The Role of the Gluteus Maximus During Prone Hip Extension

by

Ian George Rainsford

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Supervisors: Dr Karen Estelle Welman

Co-Supervisor: Dr Rachel Elizabeth Venter

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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Date: 28 August 2015

Abstract

Background: The clinical prone hip extension (PHE) test is used to assess lumbo-pelvic function with a large focus placed on the activation of the gluteus maximus (Gmax), and is also used as a prescribed exercise in the treatment of Gmax recruitment deficits. The activation sequences (AS) are compared to those of the 'golden standard' as set out by Janda (1991). Gmax activation becomes important due to its role in injury prevention as well as maintenance of lower limb alignment. Previous research into the AS reveals no consistent order, questioning the functionality of the PHE.

Objective: The current study set out to determine whether a consistent AS exists during the PHE and, in the presence of an erroneous AS, whether one can achieve the proposed AS with concentrated gluteal training. The current study also looked into the AS of more functionally loaded movements. The study further looked at the influence of improved Gmax recruitment on lower limb alignment.

Methods: Pre- (n=18) and post-testing (n=7) of the muscle AS (time-normalized onsets) (with electromyography) were assessed in healthy young club-level netball players during the PHE, quadruped opposite arm/leg extension (QALE), and the single limb squat (SQT) along with lower limb alignment (valgus and knee-over-toe angles). The following muscles were included in the assessment: Gluteus maximus, bicep femoris, and lumbar erector spinae. Onsets were reported relative to gluteus maximus. Following pre-testing the players then entered a nine-week gluteal training intervention.

Results: No consistent AS was noted at pre-testing (n=18) with the Gmax onset occurring after that of the lumbar erector spinae in both non-dominant and dominant PHE. At post-testing (n=7) the Gmax onset occurred earlier (non-dominant first and dominant second) with the lumbar erector spinae shifting later (dominant significantly, $p<0.05$). During the QALE and SQT movements, Gmax onset was consistently not the first muscle to become active at pre- and post-testing. No change in lower limb alignment was observed with no change in gluteal muscle onset or amplitude ($p>0.05$) during the SQT.

Conclusion: The gluteal training intervention seems to have improved gluteal recruitment during the PHE but this did not have an influence on lower limb alignment during the SQT bringing to question the usage of the PHE in the assessment of Gmax function. The AS (both non-dominant and dominant PHE) agree more closely with the suggested norm and hence lends weight that it can be used as a reference. The QALE and SQT don't appear to be suitable replacements for the PHE.

Opsomming

"Prone hip extension (PHE)" is 'n kliniese toets en word gebruik om die funksionering van die lumbo-pelviese kompleks te evalueer, met die hooffokus die aktivering van die gluteus maksimusspier (Gmax). Die toets word ook as oefening gebruik om wanbalanse in die aktivering van die Gmax aan te spreek. Die 'goue standaard' waaraan die aktiveringsvolgorde (AS) gemeet word, is deur Janda (1991) bepaal. Die Gmaks speel 'n belangrike rol in die voorkoming van beserings en in die belyning van die onderbeen, daarom word die aktivering daarvan as baie belangrik beskou. Geen vorige navorsing kon 'n konstante AS identifiseer nie en dus word die funksionaliteit van die "PHE" bevraagteken.

Doelwitte: Die hoofdoel van hierdie studie was om te bepaal of daar 'n konstante AS tydens die "PHE" is, en indien daar 'n 'foutiewe' AS geïdentifiseer is, of dit reggestel kon word deur spesifieke gluteale oefeninge te doen. Daar is ook gekyk na die AS wat voorkom tydens meer funksionele bewegings. Laastens het die studie ten doel gehad om vas te stel wat die invloed van 'n verbeterde Gmaks aktivering op die belyning van die onderbeen sal wees.

Metodes: Die spieraktiveringspatrone (tyd-genormaliseerde aanvang) van jong, gesonde klub netbalspelers is tydens die uitvoering van 'n PHE, "quadruped opposite arm/leg extension" (QALE) en enkelbeen squatbeweging (SQT) gemeet. Die belyning van die onderbeen (valgus- en knie oor die tone hoek) is ook gemeet. Pre- (n=18) en post-toetsing (n=7) is deur middel van elektromiografie gedoen. Die volgende spiergroepe is ingesluit: Gmax, bisep femoris en die lumbale erector spinae. Die aanvang van aktivering word relatief tot die aanvang van die Gmax weergegee. Na afloop van die pre-toetsings, het die netbalspelers 'n nege weke gluteale intervensieperiode ondergaan.

Resultate: Daar is geen konstante AS opgemerk tydens die pre-toetsings (n=18) nie, maar die aanvang van Gmax-aktivering het eers na die lumbale erector spinae in beide linker en regter PHE plaasgevind. Tydens die post-toetsing (n=7) was die aktivering van die Gmax vroeër (links eerste en regs tweede) met die aktivering van die lumbale erector spinae wat later plaasgevind het (regs was betekenisvol, $p<0.05$). Die Gmax was konstant nie die eerste spier wat geaktiveer word tydens die uitvoering van die QALE en die SQT in die pre- en post-toetsings nie. Geen verandering in die belyning van die onderbeen is opgemerk met die aanvang van aktivering van die gluteale spier of die maksimale aktivering ($p>0.05$) tydens die SQT nie.

Samevatting: Dit blyk dat die intervensie van gluteale oefeninge wel 'n verbetering in gluteale aktivering teweeg gebring het tydens die PHE, maar dit het geen effek op die belyning van die onderbeen gehad nie tydens die SQT nie. Die bewinding bevraagteken die gebruik van die PHE as 'n toets vir Gmax funksie. Die AS tydens die linker en egter PHE is

baie na aan die voorgestelde norme en dus kan dit as verwysing gebruik word. Die QALE en SQT blyk nie ‘n goeie plaasvervanger te wees vir die PHE nie.

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Abbreviations

Gmax	Gluteus maximus
AS	Activation sequence
PHE	Prone hip extension
sEMG	Surface electromyography
ES_{Lumbar}	Lumbar erector spinae
Gmed	Gluteus medius
BicepFem	Bicep femoris
ContraES	Contraletral erector spinae
IpsiES	Ipsilateral erector spinae
SIJ	Sacroiliac joint
LBP	Lower back pain
PFPS	Patellofemoral pain syndrome
CAI	Chronic ankle instability
Q	Quadriceps
ITB	Iliotibial band
ACL	Anterior cruciate ligament
MVIC	Maximal voluntary isometric contraction
QALE	Quadruped opposite arm/leg extension
SQT	Single limb squat
CON	Control group
EXP	Experimental group
RMS	Root mean square
SD	Standard deviation
Hz	Hertz
ms	milliseconds
DOM	Dominant
NDOM	Non-dominant
Cmf	Circumference
yrs	years
LEA	Lower extremity alignment

Key Terminology

Club-level:

Netball players forming part of the second squad (third and fourth) team of the Maties (Stellenbosch University) netball club.

Prone hip extension:

Individual lies in the prone position with the forehead resting on the hands; the individual then raised a flexed (at the knee) leg into the air by performing hip extension.

Quadruped opposite arm/leg extension:

Individual is position on all fours, and then extends the opposite arm and leg away from the center of the body.

Single limb squat:

Individual performs a single limb squat (roughly to 45 degrees knee flexion) while flexing the opposite hip to raise the opposite leg off the ground in front of them.

Onset:

That time when a muscle displays an activation level of 5SD above baseline measurement.

Muscle activation sequence:

The order in which the tested muscles display onset.

Proposed ‘ideal’ muscle activation sequence during prone hip extension (Janda, 1991):

Gluteus maximus→Bicep femoris→Contralateral lumbar erector spinae→Ipsilateral lumbar erector spinae

Chapter One

Introduction

The presence of poor gluteus maximus (Gmax) activation and strength have been associated with a number of injuries or been linked to increase strain on tissues of the body (Boren *et al*., 2011; Cambridge *et al*., 2012; Distefano *et al*., 2009; Ekstrom, Donatelli & Carp, 2007; Kang *et al*., 2013; Webster & Gribble, 2013; Woodford-Rogers, Cyphert & Denegar, 1994). Komi (2011) stated that 'voluntary strength performance is determined not only by the quantity and quality of the involved muscle mass, the 'engine', but also by the ability of the nervous system, the engine controller, to effectively activate the muscles' (page 282). With this one can assume that assessing Gmax recruitment should form part of an assessment of the lower extremities.

Hip extension exercises performed in the prone position regularly form part of rehabilitation programs targeting the hip and lumbo-pelvic regions (Oh *et al*., 2007, Tateuchi *et al*., 2012) and Gmax activation. Not only is it used as an exercise, but prone hip extension (PHE) is often used as a clinical test for lumbo-pelvic-hip function (Lehman *et al*., 2004) providing insight into the recruitment patterns of the involved muscles. Janda (1991) proposed an ideal activation sequence (AS) during the PHE with many studies not identifying this pattern in the prospective studies (Bullock-Saxton, Janda & Bullock, 1994; Kang *et al*., 2012; Lewis & Sahrmann, 2009; Vogt & Banzer, 1997). The functionality of the PHE has therefore come into question along with the proposed activation sequence. This being said, no study has attempted to assess whether one can achieve this 'ideal' pattern via the implementation of the gluteal specific training intervention. It may be that the PHE is an applicable test for AS but that modern day lifestyle works against the optimal functioning of the gluteal muscles leading to the alternate findings in research.

This close attention to Gmax onset during hip extension occurs due to the importance of this muscle in injury prevention via its role in ensuring optimal lower limb alignment (Boren *et al*., 2009; Hollman, 2009; Sinsurin *et al*., 2013; Struminger *et al*., 2013). Earlier onset of the Gmax during functional tasks would perhaps ensure optimal alignment as it is believed that maintaining alignment has more to do with neural control as it does not require maximum strength (Struminger *et al*., 2013). It would therefore be interesting to investigate the role of gluteal muscle onset and lower limb alignment; specifically in a population involved in a dynamic sport that involved forces that challenge lower limb alignment. Mothersole, Cronin & Harris (2013) state that netball is such a sport with Zeller *et al*. (2003) stating that women tend to enter into lower limb malalignment more often than men.

This article-format thesis looked into the validity of the PHE test, the role of gluteal strengthening on the activation sequence during the PHE and whether or not this would have a positive outcome on lower limb alignment in netball players.

Structure of Thesis

Chapter 2

Presents the theoretical background, and overview of the most relevant literature to date.

Reference style: Harvard referencing style

Chapter 3

Article 1: Gluteus maximus onset during unloaded, quadruped, and functionally loaded tasks in club-level netball players.

Compiled under the guidelines of the Journal of Electromyography and Kinesiology.

Reference style: Adapted Harvard referencing style

Chapter 4

Article 2: A nine-week gluteal training intervention alters the timing of gluteus maximus onset during the prone hip extension test in netball players with no change in functional movement pattern.

Compiled under the guidelines of the Journal of Electromyography and Kinesiology.

Reference style: Adapted Harvard referencing style

Chapter 5

General Discussion and Conclusion

Reference style: Harvard referencing style

Chapter Two:

Theoretical Context

Lumbo-pelvic hip function plays an important role in activities of daily living. Coordinated muscle function in and around the lumbar vertebra, sacrum, pelvis and femur becomes important when looking at functional ability. As stated by Distefano *et al*. (2009), understanding the activity of muscles of the hip area during functional movements is important in rehabilitation and injury prevention programs. Tateuchi *et al*. (2012) agreed that it is necessary to take note of an imbalance in hip muscle activity as it could give insight into lumbo-pelvic hip dysfunctions. Dysfunctions include anterior and lateral pelvic tilt, excessive lumbar lordosis, and femoral malalignment. Various methods have been developed to assess for the presence of hip muscle activity imbalances. One test that is commonly used for assessment of lumbo-pelvic function is the PHE test (Lehman *et al*., 2004).

2.1. The Prone Hip Extension test:

The PHE test (see Figure 2.1) is used to assess the activation sequence of the hamstrings, the gluteus maximus (Gmax) and the lumbar erector spinae in terms of their role in lumbo-pelvic hip stability (Vogt & Banzer, 1997). The activation sequence is thought to mimic that which takes place during gait (Lehman *et al*., 2004) with extension of the hip serving to ensure that economical movement during human locomotion is achieved (Vogt & Banzer, 1997). The PHE test has shown to have good repeatability when evaluating activation sequence of the muscles involved during hip extension in healthy individuals (Bullock-Saxton *et al*., 1994). The test is however not functional in nature and therefore the results of the testing may not be easy to extrapolate into more functional movements such as walking (Lewis & Sahrmann, 2009). Cochrane and Barnes (2015) and Tateuchi *et al*. (2012) have argued that the use of more functional movements to assess activation patterns may be useful. A similar suggestion is made by Lehman *et al*. (2004) who found that the timing between the onsets of the various muscle during the PHE test is relatively small, which brings into the question the assessment of this movement without surface electromyography (sEMG). Regardless, the test is used clinically in evaluations of lumbo-pelvic function. In the case of a lack of sEMG it is only possible to subjectively test the activation quality/intensity as opposed to testing the activation sequence of the muscles involved.

Figure 2.1. The prone hip extension (Ian Rainsford©)

2.2. Muscle involved during the Prone Hip Extension (PHE) test

Some of the muscles involved during PHE that have been previously evaluated are the hamstrings, the gluteus maximus (Gmax) and the lumbar erector spinae (ES_{Lumbar}). These muscles form an integral role in human locomotion and the stability of the lumbo-pelvic region (Mckenzie *et al*., 2010; Neumann, 2002; Rudolph *et al*., 2001; Schmitt Tyler & McHugh, 2012).

The Gmax is the largest and most superficial of the gluteal muscle group and is situated in the posterior region of the hips just above the upper leg. It is a broad, thick, and fleshy mass of quadrilateral shape (Kang *et al*., 2012). It originates from the posterior quarter of the crest of the ilium, posterior surface of the sacrum and coccyx near the ilium, and fascia of the lumbar area. From here it runs at an oblique angle, laterally and downwards (Kang *et al*., 2012), inserting on the greater trochanter and the iliotibial band. The Gmax can be considered the largest and strongest muscle in the human body.

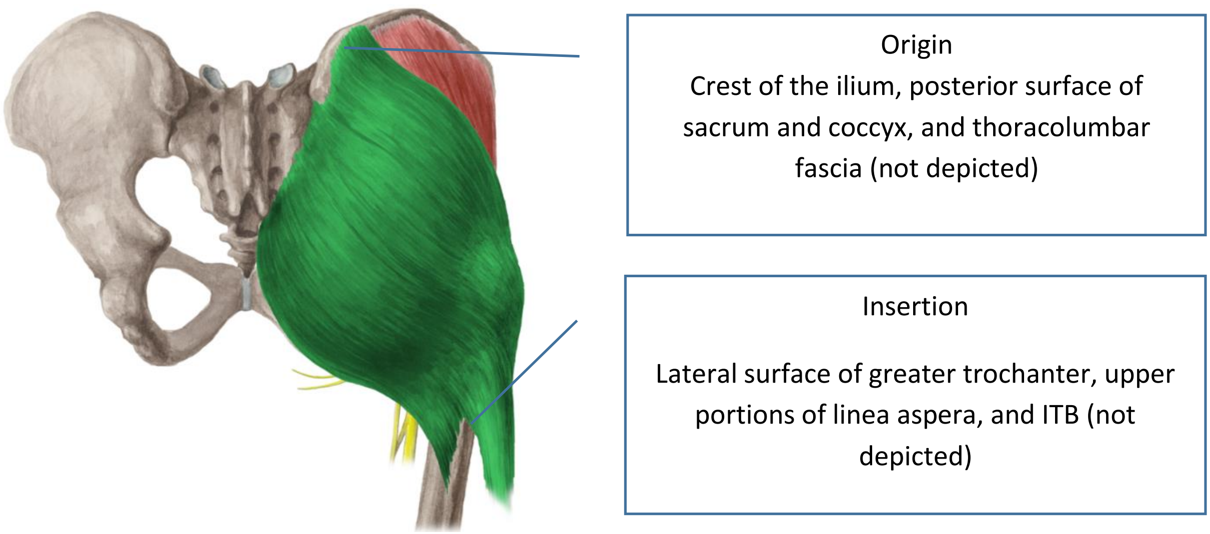

Figure 2.2. The Gluteus Maximus (Kenhub© (www.kenhub.com) / Illustrator: Liene Znotina)

The gluteus medius (Gmed), not often monitored during the PHE test, originates on the outer surface of the ilium between posterior and middle gluteal lines. It then runs obliquely down and laterally and inserts on the posterolateral surface of the greater trochanter (Neumann, 2010). It is important to assess Gmed activity during PHE as the posterior and middle fibres have a secondary role of hip extension (Neumann, 2010).

