occur, or
- If a serious or unexpected adverse event occurs, or
- 14 days prior to the expiry date if renewal is required.
- An application for renewal may be made with a Form B three years running, after which a new application form (Form A), providing comprehensive details, must be submitted.

Regards,

Associate Professor Stephan Millett
Chair Human Research Ethics Committee

Appendix B. Ethics approval letter from Aspetar

Qatar Orthopaedic and Sports Medicine Hospital

Dr. Timothy Mitchell
Senior Physiotherapist
Aspetar

22nd September 2010

Full title of study – An investigation into the influence of changes in static single leg standing posture on hip and thigh muscle activation in a pain free population

Dear Dr Mitchell,

The above mentioned study was reviewed by the Aspetar Human Research Ethics Committee on 15thh September 2010.

The members of the Committee present gave a favorable ethical opinion of the application and the supporting documentation. Therefore, I am happy to inform you that your protocol assessing body posture in single leg stance and its impact upon muscle activation has been approved on the understanding that you will follow the conditions of the approval as described in the Aspetar Human Research Ethics Committee Terms of Reference and associated documents.

Documents approved at the meeting where –

1. Ethics Application
2. Subject information sheet and consent (English and Arabic)

The members of the Ethics Committee present at the meeting where

- Dr Gerard Saillant (Chair)	Orthopaedic Surgeon
- Nadia Gaoua	Clinical Psychologist
- Dr Nebosja Popovic	Orthopaedic Surgeon
- Bala Krishnan	Quality Director
- Saud Al Hamad	Lawyer and Cleric
- Dr Jean Claude Chatard	General Practitioner

The ASPETAR Human Research Ethics Committee follows the guidelines set out by the Australian Health and Medical Research Council (2007) on the conduct of Trials involving human subjects, and by the Emiri Decree No 1 2008, is authorised to carry out the ethical review of clinical, basic and applied science research being conducted in the Aspire Zone Foundation.

Best regards,

Justin Grantham
Director of Research and Education

P.O. BOX 29222, Doha, State of Qatar, Telephone +974 4132000, Facsimile +974 4132020
Email: info@aspetar.com, www.aspetar.com

Appendix C. Subject Information Sheet

Subject Information Sheet

Title of Project: ***An investigation into the influence of changes in static standing posture on pelvis and hip muscle activation in a pain free population.***

Principal Investigators: **Mr Simon Prior** Musculoskeletal Physiotherapist
ASPETAR Sports & Orthopaedic Hospital, Doha, QATAR
Telephone: +974 6030541

Dr Tim Mitchell PhD Musculoskeletal Physiotherapist
ASPETAR Sports & Orthopaedic Hospital, Doha, QATAR
Telephone: +974 3016432

Prof. Peter O'Sullivan PhD
Curtin University of Technology, School of Physiotherapy, Perth, AUSTRALIA
Telephone: +61 0 9266 3629

Purpose of Study

You have been asked to participate in a study investigating physical characteristics of the lower limb and pelvis.

Lower limb and pelvis muscles have an important role in protecting you from injury. Some of these muscles have been shown to work well in some postures, but not well in others. This may mean that people who commonly adopt certain postures are at a higher risk of developing lower limb problems potentially leading to injury. This study will look at pain free males and the muscle activation around the hip and lower limb in relation to various static single leg positions.

Procedures:

If you are prepared to be involved in this study, we will require approximately 60-90 minutes of your time. You will initially be asked some basic questions relating to your medical history. You will be required to wear underwear to expose your back, hips and lower limb for placement of reflective adhesive skin markers for posture measurements and also the placement of adhesive skin muscle activation sensors.

You will have some basic measures of height and weight recorded. You will then have some measures taken while you are standing on one leg whilst the examiner directs you to various positions. The reflective markers on your skin will be used to measure the angles of your back, hips, pelvis and leg with the use of a digital camera and computer program. You will only be required to maintain each position for a few seconds. Therefore, with respect to these tests there is no excessive physical exertion.

We may ask you to the repeat the test after a few weeks or months to confirm our findings.

Risk, Discomfort and Benefits
There are minimal risks to be involved in this study. You will be asked to stand on the same leg for a few seconds and be given a rest period of one minute between positions. There is no evidence to suggest that you can injure yourself in this way. You may experience some fatigue of your back muscles or leg muscles during the test, however this is unlikely. Following this, you may experience a condition known as Delayed Onset Muscle Soreness. This is a normal aching sensation in your back, lower limb or pelvis muscles 1-3 days following an activity that you do not regularly perform. There are no long term effects of any of the above testing postures.

If you agree to take part in this study, you will become aware of your own single leg postures and the muscles recruitment involved. You will also have access to your individual results and the other measures taken at the end of the study.

Financial Obligations
In general, there are no financial obligations to you. We will conduct the study on-site at ASPETAR Sports Hospital or Aspire Sports Academy and therefore employees of the hospital can participate at a time convenient to them. Non ASPETAR employees will have to find their own transport to the hospital and again participation will be organised at a time convenient to you.

Confidentiality
You will be allocated an identification number, and your name will only appear on the identification number master list. On all other forms, only your identification number will be used. Access to the master list will be restricted to the researchers and project supervisor. We will only use the identification codes to identify you for the purposes of contacting you to organise retesting if needed.

All data recorded will be stored, using identification numbers only, at ASPETAR, in a locked filing cabinet. Information stored on computer will be password restricted to the researchers. Digital photographs will not be used for any presentations of publications without your express written consent.

The results of this study will be reported, but it will not be possible to identify individual subjects. Once the study is completed, data will be securely stored with the project supervisor for 10 years, and then will be destroyed. This is a requirement of Curtin University of Technology.

Request for More Information
You are encouraged to discuss any questions or concerns with the principal investigator at any time. Contact details are listed above.

Refusal or Withdrawal
You may refuse to participate in the study. If you agree to participate, you are free to withdraw at any stage without fear of prejudice. If you decide to withdraw, please contact the principal investigator as soon as possible. If you withdraw, all your data will be destroyed.

Appendix D. Subject Consent Form

Subject Consent Form

Title of Project: ***An investigation into the influence of changes in static standing posture on pelvis and hip muscle activation in a pain free population.***

Principal Investigators: **Mr Simon Prior** Musculoskeletal Physiotherapist
ASPETAR Sports & Orthopaedic Hospital, Doha, QATAR
Telephone: +974 66030541

Dr Tim Mitchell PhD Musculoskeletal Physiotherapist
ASPETAR Sports & Orthopaedic Hospital, Doha, QATAR
Telephone: +974 33016432

Prof. Peter O'Sullivan PhD
Curtin University, School of Physiotherapy, Perth,
Telephone: +61 0 9266 3629

You are voluntarily making a decision whether or not to participate in this research study. Your signature certifies that you have decided to participate, having read and understood the information presented. Your signature also certifies that you have had an adequate opportunity to discuss this study with the researchers, and you have had all your questions answered to your satisfaction. You will be given a copy of this consent form to keep.

I, (the undersigned)____

of ____
consent to participate in this study and give permission for any results from this study to be used in any report or research paper, on the understanding that my confidentiality will be preserved. I consent to the use of my personal details only for the purpose of contacting me for the follow up retesting. I understand that I may withdraw from the study at any time without prejudice. If so, I undertake to contact the principal investigator (Telephone: 66030541) at the earliest opportunity.

Signature _____________________________ Date______________
Subject

I have explained the nature of and the procedures involved in the study to which the subject has consented to participate and have answered all questions. In my judgment, the subject is voluntarily and knowingly giving informed consent and possesses the legal capacity to do so.

Principal Investigator ______________________ Date_______________

My signature as witness certifies that the subject signed this consent form in my presence as a voluntary act and deed.
Witness _________________________________ Date_____________

Appendix E. Kinematic definitions of Angles used for Vicon Full Body Plug-in Gait Model

Kinematic Angles		
Angle	Relative/Absolute	Description
R Hip Angle X	Relative	The angles between the pelvis and the thigh in a sagittal plane
R Knee Angle X	Relative	The angles between the thigh and the shank in a sagittal plane
R Pelvis Angle X	Absolute	The angles between the pelvis and the laboratory coordinate system in a sagittal plane
R Pelvis Angle Y	Absolute	The angles between the pelvis and the laboratory coordinate system in a frontal plane
R Spine Angle X	Relative	The angles between the thorax relative to the pelvis in a sagittal plane
R Thorax Angle X	Absolute	The angles between the thorax and the laboratory coordinate system in a sagittal plane
R Thorax Angle Y	Absolute	The angles between the thorax and the laboratory coordinate system in a frontal plane

Appendix F. Marker Position for Vicon Full Body Plug-in Gait Model

Vicon Marker Label	Definition	Position on Subject
	TORSO markers	
C7	7th cervical vertebra	Spinous process of the 7th cervical vertebra
T10	10th thoracic vertebra	Spinous process of the 10th thoracic vertebra
CLAV	Clavicle	Jugular notch where the clavicles meet the sternum
STRN	Sternum	Xiphoid process of the sternum
RBAK	Right back	Anywhere over the right scapula
RSHO	Right shoulder	Acromio-clavicular joint
LSHO	Left shoulder	Acromio-clavicular joint
	PELVIS markers	
LASI	Left ASIS	Left anterior superior iliac spine
RASI	Right ASIS	Right anterior superior iliac spine
LPSI	Left PSIS	Left posterior superior iliac spine (immediately below the sacro-iliac joints, at the point where the spine joins the pelvis) This marker is used with the RPSI marker as an alternative to the single SACR marker.
RPSI	Right PSIS	Right posterior superior iliac spine (immediately below the sacro-iliac joints, at the point where the spine joins the pelvis) This marker is used with the LPSI marker as an alternative to the single SACR marker.
	Left Lower Limb Marker	
LTHI	Left thigh	Lower lateral 1/3 surface of the left thigh
LKNE	Left knee	Flexion-extension axis of the left knee
LTIB	Left tibia	Lower 1/3 surface of the left shank
LANK	Left ankle	Lateral malleolus along an imaginary line that passes through the transmalleolar axis
LHEE	Left heel	Calcaneous at the same height above the plantar surface of the foot as the toe marker
LTOE	Left toe	Second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot
	Right Lower Limb Markers	
RTHI	Right thigh	Upper lateral 1/3 surface of the right thigh
RKNE	Right knee	Flexion-extension axis of the right knee.
RTIB	Right tibia	Upper 1/3 surface of the right shank
RANK	Right ankle	Lateral malleolus along an imaginary line that passes through the transmalleolar axis
RHEE	Right heel	Calcaneous at the same height above the plantar surface of the foot as the toe marker
RTOE	Right toe	Second metatarsal head, on the mid-foot side of the equinus break between fore-foot and mid-foot

Appendix G. Surface landmarks for electrode placement (Perotto 2005)

Muscle	Electrode Placement
Gluteus Maximus	Midway between greater trochanter and the sacrum
Gluteus Medius	One inch distal to the midpoint of the iliac crest
Tensor Fascia Lata	Two fingerbreadths anterior to the greater trochanter
Semitendinosus	Midway on a line between the medial epicondyle of the femur and the ischial tuberosity
Biceps Femoris (long head)	Place electrode at the midpoint of a line between the fibula head and ischial tuberosity
Vastus Lateralis	Over the lateral aspect of the thigh, one handbreadth above the patella
Rectus Femoris	On the anterior aspect of the thigh, midway between the superior border of the patella and the anterior superior iliac spine
Adductor Longus	Palpate the tendon arising from the pubic tubercle place the electrode four fingerbreadths distal to the pubic tubercle over the muscle belly

Appendix H. Kinematic reliability repeated measures

6 Trials angles

Upright Standing			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	12.2±5.8 (2.0)	0.89(0.81-0.95)	<0.001
R Knee X	9.0±5.5 (2.0)	0.88(0.8-0.94)	<0.001
R Pelvis X	12.0±3.9 (1.1)	0.91(0.85-0.96)	<0.001
R Pelvis Y	-1.1±2.8 (1.1)	0.87(0.79-0.94)	<0.001
R Spine X	-14.8±5.4 (1.5)	0.93(0.88-0.97)	<0.001
R Thorax X	-2.7±3.9 (1.1)	0.91(0.85-0.96	<0.001
R Thorax Y	-1.8±1.6 (1.4)	0.54(0.36-0.73)	<0.001

Anterior Trunk Sway			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	21.9±5.7 (2.8)	0.81(0.69-0.90)	<0.001
R Knee X	13.3±5.8 (2.4)	0.85(0.75-0.92)	<0.001
R Pelvis X	15.7±4.4 (1.9)	0.84(0.74-0.92)	<0.001
R Pelvis Y	0.2±3.2 (1.3)	0.85(0.75-0.92)	<0.001
R Spine X	1.7±8.6 (2.6)	0.93(0.87-0.96)	<0.001
R Thorax X	17.4±6.7 (2.5)	0.89(0.80-0.95)	<0.001
R Thorax Y	-1.7±2.5 (1.2)	0.80(0.68-0.90)	<0.001

5 Trials angles

Upright Standing			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	12.0±5.7 (2.1)	0.88(0.80-0.94)	<0.001
R Knee X	8.9±5.4 (2.1)	0.87(0.78-0.94)	<0.001
R Pelvis X	11.9±3.9 (1.1)	0.91(0.85-0.96)	<0.001
R Pelvis Y	-1.1±2.8 (1.0)	0.88(0.80-0.94)	<0.001
R Spine X	-14.7±5.5 (1.4)	0.94(0.89-0.97)	<0.001
R Thorax X	-2.7±3.9 (1.2)	0.91(0.84-0.96)	<0.001
R Thorax Y	-1.9±1.5 (1.4)	0.51(0.32-0.72)	<0.001

Anterior Trunk Sway			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	21.7±5.6 (2.8)	0.79(0.66-0.89)	<0.001
R Knee X	13.4±5.8 (2.4)	0.84(0.74-0.92)	<0.001
R Pelvis X	15.6±4.4 (2.0)	0.83(0.71-0.91)	<0.001
R Pelvis Y	0.1±3.2 (1.4)	0.85(0.74-0.92)	<0.001
R Spine X	1.7±8.6 (2.6)	0.93(0.86-0.97)	<0.001
R Thorax X	17.3±6.7 (2.5)	0.89(0.80-0.95)	<0.001
R Thorax Y	-1.7±2.4 (1.2)	0.80(0.66-0.90)	<0.001

4 Trials angles

Upright Standing			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	11.9±5.7 (2.3)	0.86(0.76-0.93)	<0.001
R Knee X	8.8±5.5 (2.1)	0.87(0.77-0.94)	<0.001
R Pelvis X	11.7±3.9 (1.1)	0.92(0.85-0.96)	<0.001
R Pelvis Y	-1.1±2.9 (1.0)	0.89(0.80-0.95)	<0.001
R Spine X	-14.7±5.6 (1.5)	0.94(0.88-0.97)	<0.001
R Thorax X	-2.8±4.0 (1.2)	0.91(0.84-0.96)	<0.001
R Thorax Y	-1.9±1.6 (1.5)	0.48(0.27-0.70)	<0.001

Anterior Trunk Sway			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	21.7±5.3 (2.7)	0.77(0.63-0.89)	<0.001
R Knee X	13.5±5.6 (2.5)	0.83(0.71-0.92)	<0.001
R Pelvis X	15.6±4.2 (1.8)	0.84(0.72-0.92)	<0.001
R Pelvis Y	0.1±3.2 (1.4)	0.84(0.72-0.92)	<0.001
R Spine X	1.6±8.5 (2.5)	0.92(0.86-0.96)	<0.001
R Thorax X	17.2±6.8 (2.7)	0.87(0.77-0.94)	<0.001
R Thorax Y	-1.6±2.3 (1.2)	0.78(0.62-0.89)	<0.001

3 Trials angles

Upright Standing			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	11.8±5.7 (2.6)	0.82(0.68-0.91)	<0.001
R Knee X	8.8±5.4 (2.2)	0.85(0.72-0.93)	<0.001
R Pelvis X	11.6±4.0 (1.2)	0.92(0.84-0.96)	<0.001
R Pelvis Y	-1.0±2.9 (1.0)	0.90(0.81-0.95)	<0.001
R Spine X	-14.6±5.6 (1.5)	0.93(0.87-0.97)	<0.001
R Thorax X	-2.9±4.0 (1.2)	0.90(0.82-0.96)	<0.001
R Thorax Y	-1.8±1.8 (1.4)	0.56(0.32-0.76)	<0.001

Anterior Trunk Sway			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	21.5±5.3 (2.7)	0.77(0.60-0.89)	<0.001
R Knee X	13.3±5.5 (2.3)	0.84(0.70-0.92)	<0.001
R Pelvis X	15.5±4.2 (1.7)	0.85(0.73-0.93)	<0.001
R Pelvis Y	0.1±3.3 (1.4)	0.85(0.72-0.93)	<0.001
R Spine X	1.7±8.6 (2.2)	0.94(0.88-0.97)	<0.001
R Thorax X	17.1±7.1 (2.7)	0.88(0.77-0.94)	<0.001
R Thorax Y	-1.5±2.2 (1.2)	0.74(0.54-0.87)	<0.001

2 Trials angles

Upright Standing			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	11.9±6.0 (1.6)	.93(0.84-0.97)	<0.001
R Knee X	8.9±5.4 (1.8)	.89(0.75-0.95)	<0.001
R Pelvis X	11.4±4.1 (1.1)	.93(0.83-0.97)	<0.001
R Pelvis Y	-1.0±2.9 (1.1)	.87(0.71-0.94)	<0.001
R Spine X	-14.5±5.9 (1.2)	.96(0.91-0.98)	<0.001
R Thorax X	-3.1±3.9 (1.3)	.89(0.76-0.95)	<0.001
R Thorax Y	-2.0±1.8 (1.4)	.50(0.13-0.75)	0.005

Anterior Trunk Sway			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	21.2±5.1 (2.2)	.82(0.62-0.92)	<0.001
R Knee X	12.9±5.6 (1.9)	.89(0.76-0.95)	<0.001
R Pelvis X	15.4±4.2 (1.4)	.88(0.73-0.95)	<0.001
R Pelvis Y	0.1±3.5 (1.1)	.90(0.77-0.96)	<0.001
R Spine X	1.7±8.7 (2.2)	.94(0.87-0.98)	<0.001
R Thorax X	17.1±7.5 (2.9)	.87(0.70-0.94)	<0.001
R Thorax Y	-1.4±2.2 (1.1)	.75(0.49-0.89)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.9±6.8 (2.7)	0.86(0.77-0.93)	<0.001
R Knee X	11.7±5.6 (2.0)	0.88(0.79-0.94)	<0.001
R Pelvis X	6.6±4.6 (1.8)	0.86(0.76-0.93)	<0.001
R Pelvis Y	0.1±2.6 (1.2)	0.82(0.71-0.91)	<0.001
R Spine X	-20.5±7.3 (1.8)	0.94(0.89-0.97)	<0.001
R Thorax X	-13.9±4.2 (1.7)	0.84(0.74-0.92)	<0.001
R Thorax Y	-2.1±2.0 (1.1)	0.72(0.56-0.85)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.8±6.7 (2.6)	0.86(0.76-0.93)	<0.001
R Knee X	11.6±5.6 (2.0)	0.89(0.80-0.94)	<0.001
R Pelvis X	6.6±4.6 (1.8)	0.86(0.76-0.93)	<0.001
R Pelvis Y	0.2±2.5 (1.2)	0.81(0.69-0.91)	<0.001
R Spine X	-20.4±7.4 (1.8)	0.95(0.90-0.97)	<0.001
R Thorax X	-13.7±4.1 (1.7)	0.85(0.75-0.93)	<0.001
R Thorax Y	-2.0±1.9 (1.0)	0.76(0.62-0.88)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.8±6.4 (2.7)	0.84(0.72-0.92)	<0.001
R Knee X	11.6±5.5 (1.9)	0.88(0.79-0.94)	<0.001
R Pelvis X	6.6±4.5 (1.8)	0.85(0.74-0.93)	<0.001
R Pelvis Y	0.3±2.5 (1.2)	0.80(0.66-0.90)	<0.001
R Spine X	-20.3±7.5 (1.5)	0.96(0.92-0.98)	<0.001
R Thorax X	-13.8±4.2 (1.6)	0.87(0.77-0.94)	<0.001
R Thorax Y	-1.9±1.9 (1.0)	0.79(0.64-0.90)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.5±6.2 (2.6)	0.84(0.71-0.92)	<0.001
R Knee X	11.4±5.5 (1.9)	0.88(0.77-0.94)	<0.001
R Pelvis X	6.4±4.6 (1.7)	0.86(0.74-0.94)	<0.001
R Pelvis Y	0.4±2.5 (1.1)	0.84(0.70-0.92)	<0.001
R Spine X	-20.1±7.6 (1.4)	0.96(0.93-0.98)	<0.001
R Thorax X	-13.8±4.4 (1.4)	0.91(0.82-0.96)	<0.001
R Thorax Y	-2.0±1.8 (1.0)	0.76(0.57-0.88)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.1±6.6 (2.1)	.91(0.79-0.96)	<0.001
R Knee X	11.1±5.6 (1.4)	.94(0.87-0.98)	<0.001
R Pelvis X	6.1±4.9 (1.5)	.90(0.77-0.96)	<0.001
R Pelvis Y	0.4±2.4 (1.1)	.80(0.58-0.91)	<0.001
R Spine X	-19.9±7.7 (1.5)	.96(0.91-0.99)	<0.001
R Thorax X	-13.8±4.2 (1.4)	.90(0.77-0.96)	<0.001
R Thorax Y	-1.9±1.9 (1.3)	.64(0.29-0.84)	0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.8±6.0 (2.5)	0.83(0.72-0.92)	<0.001
R Knee X	12.0±5.6 (2.4)	0.85(0.74-0.92)	<0.001
R Pelvis X	18.9±3.2 (1.8)	0.76(0.62-0.87)	<0.001
R Pelvis Y	-0.3±2.7 (1.3)	0.82(0.71-0.91)	<0.001
R Spine X	-23.5±5.7 (1.9)	0.90(0.83-0.95)	<0.001
R Thorax X	-4.6±4.3 (1.7)	0.87(0.78-0.94)	<0.001
R Thorax Y	-2.2±2.5 (1.0)	0.87(0.78-0.94)	<0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.7±6.1 (2.5)	0.84(0.73-0.92)	<0.001
R Knee X	12.1±5.6 (2.3)	0.85(0.75-0.93)	<0.001
R Pelvis X	18.8±3.3 (1.8)	0.77(0.63-0.88)	<0.001
R Pelvis Y	-0.3±2.7 (1.3)	0.82(0.70-0.91)	<0.001
R Spine X	-23.4±5.8 (1.9)	0.91(0.83-0.95)	<0.001
R Thorax X	-4.6±4.3 (1.6)	0.88(0.79-0.94)	<0.001
R Thorax Y	-2.1±2.5 (0.9)	0.88(0.79-0.94)	<0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.6±6.2 (2.4)	0.85(0.73-0.93)	<0.001
R Knee X	11.9±5.5 (2.4)	0.84(0.72-0.92)	<0.001
R Pelvis X	18.7±3.4 (1.7)	0.80(0.66-0.90)	<0.001
R Pelvis Y	-0.3±2.8 (1.2)	0.84(0.72-0.92)	<0.001
R Spine X	-23.3±5.9 (1.6)	0.93(0.87-0.97)	<0.001
R Thorax X	-4.7±4.3 (1.6)	0.89(0.80-0.95)	<0.001
R Thorax Y	-2.1±2.4 (0.7)	0.91(0.84-0.96)	<0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.3±6.2 (2.2)	0.87(0.76-0.94)	<0.001
R Knee X	11.7±5.2 (2.5)	0.81(0.65-0.91)	<0.001
R Pelvis X	18.6±3.6 (1.6)	0.83(0.68-0.92)	<0.001
R Pelvis Y	-0.3±2.7 (1.3)	0.80(0.64-0.90)	<0.001
R Spine X	-23.3±5.9 (1.6)	0.93(0.87-0.97)	<0.001
R Thorax X	-4.7±4.4 (1.7)	0.87(0.76-0.94)	<0.001
R Thorax Y	-2.0±2.4 (0.7)	0.91(0.83-0.96)	<0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.2±6.3 (2.3)	.88(0.73-0.95)	<0.001
R Knee X	11.6±5.3 (2.3)	.84(0.65-0.93)	<0.001
R Pelvis X	18.6±3.6 (1.5)	.83(0.63-0.92)	<0.001
R Pelvis Y	-0.2±2.9 (1.1)	.87(0.71-0.94)	<0.001
R Spine X	-23.2±5.8 (1.6)	.93(0.85-0.97)	<0.001
R Thorax X	-4.6±4.3 (1.8)	.84(0.66-0.93)	<0.001
R Thorax Y	-2.0±2.3 (0.7)	.90(0.78-0.96)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.4±6.2 (2.1)	0.89(0.81-0.94)	<0.001
R Knee X	13.0±5.4 (1.9)	0.89(0.81-0.94)	<0.001
R Pelvis X	3.8±4.4 (1.6)	0.87(0.78-0.93)	<0.001
R Pelvis Y	-1.4±2.5 (1.1)	0.84(0.73-0.92)	<0.001
R Spine X	-5.3±6.9 (2.1)	0.91(0.85-0.96)	<0.001
R Thorax X	-1.5±4.4 (1.6)	0.89(0.81-0.95)	<0.001
R Thorax Y	-1.3±2.3 (1.2)	0.79(0.66-0.89)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.1±6.1 (1.9)	0.91(0.85-0.96)	<0.001
R Knee X	13.0±5.5 (1.8)	0.90(0.83-0.95)	<0.001
R Pelvis X	3.6±4.4 (1.5)	0.89(0.81-0.94)	<0.001
R Pelvis Y	-1.5±2.5 (1.1)	0.83(0.72-0.91)	<0.001
R Spine X	-5.2±7.0 (2.1)	0.92(0.86-0.96)	<0.001
R Thorax X	-1.6±4.4 (1.6)	0.88(0.79-0.94)	<0.001
R Thorax Y	-1.3±2.3 (1.2)	0.77(0.63-0.89)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.0±5.9 (1.8)	0.92(0.85-0.96)	<0.001
R Knee X	13.0±5.5 (1.6)	0.92(0.86-0.96)	<0.001
R Pelvis X	3.5±4.4 (1.4)	0.90(0.82-0.95)	<0.001
R Pelvis Y	-1.5±2.5 (1.1)	0.85(0.73-0.92)	<0.001
R Spine X	-5.1±7.1 (2.0)	0.93(0.86-0.97)	<0.001
R Thorax X	-1.6±4.4 (1.6)	0.89(0.79-0.95)	<0.001
R Thorax Y	-1.4±2.4 (1.3)	0.77(0.61-0.88)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.0±5.9 (1.8)	0.92(0.85-0.96)	<0.001
R Knee X	13.2±5.7 (1.5)	0.93(0.87-0.97)	<0.001
R Pelvis X	3.3±4.5 (1.4)	0.92(0.84-0.96)	<0.001
R Pelvis Y	-1.6±2.6 (1.1)	0.84(0.71-0.92)	<0.001
R Spine X	-5.0±7.3 (1.8)	0.94(0.89-0.97)	<0.001
R Thorax X	-1.7±4.4 (1.4)	0.91(0.83-0.96)	<0.001
R Thorax Y	-1.3±2.3 (1.3)	0.73(0.53-0.87)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.0±5.6 (1.8)	.90(0.78-0.96)	<0.001
R Knee X	13.2±5.7 (1.4)	.95(0.87-0.98)	<0.001
R Pelvis X	3.2±4.5 (1.6)	.89(0.75-0.95)	<0.001
R Pelvis Y	-1.5±2.7 (0.9)	.90(0.77-0.96)	<0.001
R Spine X	-4.8±7.5 (2.1)	.93(0.84-0.97)	<0.001
R Thorax X	-1.7±4.6 (1.4)	.91(0.79-0.96)	<0.001
R Thorax Y	-1.2±2.2 (1.2)	.76(0.50-0.89)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	14.3±5.8 (1.7)	0.90(0.82-0.95)	<0.001
R Knee X	11.1±5.9 (1.9)	0.90(0.83-0.95)	<0.001
R Pelvis X	12.6±4.3 (1.3)	0.90(0.83-0.95)	<0.001
R Pelvis Y	0.3±3.1 (1.5)	0.81(0.70-0.90)	<0.001
R Spine X	-15.8±7.2 (1.6)	0.95(0.91-0.97)	<0.001
R Thorax X	-3.6±4.1 (1.3)	0.90(0.83-0.95)	<0.001
R Thorax Y	10.3±3.3 (2.1)	0.71(0.56-0.85)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	14.2±5.8 (1.7)	0.89(0.80-0.95)	<0.001
R Knee X	11.1±5.9 (1.7)	0.91(0.85-0.96)	<0.001
R Pelvis X	12.5±4.3 (1.3)	0.89(0.81-0.95)	<0.001
R Pelvis Y	0.3±3.1 (1.4)	0.83(0.72-0.92)	<0.001
R Spine X	-15.8±7.2 (1.7)	0.95(0.91-0.97)	<0.001
R Thorax X	-3.7±4.1 (1.3)	0.90(0.82-0.95)	<0.001
R Thorax Y	10.4±3.3 (1.9)	0.73(0.58-0.86)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	14.1±6.0 (1.7)	0.90(0.79-0.96)	<0.001
R Knee X	11.0±5.9 (1.7)	0.91(0.84-0.96)	<0.001
R Pelvis X	12.4±4.4 (1.3)	0.90(0.80-0.95)	<0.001
R Pelvis Y	0.3±3.0 (1.3)	0.84(0.72-0.92)	<0.001
R Spine X	-15.8±7.3 (1.7)	0.95(0.90-0.98)	<0.001
R Thorax X	-3.8±4.0 (1.4)	0.89(0.80-0.95)	<0.001
R Thorax Y	10.3±3.5 (1.9)	0.75(0.59-0.87)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	13.8±5.9 (1.5)	0.91(0.75-0.96)	<0.001
R Knee X	10.8±5.9 (1.9)	0.90(0.80-0.95)	<0.001
R Pelvis X	12.2±4.5 (1.2)	0.91(0.79-0.96)	<0.001
R Pelvis Y	0.4±2.9 (1.3)	0.83(0.69-0.92)	<0.001
R Spine X	-15.8±7.5 (1.6)	0.95(0.90-0.98)	<0.001
R Thorax X	-4.0±4.0 (1.4)	0.89(0.79-0.95)	<0.001
R Thorax Y	10.2±3.6 (1.9)	0.75(0.57-0.88)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	13.2±5.9 (1.5)	.92(0.76-0.97)	<0.001
R Knee X	10.6±5.8 (2.0)	.88(0.72-0.95)	<0.001
R Pelvis X	11.8±4.6 (1.2)	.93(0.85-0.97)	<0.001
R Pelvis Y	0.5±3.0 (1.3)	.84(0.66-0.93)	<0.001
R Spine X	-15.6±7.6 (1.6)	.95(0.89-0.98)	<0.001
R Thorax X	-4.1±3.9 (1.5)	.87(0.72-0.95)	<0.001
R Thorax Y	9.9±4.0 (1.8)	.79(0.55-0.91)	<0.001

Right Trunk Shift

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	13.9±5.7 (2.2)	0.84(0.73-0.92)	<0.001
R Knee X	10.0±5.4 (2.2)	0.84(0.73-0.92)	<0.001
R Pelvis X	12.7±4.3 (1.4)	0.89(0.82-0.95)	<0.001
R Pelvis Y	-2.2±3.1 (1.9)	0.73(0.58-0.85)	<0.001
R Spine X	-15.7±7.0 (1.7)	0.94(0.90-0.97)	<0.001
R Thorax X	-2.9±4.4 (1.3)	0.93(0.87-0.97)	<0.001
R Thorax Y	-15.6±3.5 (2.2)	0.70(0.55-0.84)	<0.001

Right Trunk Shift

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	13.8±5.6 (2.0)	0.85(0.73-0.93)	<0.001
R Knee X	9.8±5.3 (2.2)	0.83(0.72-0.92)	<0.001
R Pelvis X	12.8±4.2 (1.2)	0.90(0.83-0.95)	<0.001
R Pelvis Y	-2.4±3.1 (1.8)	0.75(0.60-0.87)	<0.001
R Spine X	-15.7±6.9 (1.6)	0.95(0.91-0.98)	<0.001
R Thorax X	-2.9±4.4 (1.2)	0.93(0.88-0.97)	<0.001
R Thorax Y	-15.4±3.5 (2.2)	0.70(0.54-0.84)	<0.001

Right Trunk Shift

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	13.6±5.4 (2.0)	0.85(0.71-0.93)	<0.001
R Knee X	9.6±5.4 (2.2)	0.84(0.72-0.92)	<0.001
R Pelvis X	12.7±4.2 (1.2)	0.91(0.82-0.96)	<0.001
R Pelvis Y	-2.3±3.2 (1.8)	0.74(0.58-0.87)	<0.001
R Spine X	-15.7±7.0 (1.6)	0.95(0.90-0.98)	<0.001
R Thorax X	-2.9±4.5 (1.3)	0.92(0.86-0.96)	<0.001
R Thorax Y	-15.3±3.5 (2.3)	0.69(0.51-0.84)	<0.001

Right Trunk Shift

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	13.3±5.3 (2.0)	0.83(0.64-0.92)	<0.001
R Knee X	9.4±5.3 (2.1)	0.84(0.70-0.93)	<0.001
R Pelvis X	12.6±4.0 (1.2)	0.89(0.76-0.95)	<0.001
R Pelvis Y	-2.4±3.3 (1.8)	0.76(0.57-0.88)	<0.001
R Spine X	-15.6±7.0 (1.6)	0.95(0.90-0.98)	<0.001
R Thorax X	-2.9±4.5 (1.4)	0.92(0.84-0.96)	<0.001
R Thorax Y	-15.1±3.9 (2.3)	0.71(0.51-0.86)	<0.001