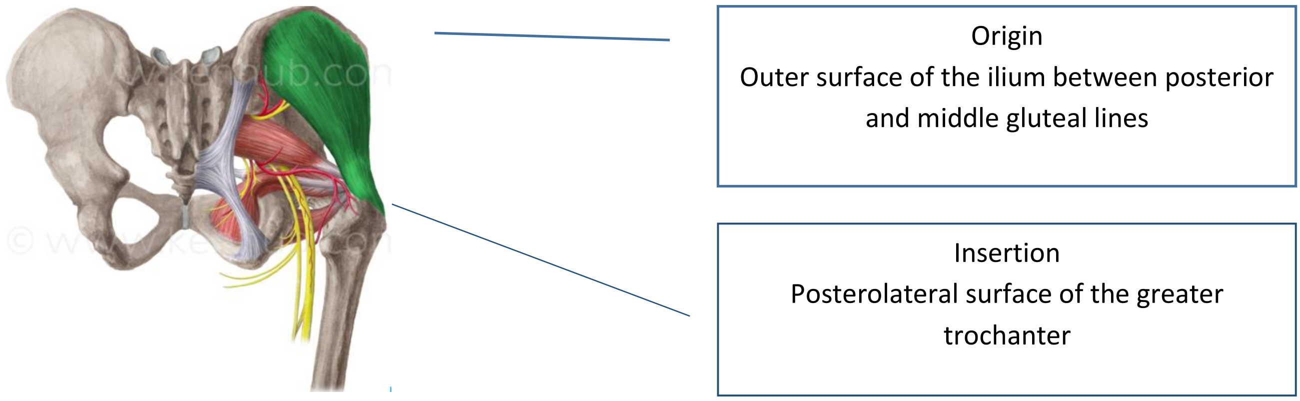

Figure 2.3. The Gluteus Medius (Kenhub© (www.kenhub.com) / Illustrator: Liene Znotina)

The hamstring muscles are multi-joint muscles situated in the posterior thigh region of the thigh. The hamstring muscle group consists of three separate muscles, namely the bicep femoris (BicepFem) (short- and long head), the semitendinosus, and the semimembranosus. The BicepFem is situated laterally while the semitendinosus and the semimembranosus are situated medially. The BicepFem muscle was of particular importance in this study as it is connected to the Gmax via the sacrotuberous ligament (Leinonen at al., 2000). The long head of the BicepFem originates from the ischial tuberosity while the short head of the BicepFem originates from the lateral lip of the linea aspera on the posterior surface of the thigh. Insertion of the BicepFem is on the lateral surface of the head of the fibula and on the lateral condyle of the tibia.

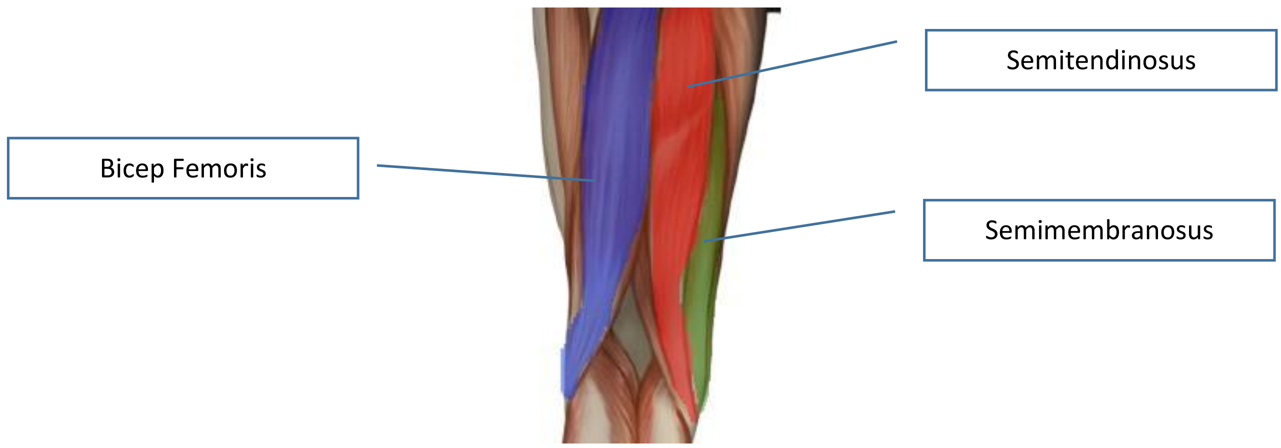

Figure 2.4. The Hamstring Muscle Group (Sports-injury-info.com©)

The erector spinae muscle group consists of three separate muscles, namely the iliocostalis, longissimus, and the spinalis. Of importance when looking at the lumbar erector spinae would be the iliocostalis lumborum and the longissimus lumborum as they produce a stability action at the pelvis during PHE (Vogt & Banzer, 1997). The iliocostalis originates from the crest of the sacrum, spinous processes of the lumbar and lower thoracic vertebras, iliac crest and angles of the ribs. It then inserts on the angles of the ribs and the transverse processes of the cervical vertebra. The longissimus originates from the transverse processes of the lumbar, thoracic, and lower cervical vertebra. It then inserts on transverse processes of the vertebra above the vertebra of origin and on the mastoid process of the temporal bone. The ES_{Lumbar} are connected to the Gmax via the thoracolumbar fascia (Leinonen *et al*., 2000).

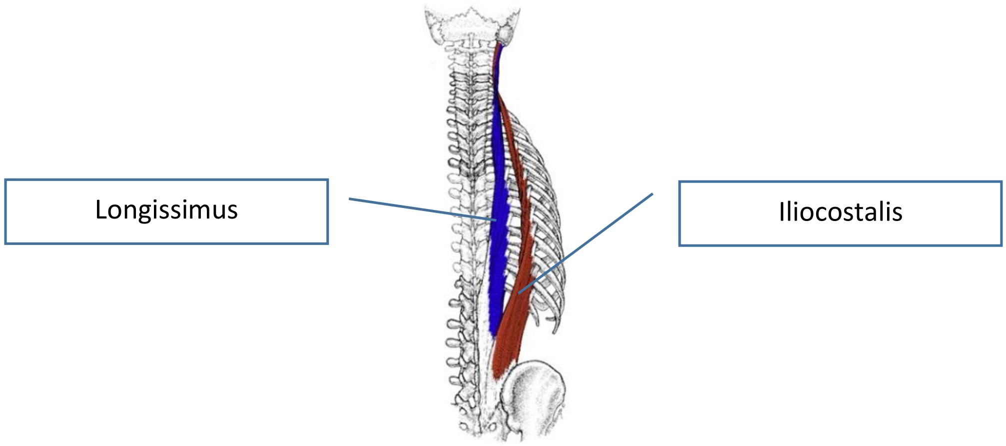

Figure 2.5. The Lumbar Erector Spinae (http://www.myweightlifting.com/erector-spinae-muscles.html)

2.3. Erector spinae and hamstring muscle functions

The ES_{Lumbar} as a group act to extend the lumbar region of the vertebral column with the iliocostalis also acts to laterally flex the vertebral column. It is widely accepted that the lumbar erector spinae are highly active, albeit erroneously, during the PHE. The contralateral lumbar erector spinae (ContraES) serve to stabilize the lumbar spine (Vogt & Banzer, 1997) during Gmax action while the ipsilateral lumbar erector spinae (IpsiES) become overly active in a faulty activation sequence. Decreased Gmax activity in comparison to hamstring activity was found to be linked to increased IpsiES activity during the PHE (Tateuchi *et al*., 2012) which could lead to increased strain on the lumbar region.

As mentioned earlier the hamstrings are multi-joint muscles spanning the knee and the hip. At the hip the BicepFem acts to extend the hip via the use of the long-head and as secondary function acts to adduct the hip (Neumann, 2010). The hamstring muscles also help to stabilize the knee joint by the transfer of load from the knee to the hip joint (Rudolph *et al*., 2001), with it being widely known that the hamstrings help with dynamic knee stabilization during walking, running, jumping, and cutting movements. Neumann (2010) suggested that the hamstrings help to control the forward lean of the body in upright posture. Eccentrically the hamstrings assist in deceleration of hip flexion and knee extension during ambulatory movements (Schmitt *et al*., 2012). At high speeds this places high demand on the hamstrings.

2.4. Gluteus maximus (Gmax) and medius (Gmed) muscle function

It is important to note that the Gmax is connected to the lumbar erector spinae via the thoracolumbar fascia and to the BicepFem muscle (hamstring muscle) via the sacrotuberous ligament (Leinonen *et al*., 2000), which explains the Gmax's role during lower extremity movements as well as pelvic and trunk stabilization (Mckenzie *et al*., 2010).

The Gmed primarily acts to produce abduction at the hip while the posterior and middle fibers can secondarily act to extend the hip (Neumann, 2010). The Gmed plays a vital role in maintaining a level pelvis in the frontal plane by stabilizing the pelvis relative to the femur (Neumann, 2010) and also help to prevent adduction of the femur (Hollman *et al*., 2009) during dynamic tasks. The Gmax primarily serves as a hip extensor and external rotator (Neumann, 2010) and can also serve to decelerate hip flexion during the swing phase and for preparation of accepting the weight of the body at the beginning of stance phase during ambulation. The Gmax can also indirectly assists with knee extension during closed chain exercises. The hamstring muscles assist the aforementioned functions during gait (Steele *et al*., 2010; Neumann, 2010). The Gmax, along with other muscles, is involved in support and progression during the gait cycle (Pandy *et al.*,2010; Lin & Kim, 2010; Anderson & Pandy, 2003). Along with the Gmed and the Vasti muscles, the Gmax provides vertical acceleration of the centre of mass and decreases the forward momentum of the body during the early part of stance phase (Hamner, Seth & Delp, 2010; Pandy *et al*., 2010); thereby assisting in maintaining an upright posture (Kang *et al*., 2013). The Gmax, along with knee and ankle extensors, assists with raising the body's centre of mass when walking uphill with higher levels of Gmax activation when walking at an incline of nine degrees in comparison to walking on level surfaces (Franz & Kram, 2012). The gluteal muscle group is also a major contributor of explosive power in activities such as jumping and running (Crow *et al*., 2012) and as such serves an important role in dynamic sporting activities. Along with the abdominal muscles the Gmax forms a force couple that posteriorly tilts the pelvis; this ensures that excessive lordosis is avoided (Neumann, 2010) thereby lowering the risk of injury to surrounding structures. The Gmax is also known to decrease the load/strain on the lumbar extensors during lumbar extension by taking on most of the load when the moment arm of the load is the greatest (Neumann, 2010). One can therefore assume that with decreased Gmax strength or activity that there will be less protection against lower back injuries during the lifting of loads. The Gmax provides stability to the sacroiliac joint (SIJ) via its attachment to the thoracolumbar fascia (Barker *et al*., 2014). The large portion, approximately 70%, of the Gmax fibers that cross the SIJ indicates that it may contribute to force closure; thereby stabilizing the joint (Barker *et al*., 2014; Kang *et al*., 2013). Results from the study by Barker *et al*. (2014) suggest that the Gmax could play a major role in SIJ compression, and hence stabilization, during activities such as walking, running, and swimming. The Gmax also assists with load transfer between limbs and trunks (Barker *et al*., 2014; Kang *et al*., 2013; Leinonen *et al*., 2000), thereby ensuring optimal distribution and transfer of forces during dynamic activities.

2.5. Gluteus maximus and medius and lower limb alignment

Neumann (2010) states the following (page 82): 'The hip joint serves as a central pivot point for the body as a whole. This large ball and socket joint allows simultaneous, triplanar movements of the femur relative to the pelvis, as well as the trunk and pelvis relative to the femur. Lifting the foot off the ground, reaching towards the floor, or rapidly rotating the trunk and pelvis while supporting the body over one limb typically demands strong and specific activation of the hips' surrounding musculature'. This paragraph by Neumann (2010) sums up the importance of the hips muscles (including the gluteal muscles) during dynamic sporting activities and simply put by Fauth *et al*. (2010): poor strength in the gluteal muscles leads to mal-alignment of the lower extremities.

Lower limb alignment during dynamic/functional tasks is maintained by the eccentric functions of the gluteal muscles. The Gmax acts to eccentrically control/limit internal rotation of the femur while both the Gmax and the Gmed eccentrically act to control/limit excessive femoral adduction (Behm *et al*., 2005; Powers, 2010; Struminger *et al*., 2013). This is further reinforced by Hollman *et al*. (2009) that state that Gmax and Gmed assist in maintaining alignment between the femur and the pelvis in the sagittal, frontal, and transverse planes when they are recruited at appropriate levels to meet external demands during weight bearing. The same authors also found that Gmax activation levels were negatively correlated with knee valgus indicating that decreased Gmax activity could lead to increased knee valgus angles. In a study on lower limb alignment and hip muscle activation, Nguyen *et al*. (2011) evaluated the single limb squat (SQT) in men and women. They noted that a decrease in Gmax activation lead to an increase in femoral internal rotation. They also noted a negative relationship between Gmed activation and hip abduction strength and between Gmax activation and decreased hip extensor strength. They proposed that greater Gmax and Gmed activation was required in order to perform a single limb squat due to the lower levels of strength in these muscles. Similar high Gmax activation levels were noted in women during a SQT in a study by Zeller *et al*. (2003). Nine healthy men and nine healthy women, all collegiate athletes, participated in the study and it was found that women started in and remained in a greater valgus position than the men. This was accompanied by higher Gmax activation levels in the women during the SQT (albeit it not statistically significant). The authors suggest that this could point to decreased control of the hip musculature which in turn increases the risk of injury to the lower limb. The authors also believe that this lack of control would be even more noticeable during jumping or landing tasks. Contrary to these findings, Dwyer *et al*. (2010), found no difference in knee valgus between men and women during the SQT. Differences in findings could be put down to speed of movement, depth of the single limb squat, and methods of measuring knee valgus. Keeping in mind the belief that jumping and landing tasks might challenge women further in terms of the control of hip muscles (Zeller *et al*., 2003) it might be beneficial to look at gluteal muscle activity during such tasks. Sinsurin *et al*. (2013) conducted a study on 18 athletes. Nine of the men played basketball and nine played volleyball. The participants were evaluated in terms of landing from a jump with specific attention placed on knee valgus. Peak knee valgus angles were observed during the first 200ms after landing. Another study into hip muscle activity during single leg landing revealed that Gmax activity in women was decreased post landing in comparison to males (Zazulak *et al*., 2005). Keeping in mind that women tend to start and remain in a more valgus position during a SQT (Zeller *et al*., 2003); and that (although the study focused on men) peak valgus angles can occur immediately after landing (Sinsurin *et al*., 2013); along with the possible role that the gluteal muscles play in resisting knee valgus; one can assume that women are at greater risk for injury to the lower extremities due to altered gluteal function leading to lower limb malalignment during jump and landing tasks. One can assume that strengthening the gluteal muscles would result in improvements in lower limb alignment due to the ability to resist the forces leading to malalignments. A study that initiated an eight week functional hip stabilization program on 28 healthy women (aged 20.71 ± 1.72) observed improved lower limb kinematics. Improvements were noted in knee abduction and femoral internal rotation. This was accompanied by improvements in hip abduction and external rotation torques indicating that there was an improvement in lower limb alignment with an increase in gluteal muscle strength (Baldon *et al*., 2012). This possibly highlights the role played by the gluteal muscles in lower limb alignment. There is however enough contradictory evidence to question if muscle activity or muscle strength plays the largest role.