Right Trunk Shift

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	12.7±5.5 (1.9)	.85(0.53-0.94)	<0.001
R Knee X	9.1±5.2 (2.0)	.84(0.63-0.94)	<0.001
R Pelvis X	12.2±4.1 (1.0)	.93(0.76-0.97)	<0.001
R Pelvis Y	-2.2±3.6 (1.6)	.82(0.62-0.92)	<0.001
R Spine X	-15.4±7.0 (1.5)	.95(0.89-0.98)	<0.001
R Thorax X	-3.0±4.3 (1.2)	.93(0.84-0.97)	<0.001
R Thorax Y	-14.9±4.6 (2.0)	.83(0.63-0.92)	<0.001

Lateral Pelvic Drop

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.5±7.0 (1.7)	0.93(0.88-0.97)	<0.001
R Knee X	10.7±7.7 (1.8)	0.95(0.91-0.98)	<0.001
R Pelvis X	13.7±4.4 (1.2)	0.91(0.84-0.96)	<0.001
R Pelvis Y	6.4±2.9 (1.1)	0.84(0.72-0.92)	<0.001
R Spine X	-16.5±6.7 (4.0)	0.74(0.58-0.86)	<0.001
R Thorax X	-4.0±4.8 (2.1)	0.83(0.72-0.92)	<0.001
R Thorax Y	-1.7±3.1 (2.8)	0.54(0.36-0.74)	<0.001

Lateral Pelvic Drop

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.3±6.9 (1.7)	0.94(0.88-0.97)	<0.001
R Knee X	10.8±7.7 (1.8)	0.95(0.91-0.98)	<0.001
R Pelvis X	13.5±4.3 (1.2)	0.92(0.85-0.96)	<0.001
R Pelvis Y	6.3±3.0 (1.0)	0.85(0.75-0.93)	<0.001
R Spine X	-16.3±6.6 (4.2)	0.71(0.55-0.85)	<0.001
R Thorax X	-4.2±4.9 (2.2)	0.83(0.72-0.92)	<0.001
R Thorax Y	-1.9±3.4 (2.8)	0.59(0.39-0.77)	<0.001

Lateral Pelvic Drop

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.1±6.9 (1.8)	0.93(0.87-0.97)	<0.001
R Knee X	10.8±7.7 (1.8)	0.95(0.91-0.98)	<0.001
R Pelvis X	13.4±4.4 (1.2)	0.92(0.85-0.96)	<0.001
R Pelvis Y	6.2±3.0 (1.1)	0.85(0.74-0.93)	<0.001
R Spine X	-16.0±6.7 (4.4)	0.68(0.49-0.84)	<0.001
R Thorax X	-4.4±5.0 (2.2)	0.83(0.71-0.92)	<0.001
R Thorax Y	-2.1±3.7 (2.8)	0.64(0.43-0.81)	<0.001

Lateral Pelvic Drop

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.1±6.9 (1.8)	0.93(0.85-0.97)	<0.001
R Knee X	10.9±7.7 (1.7)	0.96(0.91-0.98)	<0.001
R Pelvis X	13.3±4.4 (1.3)	0.91(0.81-0.96)	<0.001
R Pelvis Y	6.2±2.9 (1.0)	0.86(0.73-0.94)	<0.001
R Spine X	-15.9±7.0 (4.8)	0.65(0.42-0.83)	<0.001
R Thorax X	-4.3±5.1 (2.4)	0.82(0.66-0.92)	<0.001
R Thorax Y	-2.0±3.5 (2.8)	0.57(0.31-0.78)	<0.001

Lateral Pelvic Drop

Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	14.9±6.8 (1.4)	.95(0.85-0.98)	<0.001
R Knee X	11.0±7.5 (1.4)	.97(0.92-0.99)	<0.001
R Pelvis X	13.0±4.5 (1.0)	.94(0.81-0.98)	<0.001
R Pelvis Y	5.9±2.9 (1.1)	.84(0.65-0.93)	<0.001
R Spine X	-15.5±7.5 (5.5)	.58(0.21-0.81)	0.003
R Thorax X	-4.4±4.8 (2.7)	.75(0.47-0.89)	<0.001
R Thorax Y	-2.0±3.3 (3.3)	.36(-0.11-0.69)	0.061

Lateral Pelvic Raise			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.6±7.2 (1.6)	0.95(0.92-0.98)	<0.001
R Knee X	9.9±6.0 (2.2)	0.87(0.79-0.94)	<0.001
R Pelvis X	14.6±4.5 (1.3)	0.92(0.86-0.96)	<0.001
R Pelvis Y	-7.6±2.7 (1.5)	0.75(0.61-0.87)	<0.001
R Spine X	-17.8±7.0 (1.6)	0.95(0.90-0.97)	<0.001
R Thorax X	-3.8±4.4 (1.3)	0.93(0.87-0.96)	<0.001
R Thorax Y	-2.1±2.7 (2.1)	0.63(0.45-0.79)	<0.001

Lateral Pelvic Raise			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.5±7.2 (1.6)	0.95(0.91-0.98)	<0.001
R Knee X	9.9±5.9 (2.3)	0.86(0.77-0.93)	<0.001
R Pelvis X	14.4±4.5 (1.3)	0.92(0.86-0.96)	<0.001
R Pelvis Y	-7.7±2.7 (1.4)	0.79(0.66-0.89)	<0.001
R Spine X	-18.0±7.3 (1.4)	0.96(0.93-0.98)	<0.001
R Thorax X	-4.0±4.6 (1.2)	0.94(0.89-0.97)	<0.001
R Thorax Y	-2.1±2.7 (2.1)	0.59(0.40-0.77)	<0.001

Lateral Pelvic Raise			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.6±7.1 (1.6)	0.95(0.91-0.98)	<0.001
R Knee X	10.1±5.9 (2.0)	0.89(0.81-0.95)	<0.001
R Pelvis X	14.3±4.5 (1.3)	0.92(0.85-0.96)	<0.001
R Pelvis Y	-7.6±2.7 (1.2)	0.83(0.70-0.91)	<0.001
R Spine X	-17.9±7.5 (1.4)	0.96(0.93-0.98)	<0.001
R Thorax X	-4.0±4.7 (1.2)	0.94(0.88-0.97)	<0.001
R Thorax Y	-2.0±2.7 (2.1)	0.60(0.39-0.78)	<0.001

Lateral Pelvic Raise			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.7±6.9 (1.5)	0.95(0.91-0.98)	<0.001
R Knee X	10.1±5.8 (2.3)	0.86(0.75-0.94)	<0.001
R Pelvis X	14.4±4.5 (1.2)	0.93(0.86-0.97)	<0.001
R Pelvis Y	-7.6±2.8 (1.3)	0.83(0.69-0.92)	<0.001
R Spine X	-17.8±7.7 (1.2)	0.97(0.95-0.99)	<0.001
R Thorax X	-4.0±4.9 (1.2)	0.95(0.89-0.97)	<0.001
R Thorax Y	-1.9±3.0 (2.0)	0.66(0.44-0.83)	<0.001

Lateral Pelvic Raise			
Angle	Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	15.8±7.0 (1.4)	.96(0.90-0.98)	<0.001
R Knee X	10.3±6.2 (1.9)	.91(0.80-0.96)	<0.001
R Pelvis X	14.2±4.4 (1.2)	.93(0.83-0.97)	<0.001
R Pelvis Y	-7.6±2.8 (1.2)	.82(0.62-0.92)	<0.001
R Spine X	-17.8±7.9 (0.9)	.98(0.96-0.99)	<0.001
R Thorax X	-4.1±5.0 (1.0)	.96(0.91-0.98)	<0.001
R Thorax Y	-1.8±3.2 (2.1)	.66(0.34-0.84)	<0.001

Appendix I. EMG Reliability repeated measures

6 Trials EMG

Upright Standing			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.87 ± 1.80(2.46)	0.29(011-0.52)	<0.001
BF	18.76 ± 22.77(7.93)	0.90(0.82-0.95)	<0.001
Gmax	9.25 ± 7.12(2.65)	0.87(0.77-0.93)	<0.001
Gmed	25.08 ± 18.34(3.15)	0.97(0.94-0.98)	<0.001
RF	26.28 ± 27.93(10.03)	0.88(0.79-0.94)	<0.001
ST	17.71 ± 12.68(9.41)	0.64(0.47-0.80)	<0.001
TFL	47.96 ± 31.09(11.78)	0.89(0.80-0.94)	<0.001
VL	42.71 ± 21.39(10.24)	0.80(0.68-0.90)	<0.001

Anterior Trunk Sway			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.40 ± 4.62(0.84)	0.97(0.95-0.99)	<0.001
BF	50.19 ± 30.29(12.34)	0.87(0.77-0.93)	<0.001
Gmax	20.52 ± 12.08(3.29)	0.93(0.88-0.97)	<0.001
Gmed	29.99 ± 18.40(4.63)	0.96(0.93-0.98)	<0.001
RF	12.71 ± 12.93(4.48)	0.94(0.88-0.97)	<0.001
ST	45.88 ± 22.37(7.95)	0.88(0.80-0.94)	<0.001
TFL	26.62 ± 15.79(5.48)	0.87(0.78-0.94)	<0.001
VL	47.19 ± 21.45(10.07)	0.84(0.74-0.92)	<0.001

5 Trials EMG

Upright Standing			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.88 ± 1.99(2.57)	0.23(0.03-0.48)	0.009
BF	18.93 ± 22.96(7.78)	0.89(0.80-0.95)	<0.001
Gmax	9.23 ± 7.09(2.75)	0.85(0.74-0.93)	<0.001
Gmed	24.98 ± 18.41(3.36)	0.96(0.93-0.98)	<0.001
RF	25.93 ± 26.86(9.91)	0.85(0.74-0.93)	<0.001
ST	18.35 ± 13.34(9.46)	0.63(0.44-0.80)	<0.001
TFL	47.43 ± 30.69(10.83)	0.88(0.79-0.94)	<0.001
VL	42.45 ± 20.50(9.88)	0.79(0.65-0.89)	<0.001

Anterior Trunk Sway			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.37 ± 4.52(0.80)	0.97(0.94-0.98)	<0.001
BF	50.58 ± 31.66(12.18)	0.88(0.79-0.94)	<0.001
Gmax	20.36 ± 11.94(3.15)	0.94(0.89-0.97)	<0.001
Gmed	30.07 ± 19.04(3.91)	0.97(0.93-0.98)	<0.001
RF	13.06 ± 14.07(3.67)	0.93(0.88-0.97)	<0.001
ST	46.14 ± 22.93(8.30)	0.87(0.78-0.94)	<0.001
TFL	26.68 ± 15.60(5.94)	0.85(0.73-0.92)	<0.001
VL	47.15 ± 20.84(8.85)	0.83(0.70-0.91)	<0.001

4 Trials EMG

Upright Standing			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.89 ± 1.99(2.70)	0.27(0.02-0.56)	0.018
BF	18.71 ± 21.97(7.72)	0.87(0.75-0.94)	<0.001
Gmax	9.16 ± 7.07(2.89)	0.83(0.69-0.92)	<0.001
Gmed	24.96 ± 18.70(3.58)	0.97(0.94-0.99)	<0.001
RF	25.59 ± 26.51(10.81)	0.81(0.65-0.91)	<0.001
ST	18.90 ± 13.80(9.84)	0.67(0.45-0.83)	<0.001
TFL	47.67 ± 30.91(11.08)	0.88(0.77-0.94)	<0.001
VL	42.57 ± 21.09(10.60)	0.81(0.66-0.91)	<0.001

Anterior Trunk Sway			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.38 ± 4.40(0.80)	0.97(0.94-0.99)	<0.001
BF	50.69 ± 31.48(11.47)	0.86(0.74-0.93)	<0.001
Gmax	20.35 ± 11.97(2.93)	0.96(0.93-0.98)	<0.001
Gmed	29.83 ± 18.59(3.52)	0.96(0.92-0.98)	<0.001
RF	12.92 ± 13.44(3.60)	0.93(0.87-0.97)	<0.001
ST	46.50 ± 22.76(8.51)	0.91(0.83-0.96)	<0.001
TFL	26.52 ± 15.06(6.32)	0.82(0.67-0.91)	<0.001
VL	47.89 ± 21.44(9.60)	0.80(0.64-0.90)	<0.001

3 Trials EMG

Upright Standing			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.82±2.11 (2.51)	0.28(0.02-0.56)	<0.001
BF	18.43±21.33 (8.19)	0.87(0.76-0.94)	<0.001
Gmax	9.04±6.80 (3.00)	0.83(0.70-0.92)	<0.001
Gmed	25.10±19.33 (3.32)	0.97(0.94-0.99)	<0.001
RF	24.84±26.58 (12.59)	0.81(0.65-0.91)	<0.001
ST	19.22±14.87 (9.74)	0.67(0.45-0.83)	<0.001
TFL	46.78±31.31 (11.40)	0.88(0.78-0.94)	<0.001
VL	42.19±22.15 (10.31)	0.81(0.66-0.91)	<0.001

Anterior Trunk Sway			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.33±4.28 (0.76)	0.97(0.94-0.99)	<0.001
BF	51.14±31.95 (12.67)	0.86(0.75-0.94)	<0.001
Gmax	20.44±11.70 (2.25)	0.96(0.93-0.98)	<0.001
Gmed	29.96±18.64 (3.85)	0.96(0.92-0.98)	<0.001
RF	13.10±14.23 (3.78)	0.93(0.87-0.97)	<0.001
ST	46.40±23.45 (7.16)	0.91(0.83-0.96)	<0.001
TFL	26.87±15.42 (6.98)	0.83(0.68-0.92)	<0.001
VL	47.83±22.43 (10.74)	0.79(0.63-0.90)	<0.001

2 Trials EMG

Upright Standing			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.02±2.93 (4.14)	0.38(-0.04-0.68)	0.039
BF	18.04±19.05 (26.94)	0.90(0.77-0.96)	<0.001
Gmax	9.15±6.62 (9.36)	0.79(0.56-0.91)	<0.001
Gmed	25.81±20.33 (28.74)	0.98(0.94-0.99)	<0.001
RF	26.01±30.83 (43.60)	0.95(0.89-0.98)	<0.001
ST	19.69±15.98 (22.60)	0.69(0.39-0.86)	0.000
TFL	47.18±31.34 (44.31)	0.85(0.67-0.93)	<0.001
VL	41.80±21.17 (29.93)	0.74(0.48-0.88)	<0.001

Anterior Trunk Sway			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.28±4.21 (5.95)	0.98(0.95-0.99)	<0.001
BF	50.76±34.23 (48.41)	0.89(0.75-0.95)	<0.001
Gmax	20.17±11.49 (16.26)	0.96(0.91-0.98)	<0.001
Gmed	29.85±19.41 (27.45)	0.98(0.96-0.99)	<0.001
RF	12.66±15.09 (21.35)	0.98(0.95-0.99)	<0.001
ST	47.01±23.45 (33.17)	0.90(0.78-0.96)	<0.001
TFL	26.48±16.33 (23.10)	0.92(0.81-0.96)	<0.001
VL	45.99±21.15 (29.92)	0.76(0.51-0.89)	<0.001

Posterior Trunk Sway

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.93 ± 4.26(1.04)	0.94(0.89-0.97)	<0.001
BF	10.76 ± 6.07(6.14)	0.51(0.32-0.71)	<0.001
Gmax	6.87 ± 5.44(1.50)	0.92(0.86-0.96)	<0.001
Gmed	22.43 ± 17.42(5.23)	0.96(0.93-0.98)	<0.001
RF	49.59 ± 44.66(15.79)	0.90(0.83-0.95)	<0.001
ST	9.04 ± 7.36(8.13)	0.36(0.18-0.59)	<0.001
TFL	71.80 ± 57.65(23.25)	0.85(0.75-0.92)	<0.001
VL	56.65 ± 29.79(13.30)	0.83(0.72-0.92)	<0.001

Posterior Trunk Sway

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.86 ± 4.13(1.04)	0.97(0.94-0.98)	<0.001
BF	10.47 ± 5.81(5.18)	0.51(0.30-0.72)	<0.001
Gmax	6.74 ± 5.29(1.54)	0.94(0.89-0.97)	<0.001
Gmed	22.53 ± 18.58(3.73)	0.97(0.94-0.99)	<0.001
RF	49.52 ± 44.56(14.55)	0.95(0.90-0.97)	<0.001
ST	9.01 ± 7.61(8.68)	0.34(0.13-0.59)	<0.001
TFL	72.10 ± 57.97(24.02)	0.85(0.74-0.93)	<0.001
VL	56.41 ± 29.46(12.92)	0.85(0.74-0.93)	<0.001

Posterior Trunk Sway

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.68 ± 4.04(0.75)	0.96(0.93-0.98)	<0.001
BF	10.76 ± 6.27(5.54)	0.53(0.28-0.75)	<0.001
Gmax	6.52 ± 5.04(1.29)	0.93(0.87-0.97)	<0.001
Gmed	22.17 ± 17.85(3.22)	0.97(0.95-0.99)	<0.001
RF	48.23 ± 42.04(9.94)	0.94(0.89-0.97)	<0.001
ST	9.15 ± 8.33(9.54)	0.33(0.07-0.60)	0.006
TFL	71.29 ± 58.96(24.36)	0.82(0.67-0.91)	<0.001
VL	56.32 ± 28.76(11.82)	0.90(0.81-0.95)	<0.001

Posterior Trunk Sway

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.68±4.01 (0.78)	0.96(0.93-0.98)	<0.001
BF	10.71±6.50 (5.36)	0.54(0.29-0.75)	<0.001
Gmax	6.34±4.84 (1.28)	0.93(0.87-0.97)	<0.001
Gmed	22.12±18.37 (2.98)	0.98(0.95-0.99)	<0.001
RF	49.04±43.38 (10.42)	0.94(0.89-0.97)	<0.001
ST	9.04±9.58 (10.54)	0.33(0.07-0.60)	<0.001
TFL	70.81±58.65 (26.74)	0.82(0.67-0.91)	<0.001
VL	57.42±30.65 (10.00)	0.90(0.81-0.95)	<0.001

Posterior Trunk Sway

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.63±3.86 (5.46)	0.98(0.95-0.99)	<0.001
BF	11.03±7.27 (10.29)	0.60(0.25-0.81)	0.001
Gmax	6.34±4.76 (6.73)	0.93(0.84-0.97)	<0.001
Gmed	22.19±18.41 (26.03)	0.98(0.95-0.99)	<0.001
RF	48.43±41.01 (58.00)	0.94(0.87-0.98)	<0.001
ST	9.73±12.20 (17.25)	0.30(-0.13-0.63)	0.087
TFL	69.20±61.35 (86.77)	0.77(0.52-0.90)	<0.001
VL	58.44±31.10 (43.99)	0.91(0.79-0.96)	<0.001

Anterior Pelvic Rotation

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.36 ± 2.09(1.44)	0.74(0.60-0.87)	<0.001
BF	17.01 ± 16.37(7.57)	0.83(0.71-0.91)	<0.001
Gmax	11.12 ± 5.60(2.15)	0.88(0.80-0.94)	<0.001
Gmed	26.84 ± 25.66(3.79)	0.98(0.96-0.99)	<0.001
RF	29.22 ± 26.59(11.16)	0.84(0.73-0.92)	<0.001
ST	13.87 ± 10.61(4.87)	0.82(0.70-0.91)	<0.001
TFL	47.50 ± 29.32(12.03)	0.84(0.74-0.92)	<0.001
VL	51.15 ± 28.21(7.39)	0.93(0.87-0.97)	<0.001

Anterior Pelvic Rotation

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.18 ± 1.88(1.07)	0.81(0.68-0.91)	<0.001
BF	16.86 ± 16.58(7.41)	0.87(0.78-0.94)	<0.001
Gmax	10.89 ± 5.60(2.03)	0.88(0.78-0.94)	<0.001
Gmed	26.74 ± 26.03(3.73)	0.98(0.97-0.99)	<0.001
RF	29.22 ± 26.48(11.28)	0.83(0.71-0.92)	<0.001
ST	13.71 ± 10.74(4.95)	0.85(0.75-0.93)	<0.001
TFL	47.87 ± 29.77(12.66)	0.81(0.68-0.91)	<0.001
VL	50.87 ± 28.10(7.69)	0.93(0.88-0.97)	<0.001

Anterior Pelvic Rotation

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.04 ± 1.74(0.82)	0.80(0.65-0.91)	<0.001
BF	17.33 ± 17.69(6.60)	0.86(0.74-0.93)	<0.001
Gmax	10.58 ± 5.46(2.02)	0.87(0.75-0.94)	<0.001
Gmed	26.73 ± 26.82(3.48)	0.99(0.97-0.99)	<0.001
RF	28.83 ± 26.54(11.61)	0.81(0.66-0.91)	<0.001
ST	13.44 ± 11.16(4.52)	0.83(0.69-0.92)	<0.001
TFL	48.44 ± 29.32(13.63)	0.85(0.72-0.93)	<0.001
VL	51.19 ± 28.72(7.64)	0.93(0.87-0.97)	<0.001

Anterior Pelvic Rotation

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.93±1.59 (0.76)	0.80(0.64-0.90)	<0.001
BF	17.12±17.69 (6.92)	0.86(0.74-0.93)	<0.001
Gmax	10.36±5.54 (2.13)	0.87(0.76-0.94)	<0.001
Gmed	26.60±26.27 (3.26)	0.99(0.97-0.99)	<0.001
RF	28.65±26.47 (12.23)	0.81(0.66-0.91)	<0.001
ST	13.31±11.25 (4.97)	0.83(0.69-0.92)	<0.001
TFL	47.53±29.38 (12.04)	0.84(0.72-0.93)	<0.001
VL	50.79±28.54 (7.55)	0.93(0.86-0.97)	<0.001

Anterior Pelvic Rotation

Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	4.90±1.47 (2.08)	0.73(0.46-0.88)	<0.001
BF	17.35±18.44 (26.07)	0.88(0.73-0.95)	<0.001
Gmax	10.35±5.41 (7.64)	0.83(0.64-0.93)	<0.001
Gmed	26.57±25.35 (35.85)	0.99(0.97-0.99)	<0.001
RF	27.60±26.59 (37.60)	0.72(0.44-0.87)	<0.001
ST	13.15±11.66 (16.49)	0.93(0.85-0.97)	<0.001
TFL	48.77±30.21 (42.72)	0.81(0.60-0.92)	<0.001
VL	50.15±26.91 (38.05)	0.92(0.78-0.97)	<0.001

Posterior Pelvic Rotation			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.10 ± 1.37(0.94)	0.63(0.46-0.80)	<0.001
BF	33.66 ± 37.26(13.75)	0.86(0.77-0.93)	<0.001
Gmax	13.58 ± 13.49(3.37)	0.93(0.88-0.97)	<0.001
Gmed	31.01 ± 24.37(10.69)	0.88(0.79-0.94)	<0.001
RF	21.82 ± 16.22(8.16)	0.82(0.71-0.91)	<0.001
ST	28.41 ± 21.47(14.37)	0.69(0.53-0.83)	<0.001
TFL	41.30 ± 30.19(14.68)	0.79(0.66-0.89)	<0.001
VL	66.16 ± 30.07(12.54)	0.86(0.76-0.93)	<0.001

Posterior Pelvic Rotation			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.09 ± 1.40(1.01)	0.60(0.40-0.78)	<0.001
BF	33.00 ± 37.09(14.47)	0.88(0.79-0.94)	<0.001
Gmax	13.51 ± 13.46(3.66)	0.93(0.87-0.97)	<0.001
Gmed	31.65 ± 26.49(9.81)	0.87(0.77-0.94)	<0.001
RF	21.48 ± 16.67(7.58)	0.82(0.69-0.91)	<0.001
ST	28.83 ± 22.53(14.62)	0.64(0.45-0.81)	<0.001
TFL	41.82 ± 29.98(14.93)	0.78(0.63-0.89)	<0.001
VL	65.80 ± 30.64(12.34)	0.86(0.75-0.93)	<0.001

Posterior Pelvic Rotation			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.11 ± 1.45(1.09)	0.56(0.31-0.77)	<0.001
BF	31.76 ± 37.46(13.46)	0.94(0.88-0.97)	<0.001
Gmax	13.25 ± 12.86(3.56)	0.93(0.86-0.97)	<0.001
Gmed	31.63 ± 27.25(10.30)	0.82(0.68-0.91)	<0.001
RF	21.10 ± 16.72(7.68)	0.89(0.80-0.95)	<0.001
ST	28.89 ± 23.12(16.26)	0.74(0.56-0.87)	<0.001
TFL	42.55 ± 30.23(15.75)	0.74(0.55-0.87)	<0.001
VL	65.80 ± 29.20(11.65)	0.90(0.82-0.96)	<0.001

Posterior Pelvic Rotation			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.10±1.51 (1.19)	0.56(0.32-0.77)	<0.001
BF	31.43±39.02 (9.92)	0.93(0.87-0.97)	<0.001
Gmax	13.17±12.44 (3.49)	0.92(0.85-0.96)	<0.001
Gmed	31.59±27.23 (12.23)	0.82(0.68-0.92)	<0.001
RF	19.90±15.76 (5.32)	0.90(0.81-0.95)	<0.001
ST	25.88±22.55 (12.55)	0.75(0.57-0.88)	<0.001
TFL	43.69±31.15 (17.49)	0.74(0.55-0.87)	<0.001
VL	65.86±28.50 (9.13)	0.90(0.82-0.96)	<0.001

Posterior Pelvic Rotation			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.25±1.73 (2.45)	0.53(0.14-0.77)	0.006
BF	33.18±41.00 (57.98)	0.95(0.88-0.98)	<0.001
Gmax	12.76±12.69 (17.94)	0.98(0.95-0.99)	<0.001
Gmed	31.87±29.58 (41.83)	0.75(0.50-0.89)	<0.001
RF	19.90±15.40 (21.77)	0.85(0.68-0.94)	<0.001
ST	26.10±24.24 (34.28)	0.84(0.66-0.93)	<0.001
TFL	41.67±29.15 (41.22)	0.80(0.57-0.91)	<0.001
VL	66.66±28.16 (39.82)	0.94(0.86-0.97)	<0.001

Left Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.01 ± 1.49(1.42)	0.51(0.32-0.71)	<0.001
BF	17.38 ± 16.93(8.58)	0.76(0.62-0.88)	<0.001
Gmax	11.74 ± 9.20(2.86)	0.91(0.83-0.95)	<0.001
Gmed	32.95 ± 23.73(4.75)	0.96(0.93-0.98)	<0.001
RF	38.81 ± 31.72(14.42)	0.83(0.72-0.92)	<0.001
ST	16.35 ± 14.26(12.46)	0.53(0.34-0.73)	<0.001
TFL	67.12 ± 39.60(19.63)	0.80(0.67-0.90)	<0.001
VL	43.82 ± 20.23(13.64)	0.66(0.49-0.81)	<0.001

Left Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.08 ± 1.63(1.46)	0.49(0.28-0.71)	<0.001
BF	17.18 ± 16.20(8.83)	0.79(0.65-0.90)	<0.001
Gmax	11.81 ± 9.14(2.93)	0.94(0.89-0.97)	<0.001
Gmed	32.84 ± 23.50(4.83)	0.97(0.95-0.99)	<0.001
RF	39.97 ± 33.39(14.60)	0.82(0.70-0.91)	<0.001
ST	16.27 ± 14.44(12.51)	0.68(0.49-0.83)	<0.001
TFL	67.40 ± 39.98(19.78)	0.81(0.67-0.90)	<0.001
VL	43.70 ± 19.26(13.21)	0.65(0.46-0.81)	<0.001

Left Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.12 ± 1.63(1.47)	0.51(0.26-0.74)	<0.001
BF	16.11 ± 14.88(7.37)	0.81(0.67-0.91)	<0.001
Gmax	11.56 ± 8.78(2.22)	0.94(0.89-0.97)	<0.001
Gmed	32.53 ± 24.10(4.11)	0.98(0.96-0.99)	<0.001
RF	39.77 ± 33.91(15.32)	0.85(0.72-0.93)	<0.001
ST	15.55 ± 14.70(9.61)	0.68(0.46-0.84)	<0.001
TFL	67.22 ± 38.38(18.23)	0.81(0.66-0.91)	<0.001
VL	43.71 ± 18.57(12.85)	0.62(0.39-0.80)	<0.001

Left Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.19±1.85 (1.57)	0.52(0.26-0.74)	<0.001
BF	16.61±16.09 (7.41)	0.82(0.67-0.91)	<0.001
Gmax	11.49±8.58 (2.12)	0.94(0.88-0.97)	<0.001
Gmed	32.81±25.22 (3.59)	0.98(0.96-0.99)	<0.001
RF	40.01±36.39 (15.01)	0.84(0.71-0.92)	<0.001
ST	16.00±15.45 (9.92)	0.68(0.47-0.84)	<0.001
TFL	66.85±39.00 (18.12)	0.81(0.67-0.91)	<0.001
VL	44.28±18.11 (12.93)	0.63(0.40-0.81)	<0.001

Left Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.27±2.13 (3.02)	0.39(-0.02-0.69)	0.032
BF	17.22±18.10 (25.59)	0.85(0.67-0.93)	<0.001
Gmax	11.45±8.27 (11.69)	0.92(0.82-0.97)	<0.001
Gmed	32.60±25.52 (36.09)	0.99(0.97-0.99)	<0.001
RF	37.47±35.10 (49.64)	0.87(0.72-0.95)	<0.001
ST	16.85±18.76 (26.53)	0.89(0.75-0.95)	<0.001
TFL	65.93±39.11 (55.32)	0.78(0.55-0.90)	<0.001
VL	44.22±19.28 (27.26)	0.72(0.43-0.87)	<0.001

Right Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.67 ± 4.41(2.09)	0.90(0.82-0.95)	<0.001
BF	16.68 ± 17.60(10.13)	0.73(0.57-0.85)	<0.001
Gmax	8.87 ± 7.35(2.35)	0.94(0.90-0.97)	<0.001
Gmed	21.73 ± 16.52(4.26)	0.94(0.89-0.97)	<0.001
RF	28.04 ± 20.93(7.69)	0.86(0.77-0.93)	<0.001
ST	12.95 ± 9.00(8.07)	0.47(0.28-0.68)	<0.001
TFL	41.70 ± 25.84(13.81)	0.74(0.59-0.87)	<0.001
VL	42.64 ± 20.76(8.82)	0.86(0.77-0.93)	<0.001

Right Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	5.85 ± 4.99(1.69)	0.90(0.82-0.95)	<0.001
BF	16.96 ± 17.30(10.26)	0.71(0.54-0.85)	<0.001
Gmax	9.10 ± 7.87(1.92)	0.95(0.90-0.97)	<0.001
Gmed	22.04 ± 17.10(4.26)	0.96(0.93-0.98)	<0.001
RF	28.49 ± 21.09(8.24)	0.85(0.74-0.93)	<0.001
ST	13.21 ± 8.98(8.57)	0.49(0.28-0.70)	<0.001
TFL	42.13 ± 25.78(14.66)	0.67(0.49-0.83)	<0.001
VL	42.75 ± 21.43(8.37)	0.86(0.76-0.93)	<0.001

Right Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.01 ± 5.22(1.72)	0.92(0.84-0.96)	<0.001
BF	17.23 ± 17.69(10.79)	0.68(0.46-0.84)	<0.001
Gmax	9.26 ± 8.13(1.95)	0.95(0.90-0.98)	<0.001
Gmed	22.42 ± 18.05(3.65)	0.96(0.91-0.98)	<0.001
RF	28.33 ± 21.15(8.60)	0.82(0.68-0.91)	<0.001
ST	13.67 ± 9.85(8.96)	0.61(0.38-0.80)	<0.001
TFL	42.21 ± 24.49(16.08)	0.64(0.41-0.81)	<0.001
VL	42.94 ± 21.42(8.47)	0.87(0.75-0.94)	<0.001

Right Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.14±5.32 (1.60)	0.92(0.84-0.96)	<0.001
BF	17.67±18.84 (12.08)	0.68(0.47-0.84)	<0.001
Gmax	9.28±8.35 (1.92)	0.95(0.90-0.98)	<0.001
Gmed	22.69±18.47 (3.91)	0.96(0.92-0.98)	<0.001
RF	27.36±19.70 (8.85)	0.83(0.69-0.92)	<0.001
ST	13.23±9.92 (7.19)	0.62(0.39-0.80)	<0.001
TFL	41.55±23.78 (16.36)	0.64(0.42-0.82)	<0.001
VL	42.76±22.03 (8.45)	0.87(0.75-0.94)	<0.001

Right Trunk Shift			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.09±5.48 (7.75)	0.97(0.92-0.99)	<0.001
BF	18.12±20.10 (28.42)	0.63(0.30-0.83)	0.001
Gmax	9.37±8.66 (12.25)	0.98(0.95-0.99)	<0.001
Gmed	22.77±20.21 (28.59)	0.99(0.98-1.00)	<0.001
RF	27.84±19.63 (27.76)	0.89(0.76-0.95)	<0.001
ST	13.55±9.81 (13.88)	0.65(0.31-0.84)	0.001
TFL	42.42±23.96 (33.88)	0.57(0.20-0.79)	0.003
VL	41.87±20.41 (28.86)	0.84(0.66-0.93)	<0.001

Lateral Pelvic Drop			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.79 ± 4.66(3.21)	0.67(0.49-0.83)	<0.001
BF	34.48 ± 28.88(11.57)	0.84(0.72-0.92)	<0.001
Gmax	8.64 ± 4.91(2.51)	0.82(0.69-0.91)	<0.001
Gmed	12.70 ± 6.87(3.19)	0.83(0.70-0.92)	<0.001
RF	17.85 ± 14.87(6.89)	0.80(0.67-0.90)	<0.001
ST	20.86 ± 15.04(7.94)	0.76(0.60-0.88)	<0.001
TFL	24.08 ± 12.63(6.07)	0.80(0.66-0.90)	<0.001
VL	52.40 ± 37.57(13.24)	0.87(0.77-0.94)	<0.001

Lateral Pelvic Drop			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	6.97 ± 4.91(3.28)	0.73(0.56-0.87)	<0.001
BF	34.78 ± 29.08(12.63)	0.85(0.73-0.93)	<0.001
Gmax	8.82 ± 5.27(2.42)	0.85(0.73-0.93)	<0.001
Gmed	13.05 ± 6.98(3.14)	0.85(0.73-0.93)	<0.001
RF	18.17 ± 15.22(7.33)	0.80(0.66-0.91)	<0.001
ST	20.73 ± 15.14(8.33)	0.73(0.56-0.87)	<0.001
TFL	24.60 ± 12.61(6.19)	0.82(0.68-0.91)	<0.001
VL	53.11 ± 37.71(14.53)	0.89(0.80-0.95)	<0.001