During typical gait or ambulation the Gmax is strongly recruited at initial contact (Hamner *et al*., 2010). Gmax activation thus becomes very important when looking at lower limb alignment early in the stance phase or at initial ground contact during dynamic activities. Increased hip adduction and knee abduction have been noted in women at initial foot contact during ambulation (Wilson *et al*., 2012), this was also found during the entire duration of the stance phase during running on women (Chumanov, Wall-Scheffler & Heiderscheidt, 2008).

Struminger *et al*. (2013) suggest that muscle activation plays a greater role in the maintenance of this alignment than muscle strength does; this because the above mentioned eccentric functions do not require maximal effort. The timing and amplitude of muscle activation would therefore play the greatest role in overcoming the valgus force applied to the knee during closed chain activities such as cutting, pivoting, and landing movements. By eccentrically controlling these unwanted movements the gluteal muscles help to decrease unwanted or harmful loads on body's lower extremity structures by reducing the effect of valgus forces. At heel contact the Gmax is strongly recruited in that it extends the hip, preventing the trunk from flexing on the femur. The high level of Gmax activation during the early phases of gait become important when looking at lower limb alignment at the start of the stance phase; as the Gmax ensure that the femur is properly aligned ensuring good knee position.

2.6. Gluteus maximus and medius and injuries

In a study on sacroiliac joint (SIJ) dysfunction, Arab, Nourbakhsh & Mohammadifar (2011) evaluated 53 individuals without lower back pain (LBP), 53 with SIJ dysfunction, and 53 with LBP without SIJ dysfunction. Hamstring muscle length and Gmax strength was measured for all the subjects. In the subjects who suffered LBP, 54% presented with Gmax weakness compared to 8% in those without LBP. Gmax weakness was also significantly ($p=0.02$) more prevalent in individuals with SIJ dysfunction than those without SIJ dysfunction. Interestingly in subjects suffering from SIJ dysfunction, the individuals who tested with weakness in the Gmax had significantly ($p=0.04$) shorter hamstring muscles in comparison to those without Gmax weakness. It is suggested that the hamstring shortening might be a compensatory mechanism of stabilizing the SIJ in the presence of Gmax weakness. This possibly being achieved via the provision of tension to the sacrotuberous and long dorsal ligaments adding to force closure at the SIJ. In another study on the SIJ 15 females (aged 15-30 years) sEMG testing of the muscle contributions to the force closure of the SIJ. A significant increase in SIJ stiffness was noted with an increase in muscle activity around the SIJ with the erector spinae, bicep femoris, and Gmax having the greatest impact (Van Wingerden *et al*., 2004). Kang *et al*. (2013) support this by suggesting that altered timing of Gmax onset can lead to an impaired shock absorption mechanism at the SIJ leading to lower back pain. Nadler *et al*. (2002) observed 210 collegiate athletes of which 31 reported lower back pain during the previous year. The athletes with lower back pain had 11.7% stronger left Gmax than the right while non back pain athletes only had a deficit of 5.6%. This indicates that Gmax weakness can predispose an athlete to lower back pain.

Gluteal muscle weakness or poor activity has been linked to numerous lower extremity injuries. Both Gmax and Gmed play a role in force distribution or transfer between the lower back, hips, and knees and also play a role in lower limb alignment. Faulty control of forces acting on the lower extremities and faulty lower extremity alignment increases the risk of injuries to the lower extremities. Hip strength, consisting of gluteal muscle strength, is well established to play a role in patellofemoral pain syndrome (PFPS). In a study into hip strength in 20 females (10 with PFPS and 10 control) it was found that Gmax and Gmed weakness was present in those with PFPS in comparison to the healthy controls ($p \leq 0.007$) in hip abduction, extension, and external rotation. Within the PFPS group there was greater asymmetry present with gluteal weakness present in the injured limb compared to healthy limb (Robinson *&* Nee, 2007). In a theoretical approach to altered lower extremity alignment and PFPS, Powers (2003) state that abnormal frontal and transverse plane tibial and femoral motion may be involved in PFPS through an unfavourable change in quadriceps (Q) angle. Weakness of the Gmax and Gmed can lead to alterations in the Q angle leading to improper line of pull of the quadriceps through the patella-quadriceps-tendon complex leading to altered tracking of the patella increasing the likely of PFPS. Dolak *et al*. (2011) performed a study on females (aged between 16 and 36 years) with PFPS where 17 women underwent hip strengthening and 16 underwent quadriceps strengthening for four weeks. Following this both groups entered a further four weeks of identical functional strengthening. They found that the hip group had significantly less knee pain than the quadriceps group ($p=0.035$). Pain scores at four ($p=0.001$) and eight ($p=0.003$) weeks were also significantly lower than at baseline for the hip group while there was only a difference at 8 weeks for the quadriceps group ($p=0.028$). In a review of hip muscle strengthening and the effects on PFPS, Peters *&* Tyson (2013) found four studies that found a decrease in knee pain following a period of strengthening. In a study conducted on 139 university athletes (79 women and 60 men) over a two year period; the athletes were closely followed for the duration of the season and injury data collected. Ankle injuries accounted for 65% of the injuries, knees for 23%, and hip/back injuries 13% of the total injuries logged. The incidence of injury to women was 35% while that of the men was 22%. Overall the females presented with decreased hip abduction and extension strength (indicating Gmed and Gmax weakness respectively) and it was suggested that women would be more vulnerable to forces in the transverse and frontal planes; thus increasing risk to the lower extremities. In both men and women it was found that a decrease in isometric hip abduction and extension strength was linked to increased incidence of injury; however only a decrease in isometric hip external rotation strength was found to be significantly linked to increased injury risk (p=0.002) (Leetun *et al*., 2004). Nadler *et al*. (2000) observed 210 collegiate athletes of which 74 (35.2%) reported an injury to the lower extremities. In females who suffered lower extremity injuries there was a significant difference (p=0.02) in hip extension strength compared to uninjured athletes. It is proposed that females are more prone to changes in side-to-side strength differences due to factors such as anatomy, gait differences, and playing style. The authors suggest that the greater pelvic width may also lead to alteration in the force distribution of the pelvic musculature. A study on gluteal muscle activity on nine individuals with chronic ankle instability (CAI) (aged 20.9 ± 2.4) and nine healthy (aged 22.9 ± 4.6) revealed that there was significantly lower Gmax activity during a rotational squat (with a moderate-to-strong effect size) in the CAI group compared to healthy controls. There was no significant difference in Gmed activity (Webster & Gribble, 2012). A similar finding was found during the PHE test in individuals with CAI with the Gmax activity decreased compared to healthy controls (Bullock-Saxton *et al*., 1994). Webster & Gribble (2012) speculate that individuals with CAI are not utilizing their Gmax muscles efficiently in order to align the lower extremity thereby leading to the CAI. Weakness of the gluteals are also associated with iliotibial band (ITB) syndrome. Fredericson *et al*. (2000) found significantly weaker hip abduction strength (Gmax and Gmed) between involved and non-involved limb in female runners. The authors also noted a decrease in pain symptoms with an increase in hip abductor torque, suggesting that strengthening the gluteal muscles can lead to improvements in ITB syndrome. Anterior cruciate ligament (ACL) injuries are prevalent in many sport types and occur predominantly from non-contact situations due to excessive forces being applied to the knee during dynamic activities. In a review study into the mechanisms of an ACL injury, Boden *et al*. (2013) found that increased hip flexion (possibly due to decreased eccentric resistance from the Gmax) at injury occurrence. Through other studies they also noted increased knee abduction (occurring during knee valgus due to decreased gluteal strength or activation) increases the risk of ACL injuries. It is important to note that they reported other studies that were not in agreement with this. They also noted that females involved in your more dynamic sports such as basketball, soccer, and volleyball had a two-eight fold increased rate of ACL injury. The main risk factor determined was knee abduction. It was also noted that females have less knee stiffness and therefore perhaps less inherent protection against ACL injuries.

One can see from the above discussions that the function of the Gmax is important, and therefore techniques to investigate its functionality need to be justified and applicable. The PHE test has been used to assess Gmax function but there are individuals who have questioned its functionality (Lehman *et al*., 2004; Lewis & Sahrmann, 2002; Tateuchi *et al*., 2012). As stated by Distefano et al. (2009), it would be important to understand the activity of muscles in and around the hip during functional and more advanced exercises since this would play a vital role in injury rehabilitation and prevention programs. Tateuchi et al. (2012) agreed that it is necessary to take note of an imbalance in hip muscle activity as it could give insight into lumbo-pelvic dysfunctions such as anterior pelvic tilt and excessive lumbar erector spinae muscle activity. More functional movements could perhaps provide more insight into gluteal function. The PHE is more an open kinetic chain movement where your more functional movements are typically closed chain in nature and therefore under the influence ground reaction forces (Cochrane & Barnes, 2015).

2.7. The quadruped opposite/arm leg extension and the single limb squat

The PHE test, even though used clinically, evokes relatively low levels of gluteal activation (9.7 ± 2.9% and 20.16 ± 8.57% of maximal voluntary isometric contraction (MVIC)) (Kang *et al*, 2012; Lewis & Sahrmann, 2009). Other movements might provide greater insight into gluteal function due to the fact that they may recruit the gluteal in a more functional manner thereby eliciting both the mobility and stability/alignment function. The quadruped opposite arm/leg extension (QALE) has been shown to recruit the Gmax at relative high levels with Boren *et al*. (2011) and Ekstrom *et al*. (2007) reporting activation levels of 59.70% MVIC and 56 ± 22% MVIC respectively. The same authors reported Gmed activity of 46.67% MVIC and 42 ± 17% MVIC respectively. Riemann, Bolgia & Loudon (2012) suggest that the higher levels of gluteal activity reported during the QALE are due to the fact that the Gmax and Gmed are acting as both a hip extensor and stabilizers due to controlling movement in multiple planes. The SQT is a more dynamic and functional movement that brings in the extra challenge of dealing with the forces of gravity and the natural angle of the femur against which the gluteal muscle work in order to ensure optimal alignment during tasks. Gmax activation levels during the SQT have been reported to be 70.74% MVIC and 59 ± 27% MVIC while the Gmed activation levels have been reported to be 82.26% MVIC and 64 ± 24% (Boren *et al*., 2011; Ekstrom *et al*., 2007). It has been proposed that exercises in the standing position place more demand on gluteal function and thereby increasing activation as the gluteal help to maintain pelvis position on the femur (hip abductors) and to decrease knee valgus (as hip external rotators (Reimann *et al*., 2012). There is an on-going dispute as to the positioning of the knees during the squat with some clinicians advocating the avoidance of the knee extending forward past the toes. This stems from a study by Ariel (1974) which found that when the knee shifted forward past the toes there was an increase in shearing forces in the knee joint. Fry, Smith & Schilling (2003) replicated the conditions in the study and found a reduction in the shearing forces at the knee joint when the participants were forces to maintain a more vertically positioned tibia (i.e. knees prevented from extended past the toes). This however came at a price with further investigation revealing increased torque exerted at the hip joint; this increase exceeded 1000%. Even though the muscles surrounding the hip are large and capable of producing high levels of torque, one can assume that these forces are excessive. Observation of professional weight lifters reveals that their knees do move beyond their toes slightly (Fry *et al*., 2003) and can perhaps be seen as a normal occurrence during good form. It would be interesting to note that if the knees did move beyond the toes during a squat if there was a resulting decrease in Gmax activity.

2.8. Activation sequence for muscles involved in PHE

Janda (1991) proposed a ‘ideal’ and widely accepted activation sequence for the muscles involved in the PHE as follows: Gmax, then hamstrings, ContraES, and finally IpsiES. The sequence of activation during the PHE test has been extensively studied with conflicting results. Bullock-Saxton *et al*. (1994) conducted a study to determine the effect of ankle injury on the activation sequence. Eleven healthy men (aged 20-35) performed the PHE test from neutral to 15° hip extension. There was a high repeatability of the sequence in repeated motions of the PHE and there was a consistent pattern between limbs. They found that the onset of the four muscles occurred in a very short time span but did report that the movement was initiated by the hamstrings and ended with the onset of the Gmax. It was proposed that, in the presence of no injury, a fixed motor pattern is present. The sequence that Bullock-Saxton *et al*. (1994) found in healthy men did not agree with the proposed ‘ideal’ sequence. Vogt & Banzer (1997) performed a study on 15 right-handed men (aged 23-27 years) where once again PHE (with straight leg) was carried out from a neutral position. It was found that the IpsiES was activated first followed almost simultaneously by the ContraES and the semitendinosus. The last muscle to display activity was the Gmax which was statistically significantly later than the three muscle previously mentioned. The earlier activation of the lumbar erector spinae were proposed as a pre-activation method for the stabilization of the trunk. This was also suggested by Van Wingerden *et al*. (2001) in a study into SIJ stiffness. Once again this sequence observed by Vogt & Banzer (1997) does not agree with the proposed norm. A similar study by Lehman *et al*. (2004) on 10 healthy men revealed that the Gmax was again the last muscle to display activity with a statistically significant ($p<0.05$) delay in activation in comparison to the other muscles. Hamstrings muscles were first followed by the IpsiES and then the ContraES. The authors questioned if indeed an ideal pattern does include the Gmax activating first.

There have been more recent studies on the activation sequence during the PHE test. Lewis & Sahrmann (2009) evaluated activation sequence in eleven women (aged 27.7 ± 6.2 years) during straight leg PHE from 30 degrees of hip flexion to neutral extension. The following order was found: medial hamstrings, followed by the lateral hamstrings and the Gmax last. There was a statistically significant difference in the timing of the medial hamstrings in relation to both the lateral hamstrings ($p=0.06$) and the Gmax ($p=0.03$). When gluteal utilization cues were provided there was no change in the order but the onset times were no longer statistically different. When a hamstring cue was provided both lateral and medial hamstrings onsets were significantly different ($p<0.15$) from that of the Gmax. Gmax cueing had no effect ($p>0.16$) on the timing of the Gmax during the PHE. In a study on both genders (16 men and 15 women, aged between 20 and 36 years), Sakamoto *et al*. (2009), evaluated the activation sequence under varying conditions; knee extended (neutral hip rotation and in external hip rotation), knee flexed to 90 degrees (neutral hip rotation and in external hip rotation). The rotational movement was added in due to the oblique nature of the Gmax and its possible effect on activation sequence. With the knee extended and hip in neutral the Gmax onset was significant later ($p=0.0001$) than that of the other muscles (semitendinosus and ContraES and IpsiES) during PHE and in fact in 50% of the cases was activated prior to the initiation of the movement. With the knee flexed and hip in neutral they found a more variable pattern but the onset of Gmax was again significantly delayed in comparison to the other muscles. When lateral rotation was added to the movements there was variability in the observed activation sequence with a consistency in Gmax activating last. Another study conducted on both men and women (aged 24.3 ± 5.2 years) where the PHE test was evaluated with the movement from 30 degrees of hip flexion into 10 degrees of hip extension found that the Gmax onset was significantly ($p<0.038$) delayed to all other muscles (Tateuchi *et al*., 2012). It was also found that Gmax activation occurred after the initiation of movement. Kang *et al*. (2012) conducted a study on the PHE test with the fibre arrangement of the Gmax in mind. Thirty healthy subjects (18 men and 12 women, aged 22.8 ± 2.9 years) performed the PHE at 0, 15, and 30 degrees of hip abduction which produced significant ($p<0.001$) differences in EMG onset sequence. With the hip in neutral abduction there was delayed Gmax onset in comparison to the hamstrings whereas at 15 and 30 degrees of hip abduction the Gmax onset was before that of the hamstrings. The authors proposed that the abducted position of the femur improved the direction of the line of muscle pull leading to increased EMG activity. Another provided reason for the improved Gmax onset was that in the abducted position the increased Gmax recruitment leads to a lower demand on the synergistic muscle (the hamstring) leading to decreased utilisation of this muscle.