Lateral Pelvic Drop			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	7.19 ± 5.46(3.15)	0.81(0.66-0.91)	<0.001
BF	36.23 ± 30.30(12.68)	0.87(0.75-0.94)	<0.001
Gmax	9.15 ± 5.69(2.36)	0.91(0.83-0.96)	<0.001
Gmed	13.51 ± 7.37(3.08)	0.86(0.72-0.93)	<0.001
RF	18.63 ± 15.58(7.50)	0.89(0.78-0.95)	<0.001
ST	21.02 ± 14.87(8.61)	0.71(0.50-0.86)	<0.001
TFL	24.58 ± 12.01(5.53)	0.80(0.63-0.91)	<0.001
VL	52.75 ± 36.86(12.81)	0.94(0.87-0.97)	<0.001

Lateral Pelvic Drop			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	7.59±6.20 (2.85)	0.82(0.66-0.92)	<0.001
BF	37.98±32.78 (12.40)	0.87(0.76-0.94)	<0.001
Gmax	9.58±6.32 (1.93)	0.91(0.82-0.96)	<0.001
Gmed	13.95±7.69 (3.08)	0.86(0.73-0.93)	<0.001
RF	19.53±16.86 (5.96)	0.89(0.78-0.95)	<0.001
ST	21.27±15.09 (8.97)	0.72(0.51-0.86)	<0.001
TFL	25.27±12.02 (5.85)	0.79(0.62-0.90)	<0.001
VL	53.10±37.34 (9.67)	0.94(0.88-0.97)	<0.001

Lateral Pelvic Drop			
Muscle	Mean (mV) ± SD (SEM)	ICC (95%CI)	p-value
AL	7.78±6.88 (9.73)	0.89(0.74-0.95)	<0.001
BF	37.16±36.05 (50.98)	0.95(0.87-0.98)	<0.001
Gmax	9.96±6.91 (9.77)	0.95(0.88-0.98)	<0.001
Gmed	14.23±7.80 (11.03)	0.79(0.55-0.91)	<0.001
RF	20.14±16.58 (23.45)	0.92(0.82-0.97)	<0.001
ST	20.49±15.86 (22.44)	0.70(0.39-0.87)	0.000
TFL	25.74±12.22 (17.29)	0.79(0.54-0.91)	<0.001
VL	53.68±38.39 (54.30)	0.92(0.81-0.97)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean (mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.55 ± 1.13(0.79)	0.61(0.42-0.78)	<0.001
BF	12.45 ± 12.57(6.62)	0.81(0.69-0.90)	<0.001
Gmax	14.61 ± 14.62(3.54)	0.95(0.90-0.97)	<0.001
Gmed	37.12 ± 35.23(4.41)	0.99(0.98-0.99)	<0.001
RF	34.54 ± 27.19(12.82)	0.78(0.65-0.89)	<0.001
ST	10.10 ± 8.22(5.78)	0.63(0.45-0.79)	<0.001
TFL	82.17 ± 48.92(24.29)	0.82(0.70-0.91)	<0.001
VL	41.77 ± 20.64(10.03)	0.79(0.66-0.89)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean (mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.55 ± 1.10(0.84)	0.54(0.33-0.74)	<0.001
BF	12.72 ± 13.65(6.43)	0.88(0.78-0.94)	<0.001
Gmax	14.63 ± 14.59(3.50)	0.94(0.88-0.97)	<0.001
Gmed	37.49 ± 34.97(3.71)	0.99(0.98-1.00)	<0.001
RF	33.90 ± 26.51(13.55)	0.82(0.69-0.91)	<0.001
ST	10.18 ± 8.31(6.06)	0.60(0.40-0.78)	<0.001
TFL	82.40 ± 50.95(23.68)	0.85(0.74-0.93)	<0.001
VL	41.41 ± 20.46(10.33)	0.83(0.71-0.92)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean (mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.55 ± 1.06(0.89)	0.78(0.61-0.89)	<0.001
BF	12.68 ± 14.48(5.34)	0.93(0.85-0.97)	<0.001
Gmax	14.55 ± 14.58(3.74)	0.95(0.90-0.98)	<0.001
Gmed	37.40 ± 34.84(3.55)	0.99(0.97-0.99)	<0.001
RF	43.17 ± 26.87(12.23)	0.92(0.85-0.96)	<0.001
ST	9.78 ± 7.58(5.69)	0.74(0.55-0.87)	<0.001
TFL	79.63 ± 46.04(18.76)	0.88(0.77-0.94)	<0.001
VL	41.81 ± 20.95(9.22)	0.84(0.71-0.92)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean (mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.45±1.02 (0.52)	0.77(0.60-0.89)	<0.001
BF	12.98±15.69 (4.42)	0.92(0.84-0.96)	<0.001
Gmax	14.23±13.60 (3.05)	0.95(0.91-0.98)	<0.001
Gmed	37.17±34.48 (4.02)	0.99(0.97-0.99)	<0.001
RF	33.57±28.34 (8.19)	0.92(0.85-0.96)	<0.001
ST	9.01±7.09 (3.96)	0.75(0.56-0.88)	<0.001
TFL	79.99±48.00 (17.75)	0.88(0.77-0.94)	<0.001
VL	41.70±21.94 (9.25)	0.84(0.70-0.92)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean (mV) ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.54±1.12 (1.58)	0.84(0.65-0.93)	<0.001
BF	13.89±17.40 (24.61)	0.95(0.88-0.98)	<0.001
Gmax	14.19±13.23 (18.71)	0.97(0.93-0.99)	<0.001
Gmed	37.30±34.89 (49.34)	0.98(0.96-0.99)	<0.001
RF	34.83±29.33 (41.48)	0.95(0.88-0.98)	<0.001
ST	8.85±6.93 (9.80)	0.79(0.57-0.91)	<0.001
TFL	78.99±44.80 (63.36)	0.91(0.79-0.96)	<0.001
VL	43.13±23.88 (33.77)	0.90(0.78-0.96)	<0.001

Appendix J. Paper Submitted to BMC Musculoskeletal Disorders

The influence of changes in trunk and pelvic position during single leg standing posture on hip and thigh muscle activation in a pain free population.

Abstract

Background:

Lower limb injuries are common and relate to single leg loading and are a focus of clinical practice. The influence that trunk and pelvis posture has on lower limb muscle activation in single leg stance is unknown.

Methods:

Hip and thigh muscle activation patterns were compared in 22 asymptomatic, male subjects (20-45 years old) in paired clinically relevant test postures: Anterior Trunk Sway vs. Posterior; Anterior Pelvic Rotation vs. Posterior; Left Trunk Shift vs. Right; and Pelvic Drop vs. Raise. Surface EMG was collected from eight hip and thigh muscles calculating Root Mean Square over a stable 4 second period. EMG was normalized to an "upright standing" reference posture. Kinematic data was monitored using a 14 camera Vicon, full body plug-in Gait model (excluding upper limb and head markers). Repeated measures ANOVA was performed along with associated F tests to determine if there were significant differences in muscle activation between each measurement. An ICC value greater than 0.75 was considered a large correlation. An alpha level was set of $p<0.05$ determine significance.

Results:

Anterior Trunk Sway (compared to Posterior) increased posterior sagittal plane muscle activity with a concurrent deactivation of anterior sagittal plane muscles (p: 0.016 - <0.001). Lateral hip abductor muscles increased activation during Left Trunk Shift (compared to Right) (p :≤ 0.001). Lateral Pelvic Drop (compared to Raise) decreased activity in hip abductors and increased hamstring, adductor longus and vastus lateralis activity (p: 0.037 - <0.001).

Conclusion:

Hip and thigh muscle activity patterns in single leg stance are affected by trunk and pelvis posture. Normative kinematic and EMG data (hip and thigh) is established in asymptomatic young males. Changes in trunk position in the sagittal plane and pelvis position in the frontal plane had the greatest effect on muscle activation. This study shows clinicians should be aware that whilst hip and thigh muscle activity patterns in single leg stance can

be predictable there were also variable motor strategies displayed by individuals for some positions and this warrants further investigation as they likely are important for injury prediction.

Background

Lower limb injuries account for over 50% of injuries in athletic populations (Dick *et al.* 2007), making understanding possible mechanisms behind these injuries an important research priority. There is evidence of a relationship between single leg loading, muscle function and lower limb injuries including anterior cruciate ligament ruptures (Alentorn-Geli *et al.* 2009; Hewett *et al.* 2006), patellofemoral pain (H. R. Cichanowski *et al.* 2007b; Cowan *et al.* 2009; M. Fredericson and Yoon 2006b) hamstring muscle strains (Croisier *et al.* 2008), ilio-tibial band friction syndrome (M. Fredericson *et al.* 2000) and chronic ankle instability (Friel *et al.* 2006). Whilst most of these studies suggest that altered activation of hip and thigh muscles such as gluteus medius and gluteus maximus during single leg loading may play a role in the development of these injuries, the mechanisms behind this altered muscle function are not clear.

To date, despite single leg loading exercises being a common injury rehabilitation strategy to retrain muscle activation patterns, there is little evidence regarding how changes in trunk and pelvis position influence muscle activation patterns. There is some literature to suggest that changing posture in a sagittal plane whilst in double leg stance will change the activation of different muscles. O'Sullivan and co-workers (P. B. O'Sullivan *et al.* 2002) demonstrated differences in abdominal and back muscle activity levels when comparing active upright standing to posterior trunk sway standing. However only trunk, not hip and thigh muscle activity was recorded in this study. Wang and co-workers (Wang *et al.* 2006) measured leg, hip and trunk muscle activation during sagittal plane double leg standing postures, where the focus on movement was hip flexion and hip extension. Their results showed that with anterior trunk sway, there was an increase in hamstring and erector spinae activation (dorsal muscles), accompanied by a decrease in rectus femoris and rectus abdominus activation (ventral muscles). The opposite was found when the subject adopted a posterior trunk sway posture. Neither study evaluated single leg loading.

McCurdy and colleges compared single leg and double leg squat. They found a modified single leg squat produced higher biceps femoris and gluteus medius activity, and the double leg squat produced higher rectus femoris activity in elite female athletes(McCurdy *et al.* 2010). Troubridge (Troubridge 2000) reported a difference of activation of thigh muscles with a change in lower limb position during a double leg squat. Earl (Earl 2004) looked at the influence of three variations of hip position during a single leg stance exercise, with the addition of an external load. Electromyography (EMG) activity of three parts of gluteus medius was recorded. Their results support that alterations in hip position do influence activation of the gluteus medius muscle. In these studies, the influence of altering trunk and pelvis position was not investigated.

Two older studies (Hardcastle and Nade 1985; Inman 1947) have investigated pelvis position and muscle activation in a sagittal plane during single leg stance. They reported that moving from a "sagging" position (pelvic drop or Trendelenberg) to an elevated pelvic position, the hip abductor muscles (gluteus medius and Tensor Fascia Lata (TFL)) increased their activity.

In summary, despite what would appear to have widespread clinical application, the influence that trunk and pelvis posture has on lower limb muscle activation in single leg stance is largely unknown. The aim of this study was to investigate the influence of changes in frontal and sagittal plane positions of the trunk and pelvis on muscle activation around the hip and thigh in single leg stance in a male pain free population.

It was hypothesized that changes in both trunk and pelvic posture during single leg stance would result in predictable changes in lower limb muscle activation. Specifically, changing posture in the frontal plane would alter primarily frontal plane muscle activity, and changes of posture in the sagittal plane would alter primarily sagittal plan muscle activity.

Methods

<u>Participants</u>

Twenty two asymptomatic, male subjects aged between 20-45 years old were recruited via personal invitation and gave written informed consent to participate ensuring the rights of each subject were protected. Ethical approval was granted by the Human Research Ethics Committee of Curtin University of Technology (approval number: HR 25/2011), Perth, Australia and Aspetar Sports Medicine Hospital, Doha, Qatar. Testing took place in the biomechanical laboratories of Aspire Sports Academy, Doha, Qatar.

As body mass index (BMI) has been shown to influence EMG amplitude(Nordander *et al.* 2003) subjects were excluded if their BMI > 30. Subjects were also excluded if they: had a lower limb or back injury within the last three months that had restricted participation in their usual physical activities; or were unable to adopt and sustain the required test postures. An a priori power analysis showed that twenty subjects were required to achieve a significant difference in EMG with an alpha level of 0.05 and 80% power; accordingly 22 were recruited to allow for data loss.

Test Postures

3D Kinematic data was monitored using a 14 camera Vicon (OMG, England), Full Body Plug-in Gait model (OMG, England) (excluding upper limb and head markers), with MX-13 cameras (OMG, England) through Vicon Nexus software (OMG, England), at a sampling rate of 500 Hz.

4 pairs of common functional trunk and pelvic positions were tested. All test postures were defined relative to a reference single leg "Upright Standing" posture (**Figure 1**).

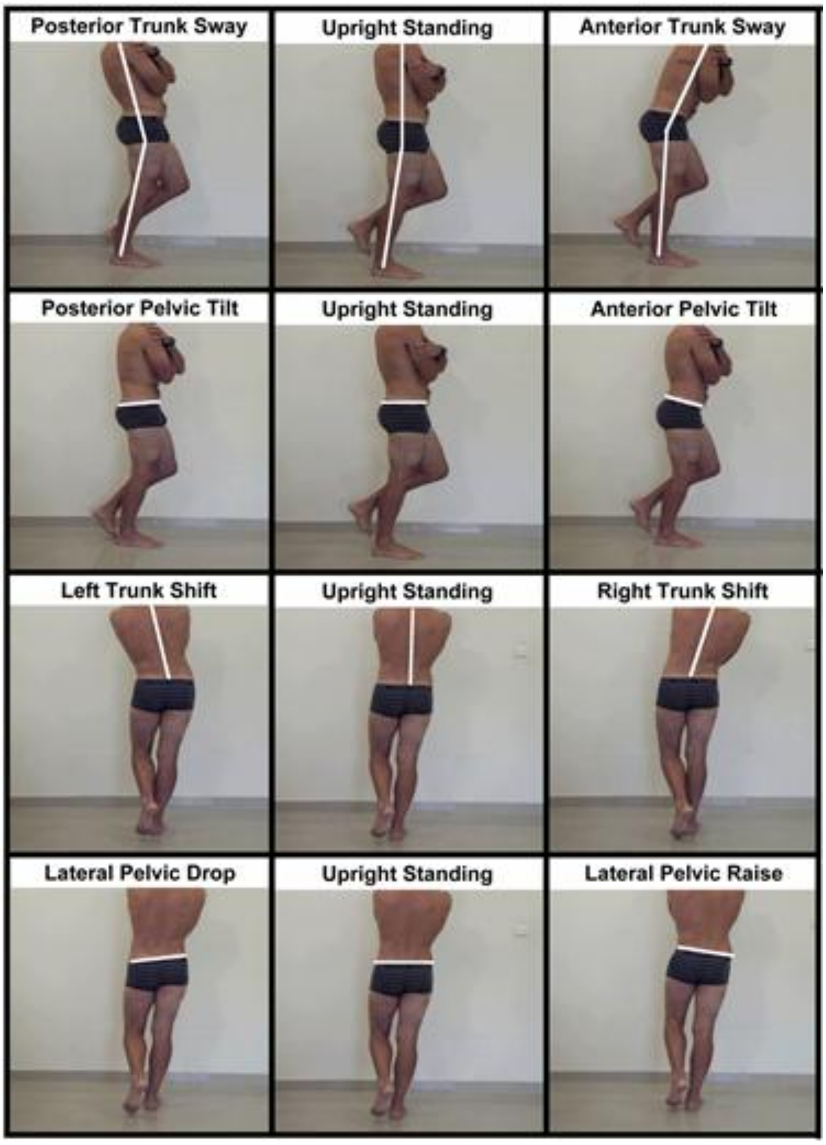


Figure 1: Depictions of each of the 4 pair wise comparison positions with the reference Upright Standing position

Upright Standing

Upright Standing was defined as a position in which the subject stood on the right leg with the right acromion, right greater trochanter, and right lateral malleolus vertically aligned (+/- 10°). The subject was instructed to unlock the right knee in slight (approximately 10°) flexion. Pelvic position was also visually monitored to ensure a neutral position in a sagittal plane and level with horizontal (i.e. no drop or raise) in the frontal plane. For each test posture, subjects stood on their right bare foot, arms folded, head stable and eyes looking forward at a fixed point. Each testing session was carried out by the same investigator. Subjects were given a visual demonstration of the required test postures, followed by consistent tactile feedback to guide appropriate test postures if required.

Pair Wise Comparison Positions

Comparisons of EMG activation were made in four paired conditions (**Figure 1**):

1. **Anterior Trunk Sway** vs. **Posterior Trunk Sway** was defined by the “Thorax Angle X” from the Full Body Plug-in Gait model. This is the position of the thorax relative to space in the sagittal plane. The Thorax Angle X from the Upright Standing posture for each subject was used as the reference angle. The Anterior Trunk Sway and Posterior Trunk Sway angles were defined as at least 15° anterior and posterior to the Upright Standing posture Thorax Angle X respectively. A positive value represents magnitude of anterior sway and a negative value represents magnitude of posterior sway.