Cochrane & Barnes (2015) evaluated the onset of the BicepFem and Gmax during the hip extension action of a deadlift, a more functional task. They found no difference between Gmax and BicepFem onset, with the Gmax onset occurring prior to hamstrings during lower loads. This sequence changed with increasing load even though the difference was not significant. There is discrepancy in the findings of the activation sequence of the muscles involved with hip extension; however it is very common that the Gmax is the last muscle to display activity. This could be a concern because of the importance of the Gmax during functional activities, in terms of mobility, stability, and alignment.

Inconsistency in the findings of the activation sequences specifically the finding that the Gmax is consistently the last muscle to become active, warrants further investigation.

2.9. Netball

Mothersole *et al*. (2013) state that netball is a sport that requires the need to resist and manage a combination of various forces that arise from actions such as landing from a jump, cutting, pivoting and landing. The same authors also found that netball requires both bilateral and unilateral landing during game time and training. Unilateral landing (65%) was found to be more prevalent than bilateral landing (35%) during the analysis of landing patterns in female netball players. As discussed earlier there tends to be greater knee valgus angles and decreased gluteal strength and activation in females with the valgus being at its peak post landing. These excessive movements at the hip joint combined with decreased strength and/or activity of the gluteal muscles can increase the likelihood of injuries to the lower extremities in netball players. It is well reported that injuries are more likely to occur during single limb activities during landing activities (Mothersole *et al*., 2013; Sinsurin *et al*., 2013). This is confirmed by Ferreira & Spamer (2010) that state that faulty landing technique is the most common mechanism of injury in netball. This being said it is likely that knee and ankle injuries are a common occurrence in netball players. In a study conducted by Coetzee, Langeveld & Holtzhausen (2014) on 1280 South African netball players at u/19 and u/21 a total of 205 injuries were sustained by 192 players (15% of the players sustained one or more injuries). Questionnaires were then used to collect data on training modalities. It was found that 51.7% of the injured players did not participate in any core stability training during the season while 57.7% of the injured players did not do any neuromuscular training to improve landing technique. Further disturbing findings were that up to 59% of the injured participants made no attempt to perform proprioceptive training. Training or playing surface was also found to be a major risk factor for injury with 80% of the injuries occurring on the cement playing surface in comparison to the synthetic surface. This is an important factor to note in netball as many South African netball players make the use of cement based training and playing surfaces. Further investigation into the distribution of injuries in the same population revealed that of the 205 injuries during the tournament, 91% of the injuries were acute in nature (Langeveld, Coetzee & Holthausen, 2012). Of the 205 injuries, 36.1% were at the ankle joints and 18.5% were at the knee joints. Alarmingly up to 48.7% of the ankle injuries were recurrent in nature possibly alluding to inappropriate rehabilitation or correction of movement/muscular dysfunction. The ankles (39.13%) and the knees (28.26%) were also found to be the most prevalent sites of injury in another study on elite u/19 South African female netball players (Ferreira & Spamer, 2010). Very similar studies were found by Pillay & Frantz (2012) in a study on 360 South African netball players. The ankles accounted for 37.5% and the knees 28.6% of all injuries at a national netball tournament. These studies go to show that knee and ankle injuries are very common in netball. Earlier discussions reveal that the gluteal muscles play a large role in lower limb alignment and injury prevention in the lower extremities and further investigation into gluteal function in netball players is warranted.

Problem Statement

Various studies have evaluated whether or not there is a consistent pattern of muscle activation during the PHE. The hope is to justify the widely accepted ideal activation pattern previously described (Bullock-Saxtion *et al*., 1994; Cochrane & Barnes, 2015; Kang *et al*., 2013; Lehman *et al*., 2004; Lewis & Sahrmann, 2009; Sakomoto *et al*., 2007; Tateuchi *et al*., 2012; Vogt & Banzer, 1997). However, the conflicting results either indicate poor AS or bring into question the proposed ‘ideal’ activation pattern (Janda, 1991) with the Gmax regularly found to be the last muscle to be activated.

The possibility of poor AS of the hip extensor chain is very possible due to relatively sedentary lifestyles seen in modern times. It has been reported that many adults are spending up to 70% of the waking day in a seated position (Owen *et al*., 2010) and this increased sitting time accompanied by less time spent moving could lead to a decrease Gmax recruitment, as the Gmax is known to contribute significantly to postural and functional abilities such as typical gait (Ayotte *et al.*, 2007). This could be equated to the effect seen in muscles surrounding a joint during a time of immobilization, which leads to atrophy and decreased muscle activation/neural excitation. If this was the case, one may see a low number of evaluated hip extensor chain firing patterns agreeing with the norm. Faulty coaching techniques or, in the case of recreationally active individuals, improper focus of strength training could place too much emphasis on other muscle groups (i.e. quadriceps and abdominals) leading to poor training of the Gmax. This would also surely affect an individual's ability to optimally recruit this large muscle.

The ability of the PHE to evaluate lumbo-pelvic function becomes questionable on account of previous studies reporting conflicting results, or perhaps the proposed 'ideal' firing pattern of the hip extensor chain is flawed. This proposed AS provides a standard upon which therapeutic evaluations are based, but if the norm is invalid (i.e. early activation of the hamstrings or ES_{lumbar} prior to the Gmax) it would make attaining it very challenging. Therefore, if the proposed AS norm for this muscles chain is indeed optimal but the evaluation method does not have the capability to display improved recruitment/activation, then the evaluation method needs to be altered.

Assuming the 'ideal' activation pattern for the hip extensor chain is as described by Janda (1991), that is to say, Gmax → hamstrings → ContraES→ IpsiES, then the need to evaluate whether or not the PHE is an acceptable test for assessing hip extensor chain firing patterns becomes important. It is also important to assess whether or not gluteal training could have a beneficial effect in 'normalizing' the order of muscle activation in the presence of an incorrect AS. To the researchers knowledge this has not yet been assessed.

Furthermore, gluteal activation and strength have been shown to play a role in lower limb alignment and hence in the prevention of lower extremity injuries. A decreased focus on gluteal muscle strength and activity in sports such as netball can increase the likelihood of injury to the lower as a result of poor lower limb alignment (Ferreira & Spamer, 2010; Mothersole *et al*., 2013; Sinsurin *et al*., 2013). It has also been found that the most common mechanism of injury to the lower extremities in netball occurs during unilateral landing (Ferreira & Spamer, 2010; Mothersole *et al*., 2013; Sinsurin *et al*., 2013) and that there is lower Gmax activity post-landing in women (Zazulak *et al*., 2005). Peak knee valgus positions are also reported to occur immediately following landing from a single limb jump (Sinsurin *et al*., 2013). Ankle and knee injuries are very common in netball (Coetsee *et al*., 2014; Ferreira & Spamer, 2010; Pillay & Frantz, 2012) and it has been shown in research that ankle and knee injuries have been linked to gluteal muscle weakness (Boden *et al*., 2003; Bullock-Saxton *et al*., 1994; Dolak *et al*., 2011; Fredericson *et al*., 2000; Peters & Tyson, 2013; Robinson & Nee, 2007; Webster & Gribble, 2012). Increased valgus forces have also been observed during the gait cycle of women during regular ambulation and running (Chumanov *et al*., 2008; Wilson *et al*., 2012). It can, therefore, be assumed that women are at a higher risk for injuries to the lower extremities. In addition, netball participation provides and increased risk due to the single limb landing strategies employed. Consequently, there is a need to investigate gluteal muscle function and lower limb alignment in this population. If it can be shown that gluteal training could have a positive effect on 'normalizing' faulty activation sequences during hip extension movements with a concomitant improvement in lower limb alignment it would provide valuable information to injury prevention and rehabilitation exercises.

Research Aims

Primary Aim:

Comparing the PHE to other functional movements as therapeutic assessment methods for gluteus maximus onset after a nine-week gluteal training program.

Secondary Aim:

The secondary aim of this study was to investigate the role of the gluteal muscles and gluteal strengthening in lower limb alignment in club-level netball players after a nine-week therapeutic exercise intervention.

Objectives:

The objectives of the study were to

1. Describe existing pre-intervention muscle recruitment patterns during the PHE in recreational netball players. (Chapter 3: Article 1)
2. Determine gluteal onset during hip extension movements (Chapter 3: Article 1)
3. Determine if a nine-week gluteal training intervention program could affect the onset of muscle activation in the hip extension chain during various exercise postures. (Chapter 4: Article 2)
4. Determine whether or not a nine-week gluteal training intervention program will effect lower limb alignment during a single limb squat functional task (Chapter 5: Article 3)

Chapter Three

Article One

Gluteus maximus onset during unloaded, quadruped, and functionally loaded tasks in club-level netball players.

Mr. Ian George Rainsford (Corresponding author: irainsford@sun.ac.za)

Dr. Rachel Elizabeth Venter

Dr. Karen Estelle Welman

Department of Sport Science, Movement Laboratory, Stellenbosch University, Matieland, 7602, Western Cape, South Africa

Keywords: Gluteus maximus, Prone hip extension, Electromyography, Onset

Abstract

The purpose of this study was to compare electromyographic analysis of the gluteus maximus, bicep femoris and lumbar erector spinae muscle activation sequences in young healthy netball players. Eighteen women performed bilateral prone (PHE), quadruped (QALE) and single limb (SQT) functionally loaded hip extension exercises while surface electromyography was recorded from hip and lumbar spine extensor musculature. No consistent activation sequence was noted during the three exercises. Gluteus maximus onset was earlier than bicep femoris for dominant PHE ($p<0.001$), and earlier than gluteus medius for non-dominant PHE ($p<0.001$). Ipsilateral erector spinae and bicep femoris onset was earlier than gluteus maximus in dominant and non-dominant QALE respectively ($p<0.001$). Gluteus maximus onset showed no difference compared to other muscles during both SQT ($p>0.05$). The muscle activation sequences were contradictory to that proposed by Janda (1991) during prone, quadruped and single limb functionally loaded hip extension exercises.

1. Introduction

Observing muscle activation sequences (ASs) during prone hip extension (PHE) is commonly used during lumbo-pelvic function assessments, even though the order of muscle ASs during PHE has been widely debated (Lehman et al., 2004). The PHE specifically assesses musculoskeletal dysfunction and gluteus maximus (Gmax) activation, and may also be recommended as an exercise for rehabilitation (Lehman et al., 2004; Lewis and Sahrmann, 2009). A widely accepted AS was first proposed by Janda (1991) i.e. Gmax→hamstrings→contralateral lumbar erector spinae (ContraES)→ipsilateral lumbar erector spinae (IpsiES). Some studies have indicated that medial hamstring, then lateral hamstring muscles are the first muscles to display surface electromyography (sEMG) activity with Gmax being the last (Bullock-Saxton et al., 1994; Kang et al., 2012; Lewis and Sahrmann, 2009; Vogt and Banzer, 1997); while others reported no consistent pattern (Lehman et al., 2004; Pierce and Lee, 1990). Possible reasons for the inconsistent findings could include methodological differences, gender, and exercise experience. However, the Gmax appears to be consistently the last muscle to display sEMG activity (Bullock-Saxton et al., 1994; Kang et al., 2012; Lehman et al., 2004; Vogt and Banzer, 1997). It is believed that faulty ASs (i.e. premature activation of spinal erector and hamstrings or a delay in gluteal muscle activation) could increase injury risk and lower extremity malalignment (Lewis and Sahrmann, 2009). During hip extension, weak or delayed Gmax activation may result in compensatory strategies such as tight hamstring muscles, excessive anterior tilt, lumbar lordosis associated with strong ES_{Lumbar}, and lumber rotation (Choi et al., 2015).

In closed kinetic chain movements, like cutting, pivoting and landing, a valgus force is exerted on the knee via a combination of hip adduction and internal rotation (Hollman et al., 2009). Non-contact knee injuries often reported during single limb landing activities (Mothersole et al., 2013; Sinsurin et al., 2013). Mothersole et al. (2013) found that unilateral landings are 30% more common than bilateral landings in netball. The Gmax, along with gluteus medius (Gmed), acts to maintain lower limb alignment by eccentrically controlling the adduction and internal rotation of the thigh (Boren et al., 2011; Struminger et al., 2013). Lehman et al. (2004) suggested that a difference in ASs decreases pelvic stability during gait thereby affecting the body’s mechanical efficiency. Early hamstring activation contributes to hip dysfunction and anterior hip pain due to increased anterior joint forces (Lewis and Sahrmann, 2009). Consequently faulty ASs should be corrected to ensure decreased stress on the hip joint and spine.

During the PHE, Lewis and Sahrmann (2009) found Gmax activation at low levels of about 9.7 ± 2.9% of maximal voluntary isometric contraction (MVIC) and Kang et al. (2012) reported Gmax activation at 20.2 ± 8.6% MVIC. The Gmax muscle is also recruited during the quadruped opposite arm and leg extension (QALE) with 56-60% MVIC (Boren et al., 2011; Ekstrom et al., 2007). The single limb squat (SQT), which is even more functional, has shown to recruit the Gmax at 59-71% MVIC) (Boren et al., 2011; Distefano et al., 2009). In both QALE and SQT the Gmax may be required to produce a mobilisation and stabilization function. The more unstable body position during the QALE and SQT movements, in comparison with the PHE, may possibly evoke more Gmax activation.

The aim of this study was to investigate whether female netball players use a distinct and consistent muscle AS when extending the hip during prone and functional movements. Examining hip extensor muscle activity under various functional conditions may provide insight into effective Gmax activation for clinical evaluation and interventions; thereby establishing the appropriateness of the PHE test.

2. Methods

2.1. Participants

Of 20 individuals who volunteered, 18 apparently healthy club-level netball players from the same university club met the inclusion criteria (age = 19.1 ± 1.3 years, body weight = 65.4 ± 7.0 kg and height = 172.6 ± 6.7 cm; Table 3.1). Players were excluded if they had any lower back, lower extremity or pelvic girdle injuries/pain in the preceding six months, or if they had been diagnosed with any neurological or musculoskeletal conditions. Prior to participation, players completed a medical information questionnaire (appendix C), were informed of any risks or discomforts and that they may withdraw at any time, after which they gave written informed consent (appendix B). This descriptive study was approved by the Stellenbosch University's Human Research Ethics Committee (HS941/2013).

Table 3.1
Participant descriptive statistics (n= 18)

Variable	Mean	SD	Range
Age (years)	19.1	±1.3	3
Height (cm)	172.6	±6.7	21
Weight (kg)	65.4	±7.0	25.4
BMI (kg.m^{-2})	21.9	±1.6	5.1
Waist Circumference (cm)	97.21	±4.51	13.9.
Limb Dominance	Right		Only Right

BMI: Body Mass Index; SD: Standard Deviation

2.2. Experimental procedures

The netball players wore their own tight fitting athletic shorts, a loose fitting t-shirt and were unshod for the testing. Upon arrival at the Movement Laboratory (Stellenbosch University) the participants' height and body mass were assessed using the Detecto® mechanical scale and stadiometer (Webb City, Missouri, U.S.A). Maximal gluteal circumference was measured using a Lufkin® tape measure (Executive Thinline, Apex Tool Group Pty Ltd, Melbourne, Australia) and recorded to one decimal place. All measurements were done and instructions given by a qualified clinical exercise therapist. The players performed three single limb exercises under sEMG recordings i.e. the PHE, QALE, and SQT (Fig 3.1). Ten repetitions were performed bilaterally with a 3-s pause between repetitions. Before data collection, participants were instructed as to the proper technique and were allowed to perform two supervised practice repetitions. Participants were coached to adhere to the following cues: level hips, no lumbar hyperextension, and weight on the heel during the SQT.

a b c

Fig. 3.1. Exercises performed for testing: a) PHE, b) QALE, c) SQT.

2.3. Surface electromyography

Surface electromyography (sEMG), using the Telemyo DTS system (Noraxon Inc., Scottsdale, Arizona, USA), quantified the activity level of the erector spinae, Gmax and bicep femoris (BicepFem). The sEMG signals were recorded using the MyoResearch XP (version 1.08) Master data acquisition system (Noraxon, USA Inc., Scottsdale, Arizona). The electrode placement sites were cleared of unwanted hair, skin was debrided and cleaned with alcohol swabs (Intra-tester ICC = 0.60). Pre-gelled Ag-AgCl Nicolet® (Biomedical, Division of VIASYS, Madison, USA) dual disposable electrodes with an inter-electrode distance of 1cm were applied over four muscle sites: bilateral lumbar erector spinae, 2cm laterally from L5/S1 vertebra (Behm et al., 2005); bilateral Gmax, 34% the distance from the 2nd sacral vertebrae to the greater trochanter (Rainoldi et al., 2004); bilateral BicepFem, 35% the distance from the ischial tuberosity to the lateral side of the popliteal fossa (Rainoldi et al., 2004); bilateral Gmed 50% the distance of the line extending from the iliac crest to the greater trochanter (Hermens and Fredriks, date unknown). The wireless sEMG sensors were applied using double sided tape. Site location was performed via manual palpation, followed by a signal check. Raw EMG signals were processed into root mean square and a Butterworth filter with a band-pass filter of 20-500Hz was used and collected at a sampling rate of 1000Hz.

The baseline sEMG for each muscle in each movement was calculated over 5-s in the starting position. The onset of sEMG activity of each muscle was determined when the sEMG amplitude exceeded five standard deviations of the determined baseline level for a minimum of 50ms (Brindle et al., 2003; Wilson et al., 2012). The onset of the first repetition was used for analysis. Similar to Lewis and Sahrmann (2009), an improper return to baseline with repeated repetitions was noted in the current study. Muscle onset was reported relative to the Gmax onset which was seen as zero. A negative value would indicate that the other muscles activated before the Gmax. Matlab® (MathWorks Inc. Natick, MA, USA) was used for onset analysis. When the onset was not visually determined acceptable (using graphic plots) appropriate changes were made to the Matlab® (in a blinded manner) to reduce the chance of a false onset.

2.4. Statistical analysis

Statistical analysis was performed with Statistica version 12 (StatSoft, Inc., Tulsa, OK, USA) and Microsoft© excel 2013 (Microsoft Corporation®, Redmond, USA). Tests for normality using skewness revealed non-normally distributed data and therefore non-parametric Friedman ANOVA's were performed to determine any significant difference in the timing of the onset of the muscles during the PHE, QALE, and SQT with Wilcoxon matched pairs confirmation (Bonferroni correction at $p<0.005$). Ass were reported relative to Gmax (zero-point) and each muscle group was provided a number and activation sequences described accordingly. Alpha level was set at 0.05.

3. Results

3.1 Timing of muscle activation during PHE

There was a significant difference in the timing of the onsets of the muscles during the dominant (main effect $p=0.001$) and non-dominant (main effect $p=0.001$) PHE (Fig 3.2). For the dominant PHE, three (18.75%) participants initiated the movement with the ContraES, nine (56.25%) with the IpsiES, and six (37.50%) with the Gmax. Fifteen (93.75%) participants displayed Gmax onset prior to BicepFem activity, with three (18.75%) showing the reverse sequence. Two participants' data were excluded due to outliers in terms of excessive onset time values.

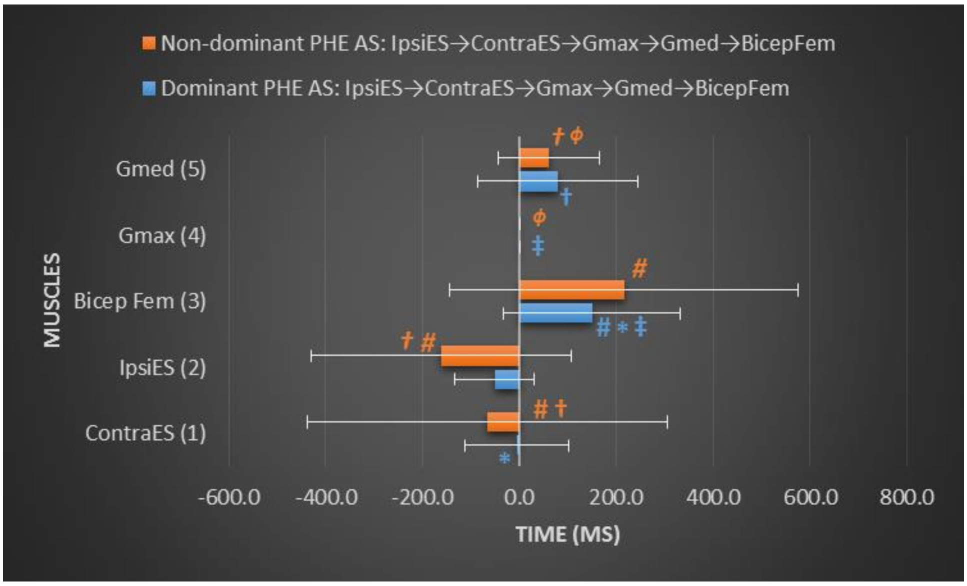

Fig 3.2. Mean muscle onsets relative to Gmax during PHE.
Gmed = gluteus medius, Gmax = gluteus maximus, BicepFem = bicep femoris, IpsiES = ipsilateral lumbar erector spinae, ContraES = contralateral erector spinae, PHE = Prone hip extension.
Non-dominant: † p = 0.003, ϕ p = 0.005, # p = 0.002.
Dominant: † p = 0.002, ‡ p = 0.002, * p = 0.005, # p < 0.000.

For the non-dominant PHE, twelve (66.67%) participants initiated the movement with the ContraES, one (0.56%) with the IpsiES and BicepFem each, and two (11.11%) with the Gmax. Twelve participants displayed BicepFem onset after that of Gmax, with two showing the reverse sequence.

3.2. Timing of muscle activation during QALE

Analysis of the dominant QALE the first active muscle was the IpsiES reveals that the dominant IpsiES and the Gmax last. There was a significant difference in the timing of the various muscles during the dominant QALE (main effect p=0.01). During the non-dominant QALE the first muscle to become active was the BicepFem and Gmax the last (Fig. 3.3). A difference was found in the muscles' onset timing during the non-dominant QALE (main effect p=0.001).

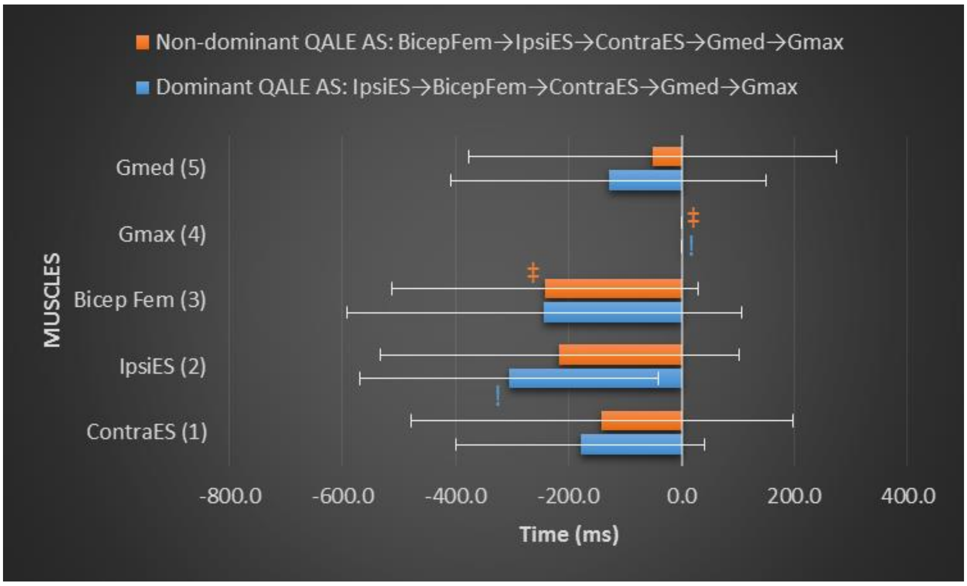

Figure 3.3. Mean muscle onsets relative to Gmax during Quadruped opposite arm/leg extension

Gmed = gluteus medius, Gmax = gluteus maximus, Bicep Fem = bicep femoris, IpsiES = ipsilateral lumbar erector spinae, ContraES = contralateral erector spinae

Non-dominant: ‡ p = 0.003

Dominant: ! p = 0.001

3.3. Timing of muscle activation during SQT

The ContraES was the first muscle to become active during the dominant SQT and Gmed last. Non-dominant SQT (Fig. 3.4) analysis revealed that the IpsiES was the first muscle to become active and Gmed last. A significant difference was found in the timing of the onset of the muscles during the non-dominant (p=0.01), but not during the dominant SQT (p=0.11).

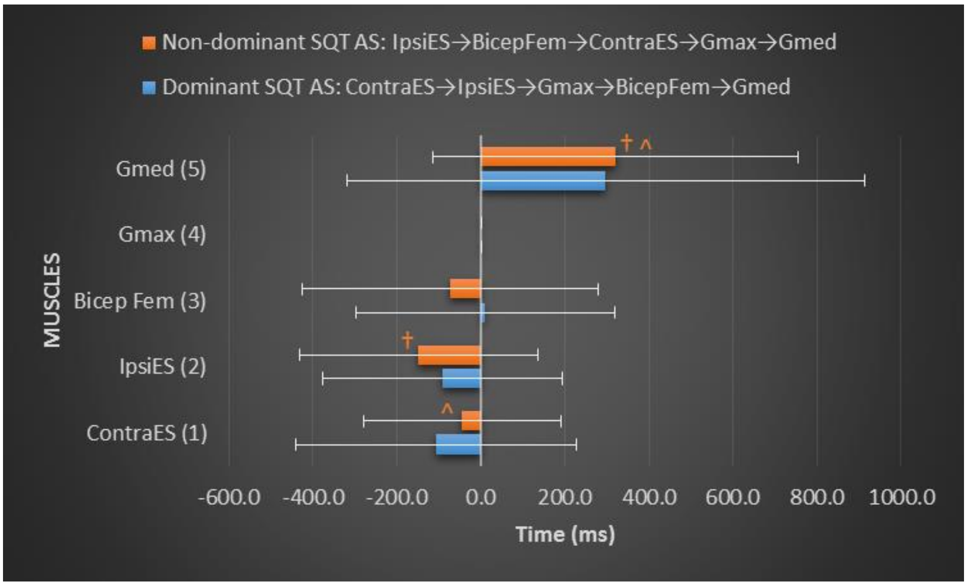

Figure 3.4. Mean muscle onsets relative to Gmax during Single limb squat

Gmed = gluteus medius, Gmax = gluteus maximus, Bicep Fem = bicep femoris, IpsiES = ipsilateral lumbar erector spinae, ContraES = contralateral erector spinae

Non-dominant: † p = 0.001, ^ p = 0.003

4. Discussion

Assessing the PHE muscle AS has been extensively researched but with conflicting results. The main findings of the study revealed no consistent AS for each of the PHE, QALE, or SQT in club-level netball players. It was noted that during dominant and non-dominant PHE (with a flexed knee) the BicepFem was the last muscle to display onset and that the Gmax was not the first muscle to become active as proposed by Janda (1991). Also not in agreement with Janda’s ideal AS was that the Gmax was consistently the last muscle to become active during the dominant and non-dominant QALE, and the ContraES and IpsiES initiated the dominant and non-dominant SQT movement respectively.

The dominant PHE showed the same AS as non-dominant PHE with the IpsiES initiated the movement followed by the ContraES. The Gmax and the ContraES displayed onsets almost identical with only a 5.9 ms separating the two onsets. In contrast to non-dominant PHE, the Gmax onset was significantly earlier than that of the BicepFem. The BicepFem onset was also significantly later than that of the IpsiES and ContraES. During the non-dominant PHE, the Gmax onset was only significantly earlier than the Gmed with both the Gmed and BicepFem onset being significantly later than the IpsiES. The early activation of the IpsiES was similar to that of Vogt and Banzer (1997) with the only difference in the sequence being that they noted the Gmax onset after that of the hamstrings. Subjects in their study were active men aged between 23 and 27 years. Lehman et al. (2004) reported early ContraES activation and found the Gmax onset to be last, while the current study found the BicepFem to be last in young men and woman. Differences in the performance of the task can account for this disparity between studies. Both Lehman et al. (2004) and Vogt and Banzer (1997) had the knee extended during PHE, while the knee was flexed in the current study. The flexed knee places the hamstrings in a position of active insufficiency (Lewis and Sahrmann, 2007), possibly decreasing its ability to perform hip extension. While in a position of knee extension the hamstrings are in ‘neutral’ length and may be more easily recruited during the PHE. However, the knee flexion position could place the limb in a position that optimizes Gmax recruitment (Kang et al., 2013). Kwon and Lee (2013) showed that PHE at 0° resulted in significantly higher BicepFem activation, whereas Gmax was more pronounced at 60, 90 and 110° knee flexion. Sakamoto et al. (2009) also performed the PHE with knee in flexion and noted that most participants (32%) initiated the PHE with either the IpsiES or the hamstrings. In contrast to Sakamoto et al. (2009), who found that the Gmax was consistently (79%) last, the current study found the BicepFem to be consistently the last. The studies used both men and woman in their early twenties.

The earlier onset of the IpsiES could be due to the flexed position of the knee decreasing the efficiency of the hamstring over the hips, thereby forcing the lumbar erector spinae to cause anterior pelvic tilt to maintain muscular efficiency (Tateuchi et al., 2012). The early onset of the IpsiES and ContraES in both non-dominant and dominant PHE has been proposed as an anticipatory mechanism (pre-movement), in order to help stabilize the trunk for the movement of the hip (Vogt and Banzer, 1997). The earlier activation of the ES_{Lumbar} may be due to weak or inactive Gmax. Other studies have shown the hamstrings to be the first muscles to display onset during the PHE (Bullock-Saxton et al., 1994; Lewis and Sahrmann, 2009; Sakamoto et al., 2009; Tateuchi et al., 2012); however these studies were performed with the knee extended. As stated before the different knee positions during the PHE tests could explain the different findings. The other key difference in the studies by Tateuchi et al. (2012) and Lewis and Sahrmann (2009) is that the PHE was performed from a hip flexion position while the current study was from neutral flexion. In a hip flexion position the moment arm of the Gmax is influenced, hence hamstring efficiency is increased while that of Gmax is decreased (Tateuchi et al., 2012). Starting the PHE in a position of relative hip flexion therefore seems to favour the early activation of the hamstrings in comparison to the Gmax, and therefore the flexed knee position may be better for the assessment of Gmax recruitment.