2. **Left Trunk Shift** vs. **Right Trunk Shift** was defined by the “Thorax Angle Y”. This is the position of the thorax relative to space in the frontal plane. The Thorax Angle Y from the Upright Standing posture was used as the reference Thorax Angle. The Left Trunk Shift and Right Trunk Shift angles were defined as at least 10° left and right of the Upright Standing posture Thorax Angle Y respectively. A positive value represents magnitude of Left Trunk Shift and a negative value represents magnitude of Right Trunk Shift.

3. **Anterior Pelvic Rotation** vs. **Posterior Pelvic Rotation** was defined by the “Pelvis Angle X”. This is the position of the pelvis relative to space in the sagittal plane. The Pelvis Angle X from the Upright Standing posture was used as the reference Pelvis Angle. The Anterior Pelvic Rotation and Posterior Pelvic Rotation angles were defined as at least 5° anterior and

posterior to the Upright Standing posture Pelvic Angle respectively. A positive value represents magnitude of Anterior Pelvic Rotation and a negative value represents magnitude of Posterior Pelvic Rotation.

4. **Lateral Pelvic Drop** vs. **Lateral Pelvic Raise** was defined by the "Pelvis Angle Y". This is the position of the pelvis relative to space in the frontal plane, and the "Lateral Pelvis" makes reference to the subjects left hemi-pelvis, contra lateral to the loaded limb. The Pelvis Angle Y from the Upright Standing posture for each subject was used as the reference Pelvis Angle. The Lateral Pelvic Drop and Lateral Pelvic Raise angles were defined as at least 5° higher and lower of the Upright Standing posture Pelvis Angle respectively. A positive value represents magnitude of Lateral Pelvic Drop and a negative value represents magnitude of Lateral Pelvic Raise.

Muscle activity

Surface EMG (using electrode placement as defined by Perotto (Perotto and Delagi 2005)) of the following muscles were recorded: gluteus maximus; gluteus medius; TFL; semitendinosus; biceps femoris (long head); vastus lateralis; rectus femoris; and adductor longus.

EMG signals were recorded using integral dry reusable electrodes with an inter-electrode distance of 20 mm (Biometrics SX230, Gwent, UK). Low impedance between electrodes was obtained by abrading and cleaning the skin with emery paper and alcohol. Signals were recorded at a sampling frequency of 1000 Hz using Biometrics hardware (Biometrics DataLOG, Gwent, UK) and dedicated software. EMG signals were amplified and filtered (band pass 30 Hz – 500 Hz, gain = 1000) and muscle electrical activity was determined by calculating the mean value of the root mean square (RMS) over a stable four second period. A common earth electrode was placed over the wrist. Raw data were visually inspected for stability and consistency prior to selection of a stable four seconds of data for analysis.

EMG for each of the paired test postures was expressed as a percentage of the reference Upright Standing posture. We normalized EMG to Upright Standing representing a submaximal voluntary contraction (SubMVC) normalization method.

Six trials of each test posture were conducted with 30 seconds rest between each trial to limit the effects of fatigue. The order of test postures was selected randomly via computer generated randomization with the exception of Upright Standing, which was always performed first and formed the reference position from which the other test postures were then guided by the examiner.

Independent knee, hip, pelvis and trunk angles in the sagittal and frontal planes (Vicon Plug-in Gait model) were also monitored for consistency across trials for each test posture.

Statistical Analysis

All data were coded and analyzed using the SPSS statistical software v19.0 (SPSS inc., USA). In order to establish the reliability of the test posture angles and reliability of muscle activation in the reference upright posture and the eight test postures, intraclass correlation coefficient ($ICC_{2,1}$) was computed (Shrout and Fleiss 1979). Repeated measures ANOVA was performed along with associated F-tests to determine if there were significant differences in muscle activation between each measurement An alpha level of $p<0.05$ was set to determine significance.

Kinematic reliability

Intraclass correlation coefficient values for each of the seven joint angles across each of the nine test postures over six trials ranged from 0.54 to 0.95 ($p<0.001$) (Supplementary material 1)

EMG reliability

The ICC values for the 72 possible values (eight muscles across nine positions) ranged from 0.29-0.97 ($p<0.001$). The majority of muscles in all positions, for all subjects over six trials showed ICC values ranging from 0.75 to 0.97 with 16 exceptions. Adductor longus displayed decreased reliability during: Upright Standing; all pelvic positions; and Left Trunk Shift with mean ICC's of 0.29-0.74. Semitendinosus activity was also less repeatable with mean ICC's 0.36-0.69 during the positions of Upright Standing, Lateral Pelvic Raise, Posterior Pelvic Rotation, Left and Right Trunk Shift, and Posterior Trunk Sway. Biceps femoris activity during Posterior Trunk Sway and Right Trunk Shift had mean ICC's 0.51-0.73. Vastus lateralis during Left Trunk Shift had a mean ICC of 0.66. Tensor Fascia Lata during Right Trunk Shift had a mean ICC of 0.74. (See supplementary material 2).

Results

<u>Kinematics</u>

Pair wise comparisons of the four paired test postures demonstrated their validity based on differences between relevant criterion trunk or pelvic angles measured. **TABLE 1** shows all angles that displayed a significant difference between paired postures. Angles not mentioned experienced no significant change and therefore displayed consistency throughout testing.

TABLE 1: Mean changes in principal angles of interest during kinematic analysis of the pair wise test posture comparisons. The shaded/* angles highlight the defining angle for each of the pair wise position.

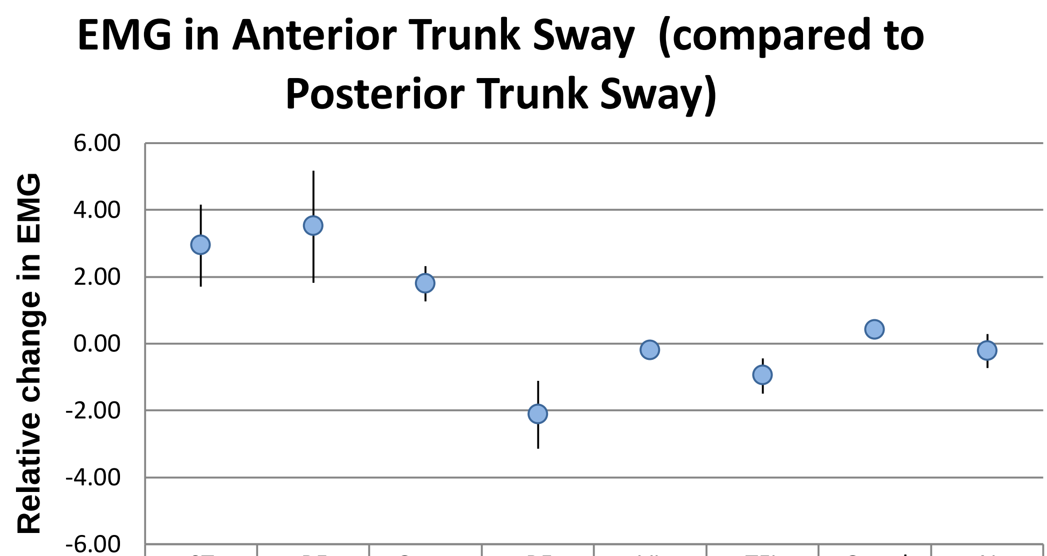
Pair wise positions	Angles	Mean change (95% CI)	P value
Anterior Trunk Sway vs. Posterior Trunk Sway	R Hip X	15° (12° - 18°)	<0.001
	R Pelvis X	9° (7° - 12°)	<0.001
	R Spine X	22° (19° - 26°)	<0.001
	R Thorax X*	**31° (28° - 34°)**	**<0.001**
Anterior Pelvic Rotation vs. Posterior Pelvic Rotation	R Hip X	16° (13° - 18°)	<0.001
	R Pelvis X*	**15° (13°- 17°)**	**<0.001**
	R Pelvis Y	1° (0° - 2°)	0.028
	R Spine X	-18° (-21 - -16°)	<0.001
	R Thorax X	-3° (-5° - -1°)	<0.001
Left Trunk Shift vs. Right Trunk Shift	R Pelvis Y	3° (1°- 4°)	<0.001
	R Thorax Y*	**26° (24° - 28°)**	**<0.001**
Pelvic Drop vs. Pelvic Raise	**R Pelvis Y***	**14° (12 - 16)**	**<0.001**

EMG

Trunk posture:

Anterior Trunk Sway vs. Posterior Trunk Sway

When comparing muscle activation in the Anterior Trunk Sway relative to Posterior Trunk Sway, the posterior sagittal plane muscles (semitendinosus, biceps femoris, gluteus maximus) all markedly increased in activation, while the anterior sagittal plane muscles (rectus femoris, vastus lateralis, TFL) showed decreased activation levels. Adductor longus showed no change (**Figure 2**).

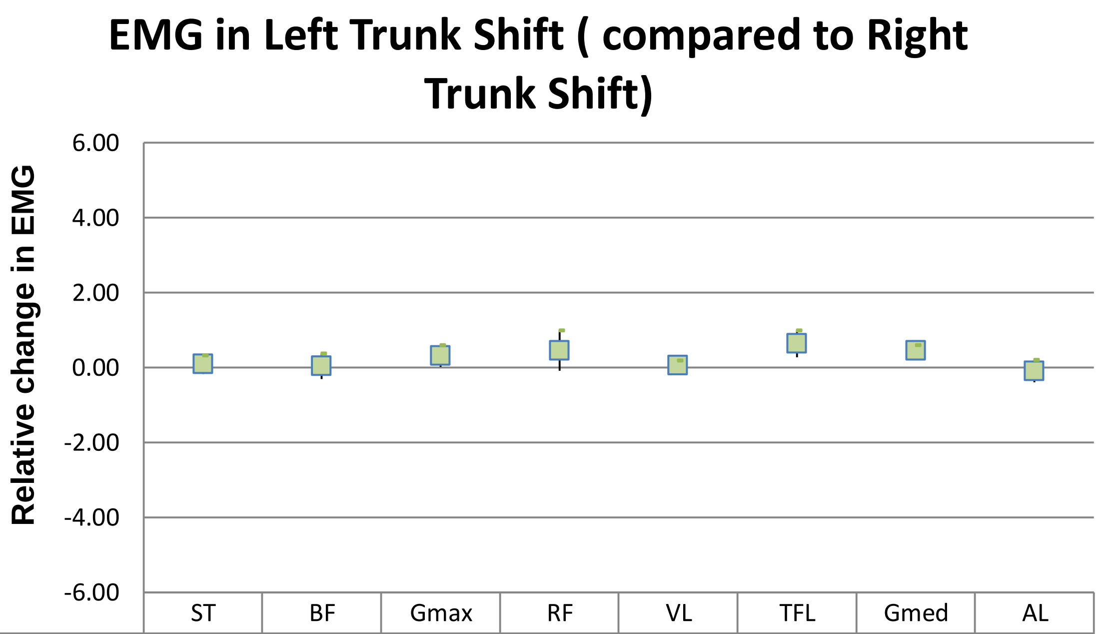


	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
Mean	2.931	3.500	1.788	-2.124	-0.220	-0.964	0.408	-0.225
Lower bound	1.701	1.819	1.262	-3.138	-0.394	-1.494	0.200	-0.738
Upper bound	4.161	5.181	2.314	-1.109	-0.045	-0.434	0.615	0.287
p value	< 0.001	<0.001	< 0.001	< 0.001	.016	.001	.001	.370

Figure 2: Muscle activation levels in Anterior Trunk Sway compared to Posterior Trunk Sway. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, semitendinosus activation is higher in Anterior Trunk Sway compared to Posterior Trunk Sway, whereas rectus femoris is activated less in Posterior Sway compared to Anterior Sway. The 95% CI are represented by the values seen in the Lower and Upper bounds. Semitendinosus (ST); biceps femoris (BF) (long head); gluteus maximus (Gmax); rectus femoris (RF); vastus lateralis (VL); tensor fascia lata (TFL); gluteus medius (Gmed); and adductor longus (AL)

Left Trunk Shift vs. Right Trunk Shift

When comparing muscle activation of Left Trunk Shift relative to Right Trunk Shift, the lateral hip abductors (gluteus maximus, gluteus medius and TFL) showed increased activation. There was no difference found in the other muscles (**Figure 3**).



	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
Mean	0.081	0.036	0.305	0.454	0.059	0.640	0.446	-0.100
Lower bound	-0.170	-0.307	0.011	-0.085	-0.069	0.281	0.297	-0.399
Upper bound	0.333	0.380	0.599	0.993	0.186	1.000	0.595	0.199
p value	.509	.828	.043	.094	.351	.001	<0.001	.494

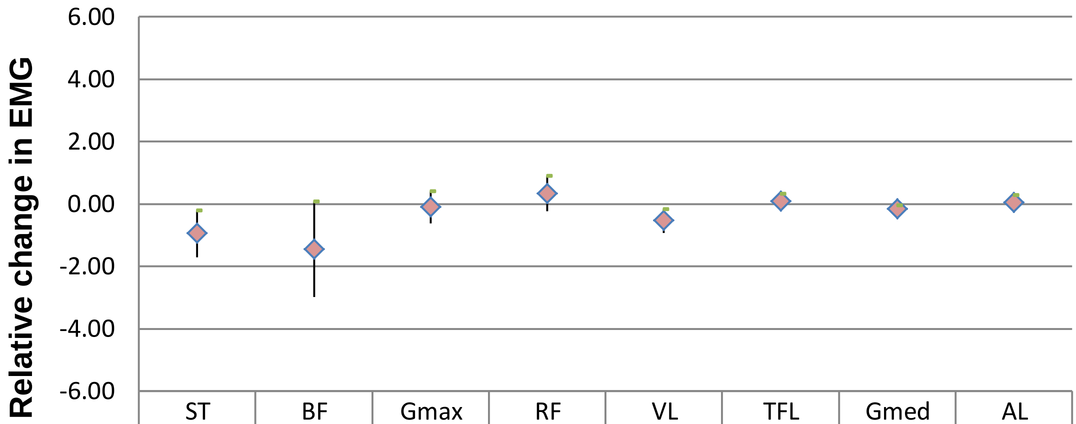
Figure 3: Muscle activation levels in Left Trunk Shift compared to Right Trunk Shift. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, gluteus maximus and tensor fascia lata activation is higher in Left Trunk Shift compared to Right Trunk Shift. The 95% CI are represented by the values seen in the Lower and Upper bounds. Semitendinosus (ST); biceps femoris (BF) (long head); gluteus maximus (Gmax); rectus femoris (RF); vastus lateralis (VL); tensor fascia lata (TFL); gluteus medius (Gmed); and adductor longus (AL).

Pelvis posture:

Anterior Pelvic Rotation vs. Posterior Pelvic Rotation

When comparing muscle activation of Anterior Pelvic Rotation relative to Posterior Pelvic Rotation, the muscles (semitendinosus, gluteus medius and vastus lateralis) all showed a decrease in muscle activation. All other muscles displayed no change (**Figure 4**).

EMG in Anterior Pelvic Rotation (compared to Posterior Pelvic Rotation)



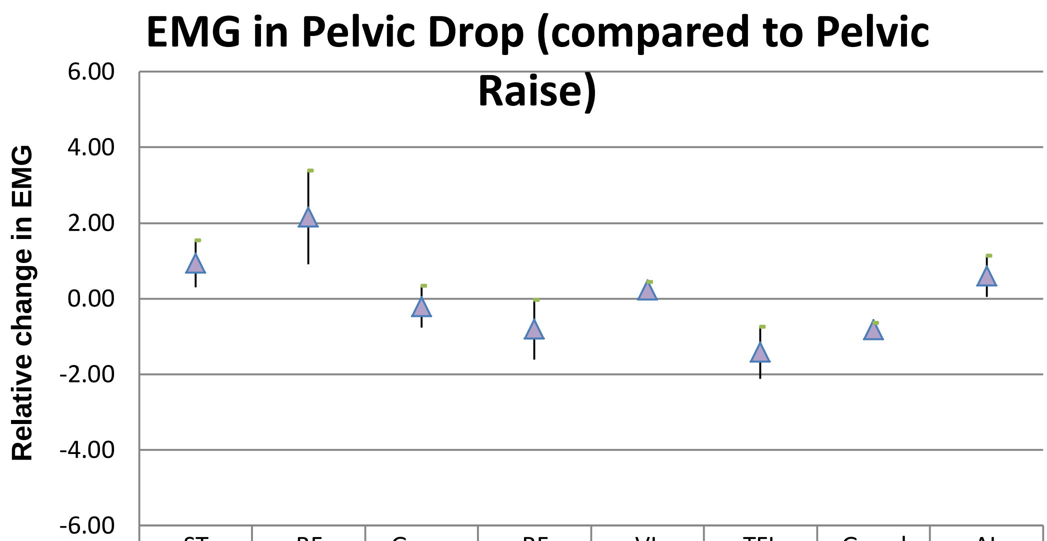
	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
Mean	-0.960	-1.455	-0.109	0.329	-0.548	0.076	-0.179	0.042
Lower bound	-1.710	-2.991	-0.625	-0.231	-0.929	-0.164	-0.318	-0.192
Upper bound	-0.209	0.081	0.407	0.889	-0.167	0.316	-0.039	0.276
p value	.015	.062	.665	.236	.007	.518	.015	.714

Muscles

Figure 4: Muscle activation levels in Anterior Pelvic Rotation compared to Posterior Pelvic Rotation. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, vastus lateralis and gluteus medius activation is lower in Left Trunk Shift compared to Right Trunk Shift. The 95% CI are represented by the values seen in the Lower and Upper bounds. Semitendinosus (ST); biceps femoris (BF) (long head); gluteus maximus (Gmax); rectus femoris (RF); vastus lateralis (VL); tensor fascia lata (TFL); gluteus medius (Gmed); and adductor longus (AL).