The one concern with the PHE test is that it is not considered functional in nature (Lewis and Sahrmann, 2009). Therefore researchers investigate other more functional movements as a possible alternative assessment tool for therapists. To the researchers' knowledge no studies have evaluated the timing of the onset of the hip extensor muscles during the QALE. The QALE involves extension of the hip using similar muscles to that involved in the PHE, but with the femur starting in a position of hip flexion. The dominant QALE was IpsiES→BicepFem→ContraES→[Gmed]→Gmax while that of the non-dominant QALE AS in the current study was found to be: BicepFem→IpsiES→ ContraES→[Gmed]→Gmax. In comparison to the PHE the Gmax onset bilaterally occurs last. During the non-dominant QALE the Gmax was significantly delayed in comparison to the BicepFem while during the dominant QALE the Gmax was significantly delayed to the IpsiES. It is interesting to note that in the majority of participants (16/18), BicepFem onset occurred before that of the Gmax during the non-dominant QALE, while it was 12/18 during the dominant QALE. This high number of earlier BicepFem onset can also be explained by the suggestion that the hamstrings have improved efficiency in comparison to the Gmax from a position of relative hip flexion (Tateuchi et al., 2012). However this is not supported by Ekstrom et al. (2007) who noted increased activity (%MVIC) of the Gmax and Gmed in comparison to the hamstrings during the QALE. Electrode placement site of the Gmax and the hamstrings differed to that of the current study. Nevertheless, drawing conclusions from two different variables (i.e. onset vs. peak activation) should be avoided.

The SQT is another functional movement that involves hip extension, using similar muscles to the PHE, but with increased demand on the gluteal muscles, as it evokes both a mobilisation and stabilization function. The gluteal muscles work to produce femoral-on-pelvic extension, prevent functional knee valgus collapse, and maintain a pelvic-on-femoral stability. Results from the current study show that the non-dominant SQT AS is IpsiES→BicepFem→ContraES→Gmax→[Gmed] while the dominant SQT has an AS of ContraES→IpsiES→Gmax→BicepFem→[Gmed]. The only significant difference in onset time was between the Gmed and both the IpsiES and ContraES. Both dominant and non-dominant SQT were initiated by either the IpsiES or ContraES; this early onset of lumbar erector spinae may be as a prevention of lateral torso flexion due to the unilateral nature of the SQT. The lumbar iliocostalis muscles act in isolation to laterally flex the torso and could therefore eccentrically act to prevent torso flexion to the opposite side during a unilateral task. Delayed Gmed onset might come as a surprise due to its widely accepted function during single limb activities in the maintenance of pelvic and femoral position (Behm et al., 2005; Neumann, 2010; Powers, 2010; Struminger et al., 2013). A possible explanation could be that the start position, used to obtain a baseline activity value to calculate Gmed onset, already had evoked a high level of Gmed activation. There may, therefore, not have been a significant change from baseline in Gmed activation during the SQT performance. It is, however, still important to evaluate onset of the Gmed during functional activities as Brindle et al. (2003) found delayed onset of the Gmed during stair climbing in individuals with anterior knee pain. There was less bias in BicepFem onset opposed to Gmax onset with only 9/18 participants displaying BicepFem activation before Gmax during the non-dominant SQT and only 7/18 during the dominant SQT. The shift to a more even spread indicates that during the SQT the Gmax is recruited earlier than during the QALE (which was confirmed by the mean onset time). It could be that the increased demands placed on the gluteal muscles during upright tasks (Reiman et al., 2012) leads to earlier recruitment of the Gmax in order to maintain lower extremity alignment (Behm et al., 2005; Powers, 2010; Struminger et al., 2013) or to prevent an anterior collapse of the torso (Hamner et al., 2010; Pandy et al., 2010). Furthermore the hip flexion angle during the SQT does not reach the same peak flexion as during the QALE, possibly ensuring more favourable conditions for improved Gmax onset times. The SQT however does not take the hip past 180° which is what occurs during ambulation.

A possible limitation of the study was assuming that an ideal PHE AS exists (Janda, 1991). This sequence is still regarded as the gold standard in clinical practice even though numerous studies have investigated this with conflicting results (Bullock-Saxton et al., 1994; Kang et al., 2012; Lehman et al., 2012; Lewis and Sahrmann, 2009; Sakamoto et al., 2009; Tateuchi et al., 2012; Vogt and Banzer, 1997). There were a number of further limitations to this study such as the exclusion of other multi-joint hip extension muscles (Neumann, 2010). The isolation of the BicepFem as a hamstring muscle was due to its connection to the Gmax via the sacrotuberous ligament (Leinonen at al., 2000) and this fascial connection is believed to have an influence in activation sequences. As shown by Kang et al. (2012) and by Sakamoto et al. (2009) Gmax activity and/or onset are influenced by hip abduction and thigh lateral rotation, respectively. This study did not account for, or prevent, hip abduction or thigh lateral rotation specifically during the PHE and QALE. Future studies should ensure to account for unwanted abduction or lateral thigh rotation. Repeated repetitions of the PHE gives rise to improper return to baseline activity between repetitions (Lewis and Sahrmann, 2009) as was found in this study. Only the first repetition could therefore be used to analyse muscle onset during the various movements. Future studies should record each repetition in isolation ensuring a new and proper baseline level between repetitions upon which to calculate onset. Finally, novelty of the current study was the assessment of Gmed, which made comparisons with other studies difficult.

5. Conclusion

This study evaluated muscle AS during the PHE, QALE, and SQT in order to describe the AS found in club-level netball players and to establish the appropriateness of the PHE test. Lehman et al. (2004) supported the need to develop and investigate other means of assessing neuromuscular function than the PHE.

The three movements included followed altered AS than the proposed AS of Janda (1991).The PHE test is likely a more appropriate test for muscle AS than the QALE and the SQT as both of these movements place the hip in a more flexed position. It may also be more beneficial to perform the PHE test with the knee flexed as opposed to the knee extended as it might optimise Gmax recruitment. Furthermore since the timespan from the first to last muscle is relatively short (timespan ranged from 144ms to 668ms), the ability to evaluate ASs during these tasks without the use of sEMG becomes questionable. Without the use of sEMG, one may only be able to subjectively assess for differences in contraction quality between the muscles in a clinical setting.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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Chapter Four

Article Two

A nine-week gluteal training intervention alters the timing of gluteus maximus onset during the prone hip extension test in netball players with no change in functional movement pattern.

Mr. Ian George Rainsford (Corresponding author: irainsford@sun.ac.za)

Dr. Rachel Elizabeth Venter

Dr. Karen Estelle Welman

Department of Sport Science, Movement Laboratory, Stellenbosch University, Matieland, 7602, Western Cape, South Africa

Keywords: Gluteus maximus, Prone hip extension, Electromyography, Onset

Abstract

The purpose of this study was to determine if one can alter the muscular activation sequence of the lumbar erector spinae, bicep femoris, and gluteal muscles during prone hip extension and more functionally loaded exercises with gluteal specific training. The suggested normal pattern is Gmax→Hamstrings→Contralateral-→Ipsilateral lumbar erector spinae (Janda, 1991).

Eighteen (nine control and nine experimental) club-level netball players underwent pre- and post-testing of the electromyographic muscle onset during the prone hip extension, quadruped opposite arm/leg extension and the single limb squat. Seven experimental players formed the final sample and participated in a nine-week gluteal training program.

Gmax onset shifted earlier in both non-dominant and dominant prone hip extension movements with the lumbar erector spinae onset (*d>1.45*) later at post-testing in the dominant prone hip extension and Contralateral erector spinae shifting later (*d=1.09)* in the non-dominant PHE. No earlier shift in Gmax onset during the more functionally loaded movements.

Gluteal training appears to alter muscle activation sequence to more closely resemble the suggested norm with Gmax onset shifting earlier in the sequence; this did not happen with the more functionally loaded movements.

1. Introduction

Netball is a dynamic sport that requires the combination of jumping, breaking/stopping, lunging, leaping, cutting, pivoting and landing movements (Saunders et al., 2010; Ferreira & Spamer, 2010; Stuelecken et al., 2013; Mothersole et al., 2013; Ellapen et al., 2015). The rapid acceleration, deceleration and directional changes exert considerable force, exposing players to a higher risk for lower limb injuries (Coetzee et al., 2014; Ellapen et al., 2015). Mostly, netball players sustain injuries of the ankle and knee (Ferreira & Spamer, 2010; Coetzee et al., 2014; Ellapen et al., 2015), followed by the lumba-pelvic-hip complex (Ellapen et al., 2015). After basketball, netball has the highest incidence of knee injuries in female athletes (Gianotti et al., 2009), in particular injuries to the anterior cruciate ligament (ACL) (Hopper et al., 1995).

A delayed (in comparison to other muscles) gluteus maximus (Gmax) onset has been associated with increased hip adduction and internal rotation, resulting in functional knee valgus collapse (Hollman et al., 2009; Wilson et al., 2011), which is frequently found in women (Chumanov et al., 2008). Excessive valgus movements at the hip joint may affect the alignment at both the knee and ankle joints (Boren et al., 2011; Cambridge et al., 2012; Distefano et al., 2009; Ekstrom et al., 2007; Kang et al., 2013; Webster and Gribble, 2013; Woodford-Rogers et al., 1994). Additionally, individuals with ankle sprain injuries show a Gmax muscle activation delay during the prone hip extension (PHE) compared to non-injured controls (Bullock-Saxton et al., 1994). Based on this, it is assumed that a Gmax onset delay may lead to lower limb injuries and lumbar dysfunction (Hungerford et al., 2003).

A difference in activation sequences (AS) (i.e. delayed Gmax recruitment) may result in pelvis instability during gait and therefore hinder mechanical efficiency (Lehman et al., 2004). Lewis and Sahrmann (2009) stated that activation of the hamstrings earlier than the gluteal muscles contribute to hip dysfunction and anterior hip pain due to increased anterior joint forces. The PHE is commonly used by rehabilitation therapists to observe gluteal muscle activation during lumbo-pelvic and musculoskeletal assessments, and also as an exercise modality (Lehman et al., 2004; Lewis and Sahrmann, 2009. Contradictory to the 'ideal' PHE muscle activation sequence proposed by Janda (1991), namely from Gmax→hamstrings→contralateral lumbar erector (ContraES) spinae→ipsilateral lumbar ES (IpsiES), other investigations reported that the Gmax was always the last muscle activated (Bullock-Saxton et al., 1994; Vogt and Banzer, 1997; Kang et al., 2012; Lewis and Sahrmann, 2009; Sakamoto et al., 2009). The conflicting outcomes suggest either poor AS's, question the proposed 'ideal' AS, or question the appropriateness of the PHE as an assessment method. The ideal AS proposes a standard upon which to base therapeutic evaluation and prescribe treatment. If the 'ideal' AS is being questioned, therapeutic evaluation becomes challenging.

Some studies have shown low levels of Gmax activation during PHE (Kang et al., 2012; Lewis and Sahrmann, 2009). Functional movements that require coordinated multi-joint movements and which evoke both the mobility and stability/alignment function of the Gmax might be more appropriate (Cochrane and Barnes, 2015). The quadruped opposite arm/leg extension (QALE) and single limb squat (SQT) have been shown to utilize elevated levels of Gmax activation (Boren et al., 2011; Distefano et al., 2009; Ekstrom et al., 2007). Assuming the proposed hip extensor AS is as described, then the validity of the PHE for assessing hip extensor AS's should be evaluated. It is also important to assess whether or not, in the presence of an inappropriate AS, gluteal training can 'standardise' the muscle activation sequence, and if PHE test is sensitive enough to determine the changes.

To the researchers' knowledge the effect of gluteal training on the AS has not been previously investigated. The aim of this study was to determine 1) if a nine-week gluteal training program could alter the timing of Gmax onset, thereby altering the pattern of muscle activation during hip extension and 2) if the PHE test is a valid and practical test to assess Gmax AS compared to other functional movements, specifically QALE, and SQT.

2. Methods

2.1. Participants

Eighteen club level female netball players from the same netball squad volunteered for the study and were randomly divided into either an experimental (EXP) or control (CON) group (Figure 4.1). The EXP engaged in a nine-week gluteal intervention in addition to their usual netball training (twice weekly), whereas the CON continued their usual netball training.

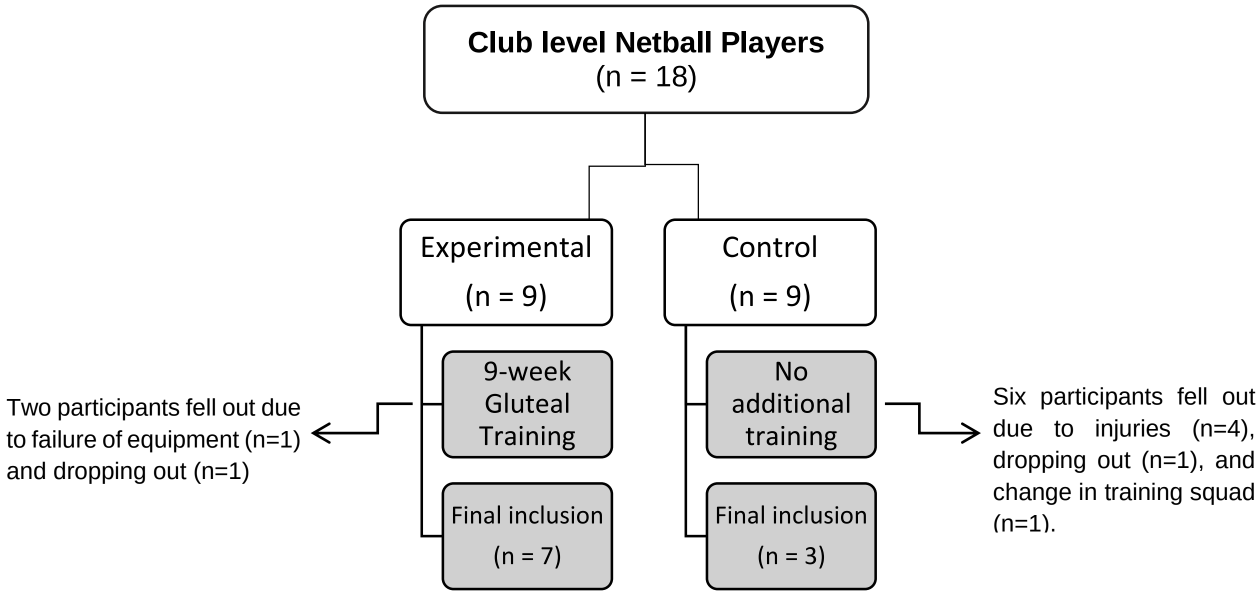


Fig 4.1. Flow diagram of participant recruitment.

Ten players with two months to four years club level experience comprised the final sample for statistical analysis (Table 4.1); of which seven were in the EXP and three in CON. Table 4.2 shows the inclusion/exclusion criteria. Prior to collecting data the researcher informed the participants of the study procedures and they completed a written informed consent (Appendix B) form and general information questionnaires (Appendix C). The study protocol was approved by the Institute's Research Ethics Committee (HS941/2013).

Table 4.1
Participant Descriptive Statistics

Participant #	Group	Age (yrs)	Height (cm)	Weight (kg)	BMI (kg.m^{-2})	Limb dominance
1	EXP	19	179.0	66.1	20.6	Right
2	EXP	18	166.0	66.5	24.1	Right
3	EXP	18	174.0	68.0	22.5	Right
4	EXP	18	172.0	59.9	20.2	Right
5	EXP	21	165.0	64.0	23.5	Right
6	EXP	21	164.0	59.1	22.0	Right
7	EXP	19	180.0	72.6	22.4	Right
Mean	**EXP**	**19**	**171.4**	**65.2***	**22.2**	
SD	**EXP**	**±1.0**	**±6.6**	**±4.7**	**±1.4**	
8	CON	21	169.0	53.0	18.6	Right
9	CON	19	161.0	61.0	23.5	Right
10	CON	20	165.0	55.0	20.2	Right
Mean	**CON**	**20**	**165.0**	**57.0***	**21.0**	
SD	**CON**	**±1.4**	**±5.7**	**±5.7**	**±3.5**	

Between groups: *p <0.05; ** p <0.01; SD: Standard Deviation; EXP: Experimental: CON: Control; yrs: Years; BMI: Body Mass Index

Table 4.2
Inclusion and exclusion criteria

Inclusion criteria	Exclusion criteria
Healthy club-level netball (woman) players from the same squad.	Lower extremity, lower back, or pelvic girdle injuries in the preceding six months. It has been shown that injuries to these areas have an influence on AS during PHE (Bullock-Saxton et al., 1994; Lewis and Sahrmann, 2009) Neurological or musculoskeletal conditions (Muscle onset is a component of the neurological and well as muscular system and therefore any conditions effecting these system could have an effect of muscle onset during movement) Failure to attend at least 80% of the training sessions

2.2. Experimental procedures

Both EXP and CON were assessed before and after a nine-week intervention. Participants wore their own tight fitting athletic shorts, loose fitting t-shirt, and no shoes. First their height (Webb City stadiometer, Missouri, U.S.A) and body mass (Detecto® mechanical scale, Missouri, USA) were assessed. Participants kicked a ball three times through a set of cones without instructions to determine limb dominance (Hoffman, 1998). A qualified clinical exercise therapist directed participants to perform three single limb exercises (PHE, QALE and SQT; Figure 4.2) for 10 repetitions bilaterally including 3-s pause between repetitions and with surface electromyography (sEMG). Exercise cues were provided which the participants had to follow i.e. keep hips level during all tasks, avoid lumbar hyperextension and their weight had to be placed on the heel of the foot with a hip hinge during the SQT. Prior to data collection the participants were allowed two-three practice repetitions. Both CON and EXP groups underwent the same protocol during pre- and post-testing with anterior and lateral video analysis carried out to assess lower extremity kinematics.

a b c

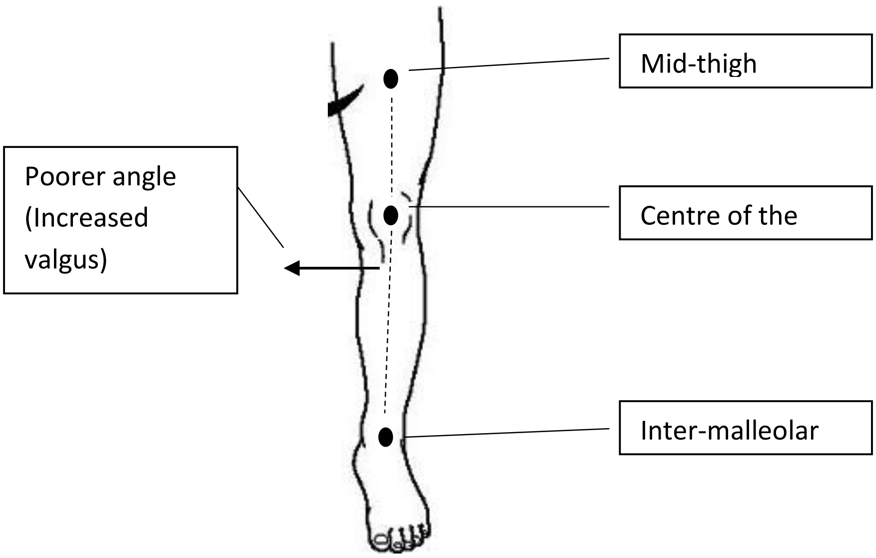
Fig. 4.2. Exercises performed during testing: a) PHE, b) QALE, c) SQT.

2.3. Electromyography recording and data analysis

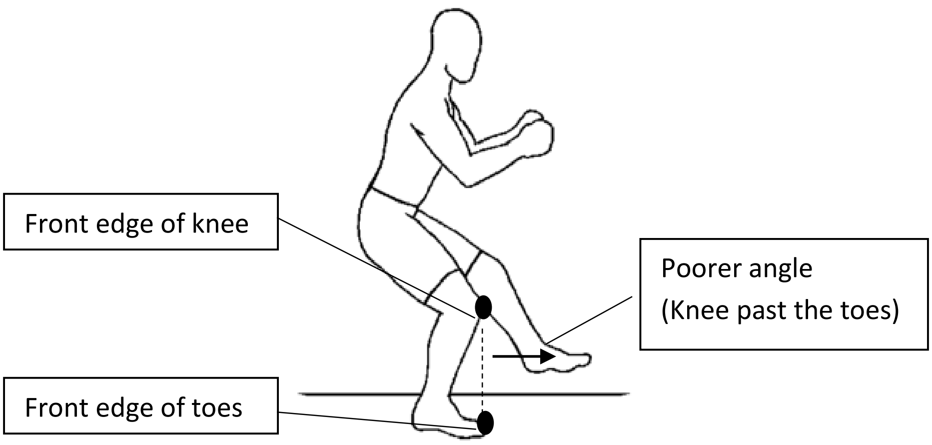
Muscle activity of the lumbar erector spinae (ES_{Lumbar}), bicep femoris (BicepFem), and Gmax was measured using the wireless Telemyo DTS system (Noraxon Inc., Scottsdale, Arizona, USA). Signal recording was analysed by the Myoresearch XP (version 1.08) Master Data acquisition system (Noraxon Inc., Scottsdale, Arizona, USA). A sampling rate of 1000Hz and a band pass filter of 20-500Hz was used and raw data was processed into root mean square (RMS) (50ms window). The electrode site was shaved, gently abraded and cleansed with an alcohol swab to reduce skin impedance (Intra-tester ICC = 0.60). Pre-gelled Ag-AgCl Nicolet® (Biomedical, Division of VIASYS, Madison, USA) dual electrodes secured with double-sided tape (inter-electrode distance of 1cm) were applied to the following sites (parallel to muscle fiber direction): ES_{Lumbar} 2cm laterally from L5/S1 vertebra (Behm et al., 2005); Gmax 34% of the distance from the 2nd sacral vertebrae to the greater trochanter and BicepFem 35% of the distance from the ischial tuberosity to the lateral side of the popliteal fossa (Rainoldi et al., 2004); the gluteus medius (Gmed) 50% of the distance of the line extending from the iliac crest to the greater trochanter (Hermens and Fredriks, date unknown). The Gmed also has fibers involved in hip extension. Onset of muscle activation was defined as that moment when the sEMG activity for each muscle exceeded 5 SD from baseline (i.e. average sEMG activity over 5-s at rest) for a minimum of 50ms (Brindle et al., 2003; Wilson et al., 2012). The onset of the first repetition was used for analysis. Muscle onset was reported relative to the Gmax onset which was seen as zero seconds. A negative value indicated that a muscle's onset occured before that of the Gmax. Analysis of onset and %MVIC was executed in Matlab® (MathWorks Inc. Natick, MA, USA). In the presence of early false onset, onset was corrected for in a blinded manner.

2.4. Kinematic Variables

Video analysis of the squat movement was carried out using version 0.8.15 of the open source Kinovea® video analysis software (Kinovea 2007, France). Video cameras (Cannon legria hfg10, Japan) were placed a distance of 2m and 1.5m from the participant laterally and anteriorly, respectively. Height of the cameras were set at hip height (iliac crest). Laterally (Figure 5.2b), knee position was investigated relative to the most anterior portion of the toes. Anteriorly (figure 5.2a), knee valgus was assessed by evaluating the angle formed by a line extending from mid-thigh, through the centre of the patella, and ending through the inter-malleolus centre point (markers were used for site identification). First repetition was used for analysis to coincide with onset recording (Intra-tester ICC = 0.97).



a)



b)

Figure 4.3. Kinematic measurements a) Knee valgus angle b) knee-over-toe position

2.4. Intervention

The EXP group completed a nine-week gluteal-specific exercise program targeting predominantly the Gmax. Participants conducted two one-hour therapist-supervised (by qualified clinical exercise therapists) sessions and one hour unsupervised (unloaded) session per week. The exercise therapists ensured that a participant's knee did not move over the toes, her weight was kept on the heel of the foot where applicable and extension of the hip while avoiding lumbar hyperextension or excessive anterior pelvic tilt. The exercise program included standing gluteal activation, unilateral wall squat, forward step up (height of 25cm), SQT, single limb stiff leg deadlift, single limb gluteal thrust, modified side plank with clam, and QALE (Appendix D). Not including the standing gluteal activation and single limb gluteal thrust, all the exercises showed a Gmax activation > 50% MVIC, some as high as 75% (see Ayotte et al., 2007; Boren et al., 2011; Distefano et al., 2009; Ekstrom et al., 2007; Simenz et al., 2012). High Gmax activity would theoretically ensure a good training adaptation on the Gmax with the purpose of changing Gmax onset timing. Exercise progression (see appendix E) was predetermined. If participants struggled with form of the exercises, the progression was postponed by one week (this however was not experienced). Both groups continued their regular netball training, fitness conditioning and matches. The EXP group intervention took place at Stellenbosch Biokinetics Centre in an indoor temperature-controlled environment (~20°C). The CON did not participate in any other exercise programmes besides the usual netball fitness conditioning like EXP. The participants in both groups participated in the exact same regular netball training program. Participants were instructed to keep an activity log for the study duration.

2.5. Statistical analysis

A Shapiro-Wilks test was used to confirm normal distribution. Descriptive data is reported as mean and standard deviation. Statistical significance level was set as at α = 0.05. A repeated measures ANOVA was completed to determine within group differences. Statistica version 12 (StatSoft, Inc., Tulsa, OK, USA) and Excel 2010 (Microsoft®, USA) were used to perform the statistical analysis. Cohen's *d* effect sizes were calculated to determine meaningful changes i.e. negligible effect (>= -0.15 and <0.15), small effect (>=0.15 and <0.40), medium effect (>=0.40 and <0.75), large effect (>=0.75 and <1.10), very large effect (>=1.10 and <1.45), and huge effect >1.45 (Thalheimer and Cook, 2002).

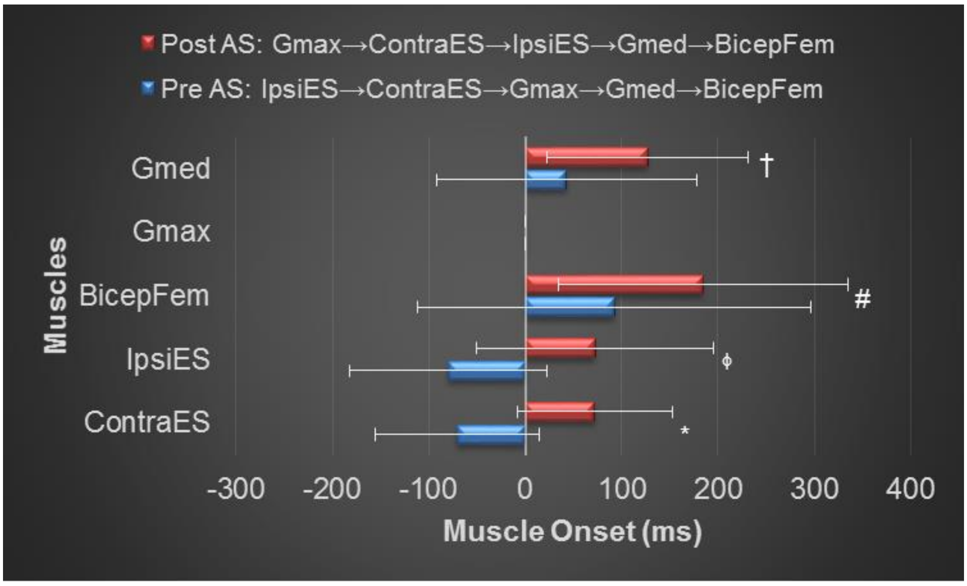
3. Results

3.1. Participants

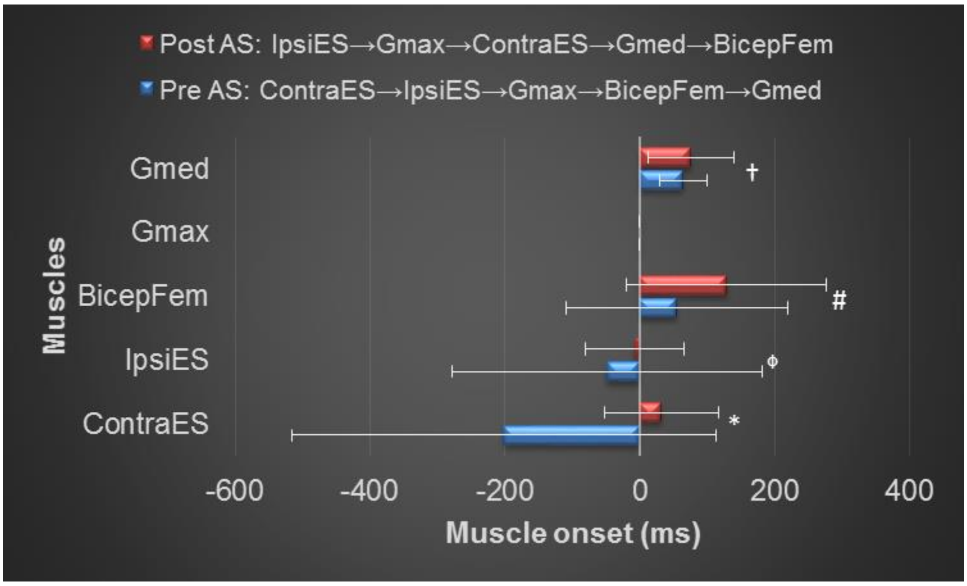
Due to the small number of participants remaining in the CON group after the intervention (Figure 4.1), the results will only report on the EXP group over time.