Lateral Pelvic Drop vs. Lateral Pelvic raise

This data is based on 20 subjects as two of the 22 subjects were unable to adopt the Lateral Pelvic Drop position. When comparing muscle activation of Lateral Pelvic Drop relative to Lateral Pelvic Raise, the lateral hip abductors (gluteus medius and TFL) showed decreased activation, as did rectus femoris. The hamstring group (semitendinosus and biceps femoris) showed increased activation along with adductor longus and vastus lateralis. Gluteus maximus displayed no change (**Figure 5**).



	ST	BF	Gmax	RF	VL	TFL	Gmed	AL
Mean	0.920	2.148	-0.220	-0.824	0.224	-1.429	-0.842	0.588
Lower bound	0.301	0.908	-0.770	-1.605	0.016	-2.117	-1.033	0.042
Upper bound	1.539	3.388	0.331	-0.043	0.432	-0.741	-0.651	1.133
p value	.006	.002	.415	.040	.037	< 0.001	< 0.001	.036

Figure 5: Muscle activation levels in Lateral Pelvic Drop compared to Lateral Pelvic Raise. Muscle activation levels are presented as the relative change in EMG to the reference Upright Standing (100%). For example, semitendinosis and adductor longus activation is higher in Lateral Pelvic Drop compared to Lateral Pelvic Raise. The 95% CI are represented by the values seen in the Lower and Upper bounds. Semitendinosus (ST); biceps femoris (BF) (long head); gluteus maximus (Gmax); rectus femoris (RF); vastus lateralis (VL); tensor fascia lata (TFL); gluteus medius (Gmed); and adductor longus (AL).

Discussion

The results of this study demonstrate that changes in trunk and pelvic posture clearly influence the levels of activation of different muscles of the hip and thigh, and that these interactions are complex in nature. Our a-priori hypothesis that changes in both trunk and pelvic posture during single leg stance would result in predictable changes in lower limb muscle activation is supported by the results, with the exception of changes in adductor longus activation within frontal plane postural changes.

Reliability of test postures and measures

Kinematic Reliability

This study has now established normative data in respect to the amount of movement demonstrated when adopting certain clinically relevant trunk and pelvic positions. To validate the Upright Standing position as the position for EMG normalization and therefore our reference posture, reliability of subject positioning was required. The ICC's of the kinematic measures showed reliability in excess of 0.75 except for Thorax Y (frontal plane) with a mean ICC of 0.54. This ICC needs to be considered in light of the magnitude of the values and the SEM of 1.4° which we contend is clinically trivial variability. Throughout the pair wise test positions, the mean ICC's of the majority of angles showed reliability over 0.70 across the six trials. Thorax Y (frontal plane) during Lateral Pelvic Drop and Lateral Pelvic Raise were the exceptions with ICC's (SEM) of 0.54 (2.8°), and 0.63 (2.1°) respectively. Similar to the Upright Stance posture, the SEM values for Thorax Y angle still suggest clinical utility.

EMG Reliability

Normalising EMG to a single leg stance reference posture as a Sub-Maximal Isometric Voluntary Contraction (SubMIVC) has also been used by Norcross et al(Norcross *et al.* 2010), with similarly small variations in reference angles reported. Although a limitation with using a SubMIVC method can be finding equivalent submaximal loads for different muscles (Allison *et al.* 1998; Dankaerts *et al.* 2004), SubMIVC has been shown to be reliable both when assessing low level muscle activity (Dankaerts *et al.* 2004; Hunt *et al.* 2003) and also in a static single leg stance position (Norcross *et al.* 2010), which closely reflects our study design.

Adductor longus and semitendinosus displayed poorer reliability which may explain why the expected change in EMG activation in our frontal plane test positions for adductor longus and semitendinosus were not observed. Of note, two other muscles, vastus lateralis and TFL displayed poorer reliability on one occasion each, but these findings did not significantly impact on the interpretation of our data. The variability displayed in activation of the adductor longus muscle is of clinical interest. During sporting activity, adductor related groin pain is a significant burden comprising approximately 8 – 16% in footballers(Ekstrand and Hilding 1999; Hägglund *et al.* 2009; Werner *et al.* 2009). The variability in activation levels of the adductor longus displayed in this normal healthy population of active males suggests this may be an avenue for examination in populations where adductor-related groin pain is of interest.

The influence of trunk posture changes:

<u>Anterior Trunk Sway vs. Posterior Trunk Sway</u>

There was a shift in patterns of activation of the hip and thigh muscles in the Anterior Trunk Sway position relative to the Posterior Trunk Sway position. These findings reflect a clear pattern of activation of the posterior hip muscles and a concurrent de-activation of the anterior hip muscles as the trunk shifts anterior to the pelvis. These findings are consistent with those of O’Sullivan et al(P. B. O'Sullivan *et al.* 2002) who reported a consistent pattern of activation of the posterior trunk muscles and de-activation of the upper anterior abdominal wall with the same body position change. This trend was also reported by Wang et al for the hip muscles(Wang *et al.* 2006). These changes likely reflect the body adapting to a shift in load demand around the hip in response to different trunk postures in the sagittal plane. This finding is clearly demonstrated in the muscle activation patterns of TFL and gluteus maximus.

Whilst we have found consistent patterns across the group, observing the individual results must not be ignored. For example, for some muscles (gluteus maximus, biceps femoris, semitendinosus, and adductor longus), a small number of subjects displayed muscle activity levels that did not fall below the Upright Standing value in either Anterior or Posterior Trunk Sway. For the few subjects that had muscle activity always above the Upright

Standing value even in Posterior Trunk Sway, this may represent a lack of automatic relaxation of muscles during postural adjustment in some individuals. These findings may have clinical implications that warrant further investigation.

Left Trunk Shift vs. Right Trunk Shift

For the lateral trunk shift condition, activation of the hip abductor muscles (gluteus maximus, gluteus medius and TFL) was demonstrated with the Left Trunk Shift position relative to the Right Trunk Shift. These findings are consistent with the lateral shift of the trunk relative to the hip resulting in a greater demand on hip abductor system. We also hypothesized we would observe an increase in adductor longus activation in Right Trunk Shift posture. The absence of this finding was reflected in the large variability in EMG response observed in this muscle. Visual graphical inspection of the individuals highlighted some subjects had increased levels of adductor longus activity that was above the Upright Standing position in either Left or Right Trunk Shift. It remains to be seen whether these variations are distributed evenly, or clustered in populations of high and low activation, and this will not likely be resolved until larger numbers of subjects are examined. This observation warrants further investigation in clinical populations to determine whether these findings show any relationship to the incidence of adductor-related injury(Hölmich 2007). To our knowledge, this is the first study that has investigated frontal plane trunk kinematics and its relation to adductor longus activation, however clinicians may use this data to therapeutic advantage when exercise is required which raises or lowers muscle activation levels.

Pelvic posture changes:

Anterior Pelvic Rotation vs. Posterior Pelvic Rotation

The differences in muscle activation when the postural adjustment was initiated via the pelvis in a sagittal plane are more difficult to interpret. There were significant reductions in activation of semitendinosus when changing from Posterior to Anterior Pelvic Rotation, and a trend in the same direction for biceps femoris. Greater hamstring muscle activation would be logically expected to control posterior pelvic rotation than anterior pelvic rotation. The non-significant result of biceps femoris may be explained via visual graphical inspection of the hamstring muscles. There were a small number of subjects that displayed a clear opposing activation pattern that suggest there exists different motor control strategies for the same task in different individuals.

In the Anterior Pelvic Rotation there was a small reduction in gluteus medius and vastus lateralis demonstrating that a change in pelvic tilt influence patterns of activation of the hip and thigh muscles. It was noted that there was significant variability in terms of the direction of the change in muscle activation in this pair wise comparison compared to the other conditions for TFL, gluteus maximus, rectus femoris and the hamstrings. This variability suggests a range of different movement strategies employed by individuals.

Lateral Pelvic Drop vs. Lateral Pelvic Raise

In the Lateral Pelvic Drop relative to Lateral Pelvic Raise position, there was a clear pattern of reduced activation of the hip abductor muscles (TFL and gluteus medius) and rectus femoris with a concurrent increased activation of the hamstrings, adductor longus and vastus lateralis muscles. These findings suggest a shift in activation away from the hip abductors to the long hip muscles in the 'Trendelenberg' posture. The Trendelenburg posture has been related with a number of clinical presentations (Hardcastle and Nade 1985) and is thought to be a relatively passive position requiring little hip abductor muscle activation. Our results support this clinical interpretation for the hip abductor muscles (gluteus medius and TFL) however the concurrent activation of the hamstrings may have clinical implications that warrant further investigation.

In contrast to the Trendelenburg position, Lateral Pelvic Raise, required greater activity in the hip abductor muscles to maintain the contralateral pelvis elevated (L.A. Bolgla and Uhl 2005). These findings may have implications for functional retraining of frontal plane muscles by focusing on simple changes to frontal plane pelvic posture during functional tasks.

Interestingly there was a divergence in the pattern of activation in semitendinosus during the Pelvic Drop condition. This means that compared with Lateral Pelvic Raise, subjects again displayed a variety of motor control strategies in these muscles to adopt the Lateral Pelvic Drop position, with some increasing and others decreasing their activation levels. The variability in activation patterns may have clinical implications in those at risk of hamstring strain. Although this data broadly suggests a group effect in these findings there is evidence in some muscles to suggest that the response to changes in both trunk and pelvic posture is variable for different individuals.

Limitations:

We are unable to recommend the use of Upright Standing in single leg stance as a SubMVC method to normalise EMG to if the muscles adductor longus and/or semitendinosus are the intended muscles of investigation. These findings only apply to asymptomatic males aged between 20 and 45 years old and therefore cannot make any conclusions about females, the very young, older, or injured subjects. Further, we looked at superficial muscles in single plane directions and where muscle loading and activation patterns are being examined. The assessment of deeper muscles and muscles in a range of multi-directional functional trunk and pelvic postures may be important.

Conclusions

This study established normative EMG data during commonly utilized clinical postures, which now allows both descriptions of motor patterns and comparison with symptomatic groups. Clinicians may take this data and immediately apply it for exercise prescription where the motor patterns were unequivocal. For example, if the goal of rehab is to increase the activity of gluteus maximus, a forward trunk position will achieve this without the patient's conscious effort. This same position will help unload rectus femoris which would be beneficial if faced with any type of strain to this musculotendinos unit especially if the patient appears to be adopting an extended trunk position. The variability of muscle activation patterns between subjects seen in adductor longus and semitendinosus could be of clinical interest and should be investigated in symptomatic groin pain and hamstring populations and provides direction for future research where excessive or unnecessary activation could have clinical implications. In a research setting this study has demonstrated Upright Standing in single leg stance as a reliable and efficient SubMVC method to normalise EMG to in the muscles investigated apart from adductor longus and/or semitendinosus.

'The author(s) declare that they have no competing interests'

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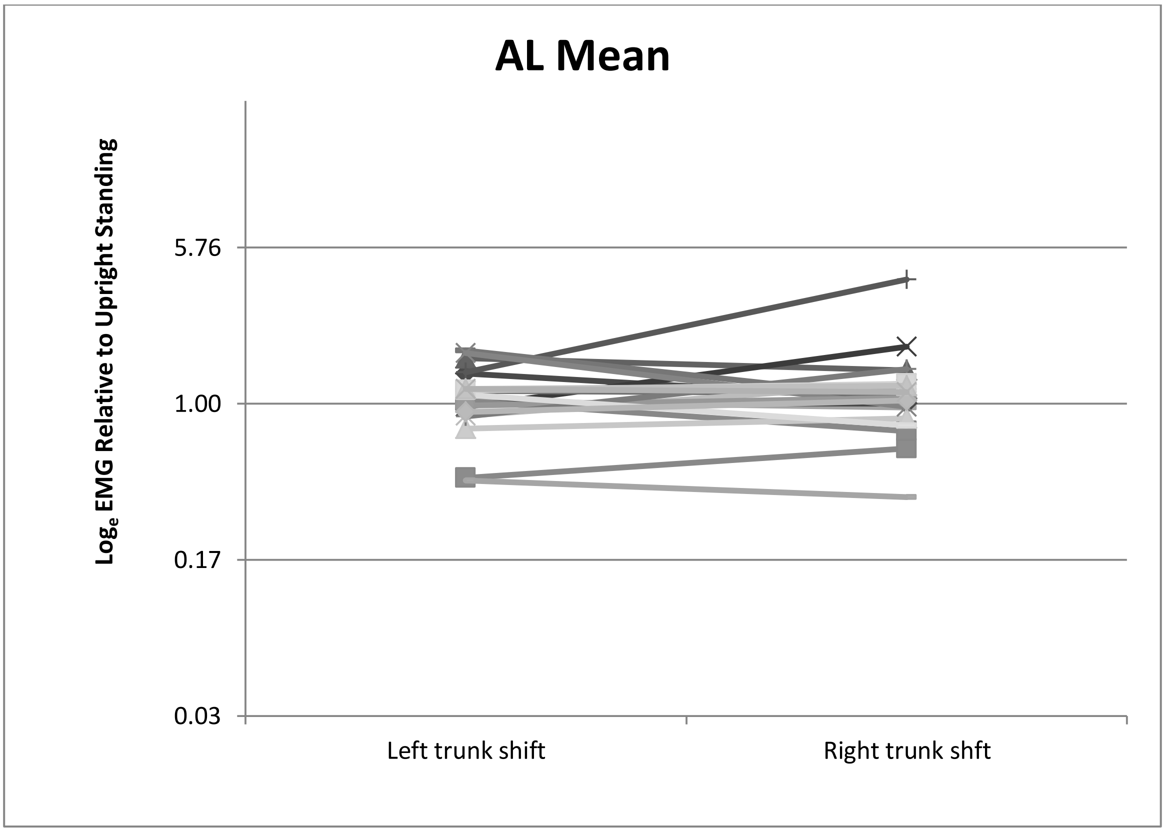
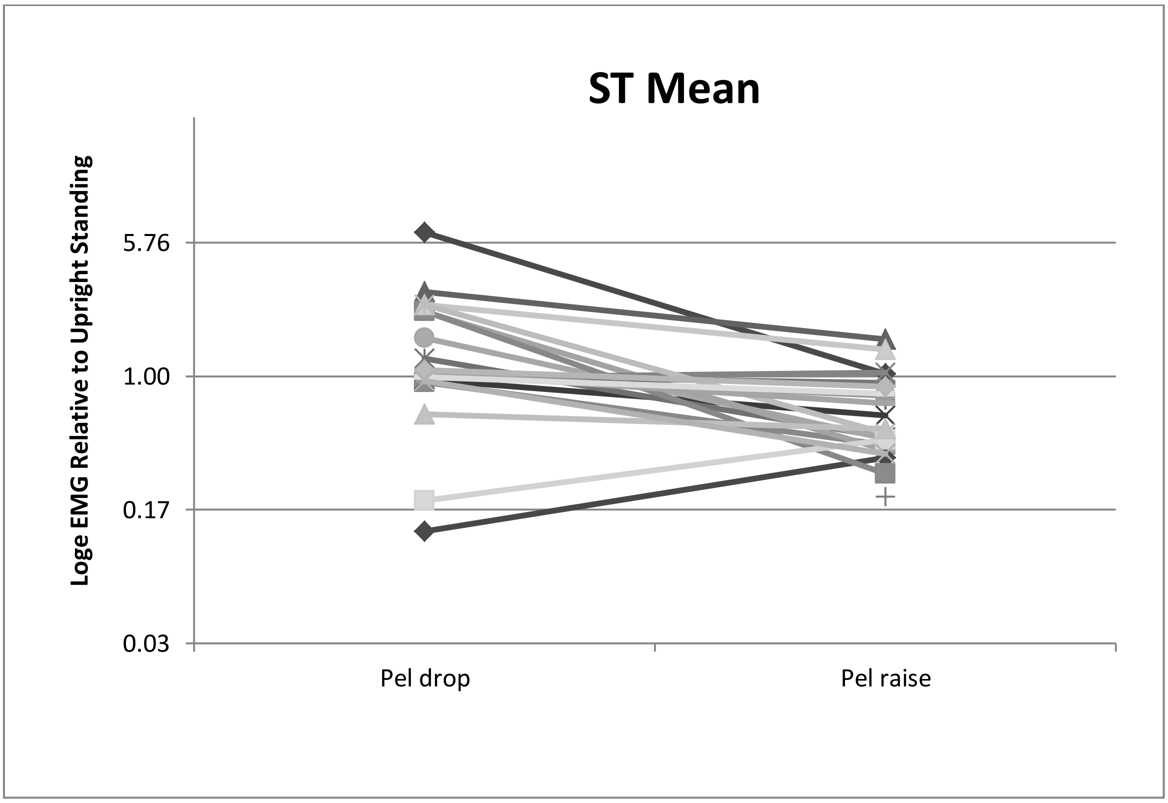
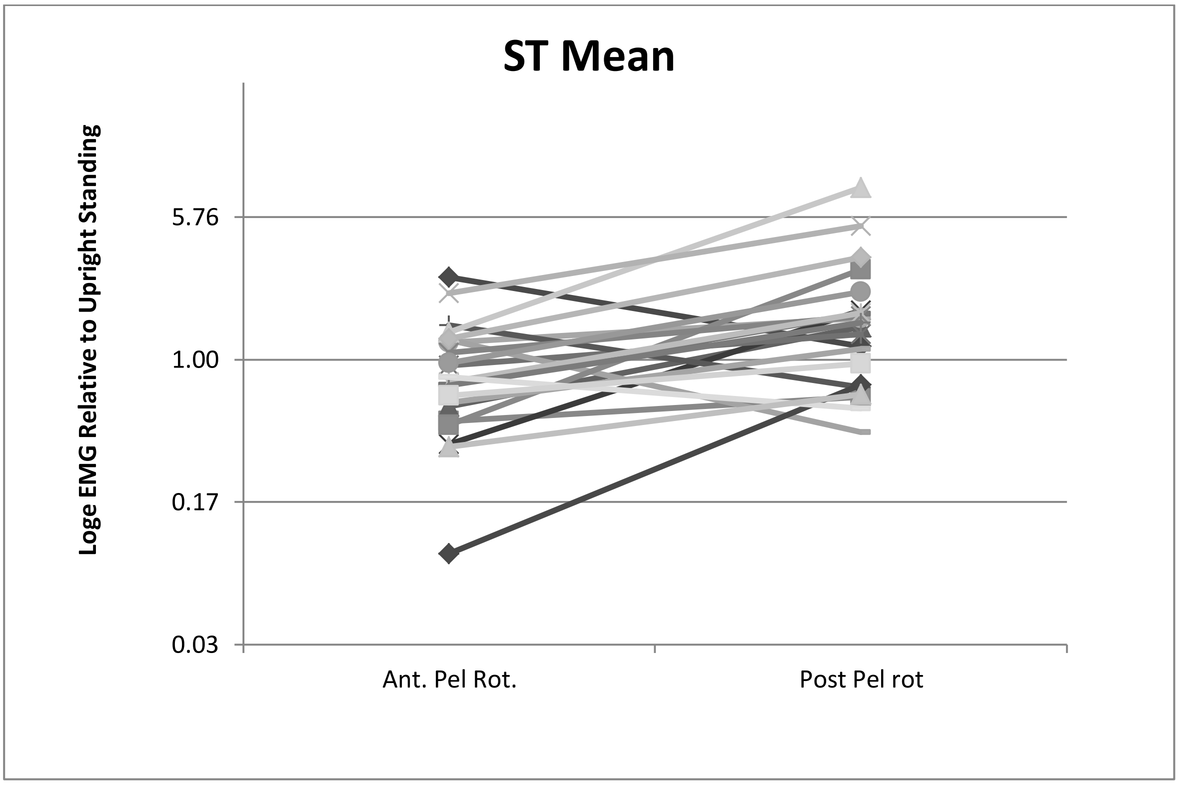
Appendix K: Individual subject changes in adductor longus activation: Left vs. Right Trunk Shift



Appendix L: Individual subject changes in semitendinosus activation: Lateral Pelvic Drop vs. Lateral Pelvic Raise



Appendix M: Individual subject changes in semitendinosus activation: Anterior vs. Posterior Pelvic Rotation



Supplementary Material 1 (Kinematic reliability)

Angle	Upright Standing Mean° ± SD (SEM)	ICC (95%CI)	p-value
R Hip X	12.2±5.8 (2.0)	0.89(0.81-0.95)	<0.001
R Knee X	9.0±5.5 (2.0)	0.88(0.8-0.94)	<0.001
R Pelvis X	12.0±3.9 (1.1)	0.91(0.85-0.96)	<0.001
R Pelvis Y	-1.1±2.8 (1.1)	0.87(0.79-0.94)	<0.001
R Spine X	-14.8±5.4 (1.5)	0.93(0.88-0.97)	<0.001
R Thorax X	-2.7±3.9 (1.1)	0.91(0.85-0.96	<0.001
R Thorax Y	-1.8±1.6 (1.4)	0.54(0.36-0.73)	<0.001

Anterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.9±5.7 (2.8)	0.81(0.69-0.90)	<0.001
R Knee X	13.3±5.8 (2.4)	0.85(0.75-0.92)	<0.001
R Pelvis X	15.7±4.4 (1.9)	0.84(0.74-0.92)	<0.001
R Pelvis Y	0.2±3.2 (1.3)	0.85(0.75-0.92)	<0.001
R Spine X	1.7±8.6 (2.6)	0.93(0.87-0.96)	<0.001
R Thorax X	17.4±6.7 (2.5)	0.89(0.80-0.95)	<0.001
R Thorax Y	-1.7±2.5 (1.2)	0.80(0.68-0.90)	<0.001

Posterior Trunk Sway			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.9±6.8 (2.7)	0.86(0.77-0.93)	<0.001
R Knee X	11.7±5.6 (2.0)	0.88(0.79-0.94)	<0.001
R Pelvis X	6.6±4.6 (1.8)	0.86(0.76-0.93)	<0.001
R Pelvis Y	0.1±2.6 (1.2)	0.82(0.71-0.91)	<0.001
R Spine X	-20.5±7.3 (1.8)	0.94(0.89-0.97)	<0.001
R Thorax X	-13.9±4.2 (1.7)	0.84(0.74-0.92)	<0.001
R Thorax Y	-2.1±2.0 (1.1)	0.72(0.56-0.85)	<0.001

Anterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	21.8±6.0 (2.5)	0.83(0.72-0.92)	<0.001
R Knee X	12.0±5.6 (2.4)	0.85(0.74-0.92)	<0.001
R Pelvis X	18.9±3.2 (1.8)	0.76(0.62-0.87)	<0.001
R Pelvis Y	-0.3±2.7 (1.3)	0.82(0.71-0.91)	<0.001
R Spine X	-23.5±5.7 (1.9)	0.90(0.83-0.95)	<0.001
R Thorax X	-4.6±4.3 (1.7)	0.87(0.78-0.94)	<0.001
R Thorax Y	-2.2±2.5 (1.0)	0.87(0.78-0.94)	<0.001

Posterior Pelvic Rotation			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	6.4±6.2 (2.1)	0.89(0.81-0.94)	<0.001
R Knee X	13.0±5.4 (1.9)	0.89(0.81-0.94)	<0.001
R Pelvis X	3.8±4.4 (1.6)	0.87(0.78-0.93)	<0.001
R Pelvis Y	-1.4±2.5 (1.1)	0.84(0.73-0.92)	<0.001
R Spine X	-5.3±6.9 (2.1)	0.91(0.85-0.96)	<0.001
R Thorax X	-1.5±4.4 (1.6)	0.89(0.81-0.95)	<0.001
R Thorax Y	-1.3±2.3 (1.2)	0.79(0.66-0.89)	<0.001

Left Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	14.3±5.8 (1.7)	0.90(0.82-0.95)	<0.001
R Knee X	11.1±5.9 (1.9)	0.90(0.83-0.95)	<0.001
R Pelvis X	12.6±4.3 (1.3)	0.90(0.83-0.95)	<0.001
R Pelvis Y	0.3±3.1 (1.5)	0.81(0.70-0.90)	<0.001
R Spine X	-15.8±7.2 (1.6)	0.95(0.91-0.97)	<0.001
R Thorax X	-3.6±4.1 (1.3)	0.90(0.83-0.95)	<0.001
R Thorax Y	10.3±3.3 (2.1)	0.71(0.56-0.85)	<0.001

Right Trunk Shift			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	13.9±5.7 (2.2)	0.84(0.73-0.92)	<0.001
R Knee X	10.0±5.4 (2.2)	0.84(0.73-0.92)	<0.001
R Pelvis X	12.7±4.3 (1.4)	0.89(0.82-0.95)	<0.001
R Pelvis Y	-2.2±3.1 (1.9)	0.73(0.58-0.85)	<0.001
R Spine X	-15.7±7.0 (1.7)	0.94(0.90-0.97)	<0.001
R Thorax X	-2.9±4.4 (1.3)	0.93(0.87-0.97)	<0.001
R Thorax Y	-15.6±3.5 (2.2)	0.70(0.55-0.84)	<0.001

Lateral Pelvic Drop			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	15.5±7.0 (1.7)	0.93(0.88-0.97)	<0.001
R Knee X	10.7±7.7 (1.8)	0.95(0.91-0.98)	<0.001
R Pelvis X	13.7±4.4 (1.2)	0.91(0.84-0.96)	<0.001
R Pelvis Y	6.4±2.9 (1.1)	0.84(0.72-0.92)	<0.001
R Spine X	-16.5±6.7 (4.0)	0.74(0.58-0.86)	<0.001
R Thorax X	-4.0±4.8 (2.1)	0.83(0.72-0.92)	<0.001
R Thorax Y	-1.7±3.1 (2.8)	0.54(0.36-0.74)	<0.001

Lateral Pelvic Raise			
Angle	**Mean° ± SD (SEM)**	**ICC (95%CI)**	**p-value**
R Hip X	15.6±7.2 (1.6)	0.95(0.92-0.98)	<0.001
R Knee X	9.9±6.0 (2.2)	0.87(0.79-0.94)	<0.001
R Pelvis X	14.6±4.5 (1.3)	0.92(0.86-0.96)	<0.001
R Pelvis Y	-7.6±2.7 (1.5)	0.75(0.61-0.87)	<0.001
R Spine X	-17.8±7.0 (1.6)	0.95(0.90-0.97)	<0.001
R Thorax X	-3.8±4.4 (1.3)	0.93(0.87-0.96)	<0.001
R Thorax Y	-2.1±2.7 (2.1)	0.63(0.45-0.79)	<0.001

Supplementary Material 2 (EMG reliability)

Upright Standing			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.87 ± 1.80(2.46)	0.29(011-0.52)	<0.001
BF	18.76 ± 22.77(7.93)	0.90(0.82-0.95)	<0.001
Gmax	9.25 ± 7.12(2.65)	0.87(0.77-0.93)	<0.001
Gmed	25.08 ± 18.34(3.15)	0.97(0.94-0.98)	<0.001
RF	26.28 ± 27.93(10.03)	0.88(0.79-0.94)	<0.001
ST	17.71 ± 12.68(9.41)	0.64(0.47-0.80)	<0.001
TFL	47.96 ± 31.09(11.78)	0.89(0.80-0.94)	<0.001
VL	42.71 ± 21.39(10.24)	0.80(0.68-0.90)	<0.001

Anterior Trunk Sway			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.40 ± 4.62(0.84)	0.97(0.95-0.99)	<0.001
BF	50.19 ± 30.29(12.34)	0.87(0.77-0.93)	<0.001
Gmax	20.52 ± 12.08(3.29)	0.93(0.88-0.97)	<0.001
Gmed	29.99 ± 18.40(4.63)	0.96(0.93-0.98)	<0.001
RF	12.71 ± 12.93(4.48)	0.94(0.88-0.97)	<0.001
ST	45.88 ± 22.37(7.95)	0.88(0.80-0.94)	<0.001
TFL	26.62 ± 15.79(5.48)	0.87(0.78-0.94)	<0.001
VL	47.19 ± 21.45(10.07)	0.84(0.74-0.92)	<0.001

Posterior Trunk Sway			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	6.93 ± 4.26(1.04)	0.94(0.89-0.97)	<0.001
BF	10.76 ± 6.07(6.14)	0.51(0.32-0.71)	<0.001
Gmax	6.87 ± 5.44(1.50)	0.92(0.86-0.96)	<0.001
Gmed	22.43 ± 17.42(5.23)	0.96(0.93-0.98)	<0.001
RF	49.59 ± 44.66(15.79)	0.90(0.83-0.95)	<0.001
ST	9.04 ± 7.36(8.13)	0.36(0.18-0.59)	<0.001
TFL	71.80 ± 57.65(23.25)	0.85(0.75-0.92)	<0.001
VL	56.65 ± 29.79(13.30)	0.83(0.72-0.92)	<0.001

Anterior Pelvic Rotation			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.36 ± 2.09(1.44)	0.74(0.60-0.87)	<0.001
BF	17.01 ± 16.37(7.57)	0.83(0.71-0.91)	<0.001
Gmax	11.12 ± 5.60(2.15)	0.88(0.80-0.94)	<0.001
Gmed	26.84 ± 25.66(3.79)	0.98(0.96-0.99)	<0.001
RF	29.22 ± 26.59(11.16)	0.84(0.73-0.92)	<0.001
ST	13.87 ± 10.61(4.87)	0.82(0.70-0.91)	<0.001
TFL	47.50 ± 29.32(12.03)	0.84(0.74-0.92)	<0.001
VL	51.15 ± 28.21(7.39)	0.93(0.87-0.97)	<0.001

Posterior Pelvic Rotation			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.10 ± 1.37(0.94)	0.63(0.46-0.80)	<0.001
BF	33.66 ± 37.26(13.75)	0.86(0.77-0.93)	<0.001
Gmax	13.58 ± 13.49(3.37)	0.93(0.88-0.97)	<0.001
Gmed	31.01 ± 24.37(10.69)	0.88(0.79-0.94)	<0.001
RF	21.82 ± 16.22(8.16)	0.82(0.71-0.91)	<0.001
ST	28.41 ± 21.47(14.37)	0.69(0.53-0.83)	<0.001
TFL	41.30 ± 30.19(14.68)	0.79(0.66-0.89)	<0.001
VL	66.16 ± 30.07(12.54)	0.86(0.76-0.93)	<0.001

Left Trunk Shift			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.01 ± 1.49(1.42)	0.51(0.32-0.71)	<0.001
BF	17.38 ± 16.93(8.58)	0.76(0.62-0.88)	<0.001
Gmax	11.74 ± 9.20(2.86)	0.91(0.83-0.95)	<0.001
Gmed	32.95 ± 23.73(4.75)	0.96(0.93-0.98)	<0.001
RF	38.81 ± 31.72(14.42)	0.83(0.72-0.92)	<0.001
ST	16.35 ± 14.26(12.46)	0.53(0.34-0.73)	<0.001
TFL	67.12 ± 39.60(19.63)	0.80(0.67-0.90)	<0.001
VL	43.82 ± 20.23(13.64)	0.66(0.49-0.81)	<0.001

Right Trunk Shift			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	5.67 ± 4.41(2.09)	0.90(0.82-0.95)	<0.001
BF	16.68 ± 17.60(10.13)	0.73(0.57-0.85)	<0.001
Gmax	8.87 ± 7.35(2.35)	0.94(0.90-0.97)	<0.001
Gmed	21.73 ± 16.52(4.26)	0.94(0.89-0.97)	<0.001
RF	28.04 ± 20.93(7.69)	0.86(0.77-0.93)	<0.001
ST	12.95 ± 9.00(8.07)	0.47(0.28-0.68)	<0.001
TFL	41.70 ± 25.84(13.81)	0.74(0.59-0.87)	<0.001
VL	42.64 ± 20.76(8.82)	0.86(0.77-0.93)	<0.001

Lateral Pelvic Drop			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	6.79 ± 4.66(3.21)	0.67(0.49-0.83)	<0.001
BF	34.48 ± 28.88(11.57)	0.84(0.72-0.92)	<0.001
Gmax	8.64 ± 4.91(2.51)	0.82(0.69-0.91)	<0.001
Gmed	12.70 ± 6.87(3.19)	0.83(0.70-0.92)	<0.001
RF	17.85 ± 14.87(6.89)	0.80(0.67-0.90)	<0.001
ST	20.86 ± 15.04(7.94)	0.76(0.60-0.88)	<0.001
TFL	24.08 ± 12.63(6.07)	0.80(0.66-0.90)	<0.001
VL	52.40 ± 37.57(13.24)	0.87(0.77-0.94)	<0.001

Lateral Pelvic Raise			
Muscle	**Mean ± SD (SEM)**	**ICC (95%CI)**	**p-value**
AL	4.55 ± 1.13(0.79)	0.61(0.42-0.78)	<0.001
BF	12.45 ± 12.57(6.62)	0.81(0.69-0.90)	<0.001
Gmax	14.61 ± 14.62(3.54)	0.95(0.90-0.97)	<0.001
Gmed	37.12 ± 35.23(4.41)	0.99(0.98-0.99)	<0.001
RF	34.54 ± 27.19(12.82)	0.78(0.65-0.89)	<0.001
ST	10.10 ± 8.22(5.78)	0.63(0.45-0.79)	<0.001
TFL	82.17 ± 48.92(24.29)	0.82(0.70-0.91)	<0.001
VL	41.77 ± 20.64(10.03)	0.79(0.66-0.89)	<0.001