3.3. Change in onset during the PHE with accompanying activation sequences

Contralateral (ContraES) (p=0.04) and ipsilateral erector spinae (IpsiES) (p=0.03) onset activated after Gmax post-intervention. Furthermore, BicepFem (p=0.26) and Gmed onset (p=0.18) were even more delayed after Gmax during dominant PHE post-intervention (Figure 4.3a). Post-intervention for non-dominant PHE (Figure 4.3b) the ContraES shifted to after Gmax (p=0.09) with IpsiES showing practically the same onset time as Gmax (p=0.56). BicepFem (p=0.19) and Gmed (p=0.62) onset responded similarly to Dominant PHE (p>0.05).



a



b

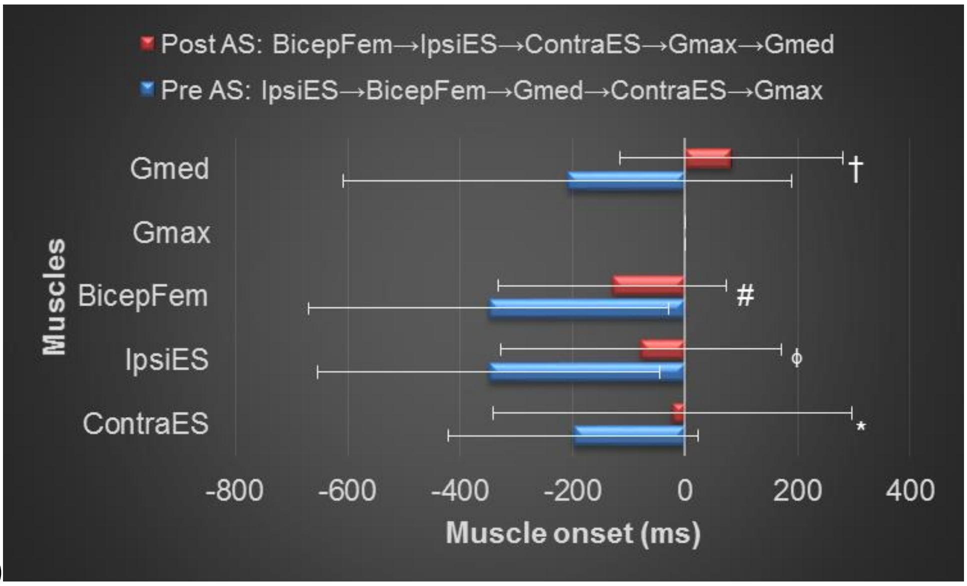
Fig 4.4. Muscle onset changes during PHE (mean ± SD): a) Dominant PHE, b) Non-dominant PHE.

a) * *d*=1.86: huge effect; ϕ *d*=1.45: huge effect; # *d*=0.56: medium effect; † *d*=0.75: huge effect

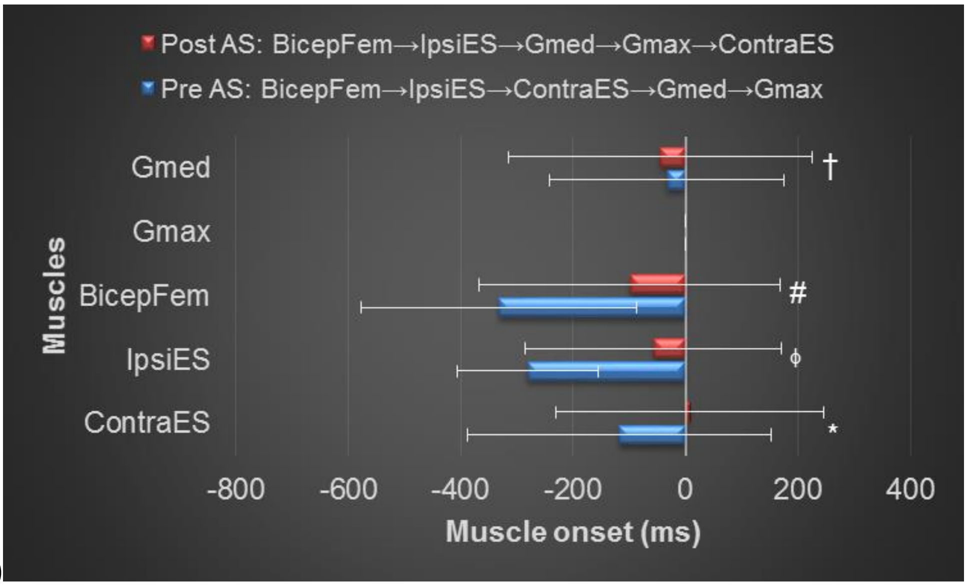
b) * *d*=1.09: large effect; ϕ *d*=0.26: small effect; # *d*=0.51: medium effect; † *d*=0.23: small effect

3.4. Change in onset during the QALE with accompanying activation sequences

All muscles for dominant QALE (Figure 4.4a) displayed later onsets ($p>0.05$), with IpsiES significantly later ($p<0.01$) than pre-testing with only Gmed activating after the Gmax post-intervention. During non-dominant QALE (Figure 4.4b) only the ContraES onset occurred after Gmax at post-testing ($p=0.33$). All other muscles displayed later onsets ($p>0.05$), with IpsiES significantly later ($p=0.04$), than pre-testing but remained before Gmax.



a)



b)

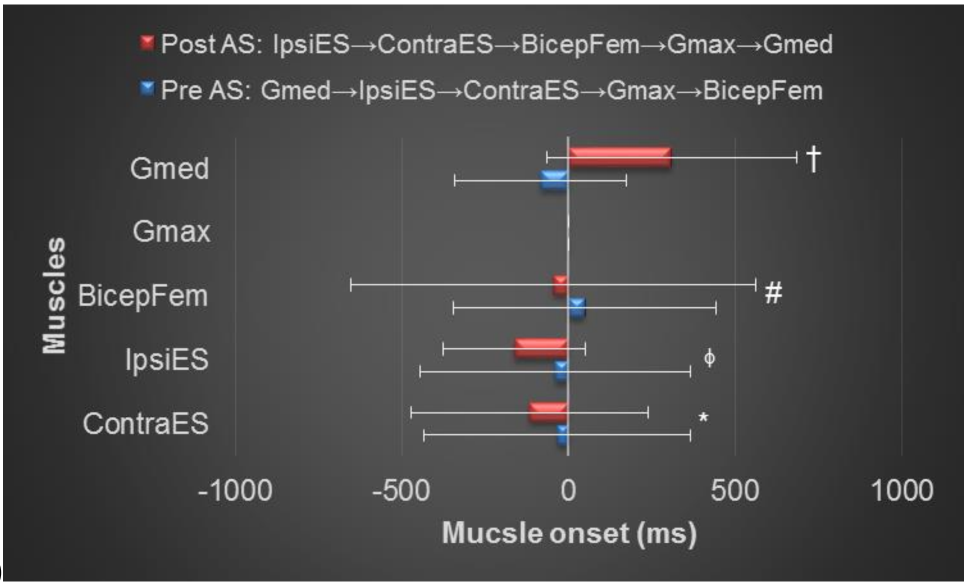
Fig 4.5. Muscle onset changes during QALE (mean ± SD): a) Dominant QALE, b) Non-dominant QALE.

a) * *d*=0.69: medium effect; ϕ *d*=1.05: large effect; # *d*=0.89: large effect; † *d*=1.00: large effect

b) * *d*=0.54: medium effect; ϕ *d*=1.23: very large effect; # *d*=0.98: large effect; † *d*=0.05: negligible effect

3.5. Change in onset during the SQT with accompanying activation sequences

In the SQT (Figure 4.5a&b) ContraES, IpsiES, and BicepFem displayed earlier onsets post-intervention ($p>0.05$) with a more delayed Gmed activating after Gmax for dominant SQT. The non-dominant SQT revealed the ContraES ($p=0.82$), IpsiES ($p=0.02$), and BicepFem ($p=0.45$) showing earlier onsets than pre-testing while the BicepFem also showing an earlier onset almost identical to Gmax.



a)

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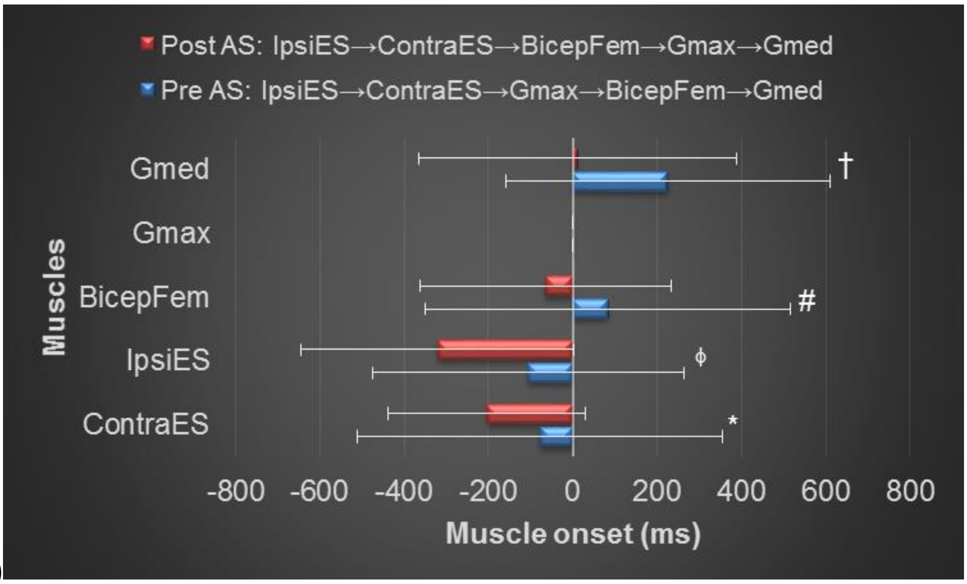

Fig 4.6. Muscle onset changes during SQT (mean ± SD); a) Dominant SQT, b) Non-dominant SQT.

a) * *d*=0.24: small effect; ϕ *d*=0.41: medium effect; # *d*=0.20: small effect; † *d*=1.32: very large effect

b) * *d*=0.39: small effect; ϕ *d*=0.67: medium effect; # *d*=0.43: medium effect; † *d*=0.61: medium effect

3.6. Kinematic Variables

Table 4.3 reveals that the intervention had a small and negligible impact on knee valgus in the dominant and non-dominant limb respectively during the SQT. The intervention had a medium effect and small effect decrease on knee over toe angle in the dominant and non-dominant limb respectively during the SQT. A decrease here is seen as favourable. The EMG variables of the Gmax during the SQT are also tabulated in Table 4.3. For Gmax-BicepFem interval a negative value is considered unfavourable as this indicates a more delayed Gmax activity in comparison to the BicepFem. No practically significant changes were note in Gmax amplitude or Gmax-BicepFem onset interval during the dominant and non-dominant SQT.

Table 4.3
Kinematic and EMG variable of the SQT

	Knee valgus angle				Gmax-BicepFem onset interval			
	pre	post	p	*d*	pre	post	p	*d*
Dominant	196.33	194.29	0.42	0.32	48.57	-45.24	0.39	0.20
Non-Dominant	190.43	190.53	0.95	0.02	82.86	-64.95	0.03	0.43
	Knee-over-toe angle				**Gmax amplitude**			
	pre	post	p	*d*	pre	post	p	*d*
Dominant	8.52	6.30	0.11	0.56	79.00	83.86	0.65	0.45
Non-Dominant	5.96	4.50	0.48	0.29	75.96	98.41	0.16	0.48

pre: pre-testing; post: post-testing; p: significance level; *d*: Cohen's effect size

4. Discussion

The main findings of this study is that gluteal training seems to be able to alter the AS of the muscles during PHE so that it more closely resembles that of the ideal AS proposed by Janda (1991). This however does not transfer to more functionally loaded movements or result in improved lower extremity alignment during a single limb squat.

Interestingly, the only drop-outs due to injury occurred in the CON group with the intervention adherence rate being above 85% for the EXP group; this alone may suggest improved injury resistance with the gluteal training. For EXP the dominant and non-dominant PHE showed favourable results post-intervention with Gmax onset occurring before ES_{lumbar} (excepting IpsiES during Non-dominant PHE which had practically the same onset time as the Gmax), BicepFem, and Gmed, suggesting that Gmax functioning improved during the intervention. Early Gmax activation may improve lumbo-pelvic stability while a delayed Gmax activation could result in anterior pelvic tilt and lumbar lordosis (Lehman et al., 2004). This then could contribute to lower extremity malalignment (Hollman et al., 2009) and increased lower limb injury risk (Boren et al., 2011; Cambridge et al., 2012; Distefano et al., 2009; Ekstrom et al., 2007; Kang et al., 2013; Webster and Gribble, 2013; Woodford-Rogers et al., 1994); specifically knee and ankle injuries, which accounted for 75% injuries experienced in the CON. Wilson et al. (2012) found that delayed Gmax onset could lead to femoral adduction and internal rotation with Hollman et al. (2009) stating that Gmax functions to resist these unwanted movements of the femur.

Following the intervention, both ContraES and IpsiES showed very large ‘improvements’ with both muscles activating before Gmax at pre-testing and after Gmax at post-testing in the dominant PHE. There was also a moderate and large improvement for BicepFem and the Gmed, respectively with both muscle groups activating later post-intervention. Non-dominant PHE also displayed favourable effects over time with all the muscles showing later onsets after the intervention. The difference to the dominant PHE was that IpsiES onset remained before that of the Gmax, but this was only by -7.43 sec which is trivial. Overall the change in the non-dominant PHE is positive with the Gmax onset which is slightly before or at a similar time as the ES_{lumbar}, BicepFem, and Gmed. The ContraES activation was greatly delayed over time during non-dominant PHE. It is possible that improvement in Gmax extension ability following the intervention was achieved; this possibly decreasing the need for contributions by the Gmed and BicepFem as synergists. Weak Gmax may increase the demands on the hamstrings, thereby increasing hamstring injury risk during functional tasks (Cochrane and Barnes, 2015). Consequently, improved Gmax function could decrease load exerted on the synergists of hip extension, which could transfer into a delayed onset of synergists since Gmax is performing most of the hip extension, as was suggested by Kang et al. (2012). The onset of ContraES and IpsiES after Gmax during the dominant PHE could be attributed to improved Gmax function post-intervention. Gmax inhibition may lead to anterior pelvic tilt owing to over activity of ES_{Lumbar} muscles (Lehman et al., 2004). Gmax assists posterior pelvic tilt (Neumann, 2010) and therefore the assumption is that it would function to prevent anterior pelvic tilt. Improved Gmax function may therefore decrease the loads on the ES_{Lumbar} preventing this anterior pelvic tilt and a possible subsequent lumbar lordosis. Vogt and Banzer (1997) suggested that early activation of the ES_{Lumbar} can be seen as a preparation to ensure trunk stability (i.e. anterior pelvic tilt and subsequent hyper-lordosis). The early onset of Gmax in the current study supports this theory, keeping in mind that muscle onsets took place over timespan 232.76ms and 174.38ms for dominant and non-dominant PHE, respectively. This is slightly quicker than found by Lehman et al. (2004), who reported a time span of 527ms. With these very short timespans it would be difficult to assess muscle activation sequence during PHE test without the use of sEMG as stated by Lehman et al. (2004). Therapists might therefore be able to assess activation quality but it would be difficult to assess onset with manual palpation.

To the researchers' knowledge, all studies on muscle activation sequence in PHE have been conducted without an intervention program. Previous studies showed that Gmax was consistently the last muscle to display activity during the PHE regardless of starting position, knee position, and onset definition (Bullock-Saxton et al., 1994; Kang et al., 2012; Lehman et al., 2004; Lewis and Sahrmann, 2009; Vogt and Banzer, 1997). The current study shows that it may be possible to achieve early onset of the Gmax through specific training. The possible reasons for the inconsistent AS in previous studies may be due to faulty training techniques (resulting in poor gluteal muscle recruitment), increased time spend sitting and decreased postural awareness (Ayotte et al., 2007). Owen et al. (2010) reported that many adults spend up to 70% of the day sitting. Increased sitting time may be detrimental to athletes such as netball players. It may therefore be warranted to include gluteal-specific training into exercise regimes. Kalantar et al. (2014) focused on muscle amplitude rather than onset, but supports this statement and found a significant increase in Gmax activation amplitude and decrease in IpsiES activation amplitude during the PHE movement.

The PHE lacks functionality and concerns exist over the application of the results; warranting testing of other movements (Lehman et al., 2004). Cochrane et al. (2015) evaluated muscle onset during the deadlift and concluded that Gmax and hamstrings displayed activity at similar times. No attempt to altering hip extensor muscle timing during the QALE has been researched. The movement starts in a more flexed position, decreasing Gmax moment arm, likely influencing muscle function. (Tateuchi et al., 2012). Clinically clients are cued to only extend the hip to neutral hip extension during the QALE, beyond which point Gmax performs work during ambulation. The SQT provides a functional challenge to Gmax function and may therefore be more valuable in to use in assessment.

There seems to be little benefit to Gmax onset during the QALE with gluteal training. During both dominant and non-dominant QALE the Gmax onset only moved from last to second last in the AS. BicepFem became the first muscle to become active and remained the first muscle in the dominant- and non-dominant QALE respectively; ES_{Lumbar} onsets occurred later. Gluteal training likely improved Gmax function, decreasing ES_{Lumbar} load for trunk and pelvic stability. The testing position, leading to decreased Gmax moment arm, (Kang et al., 2012), thereby decreasing Gmax activity, may lead to increased demand on the hamstrings (Cochrane and Barnes, 2015) and result in early BicepFem onset. Both dominant and non-dominant QALE activation sequences do not agree with the suggested ‘norm’ of the PHE (Janda, 1991). The QALE might not be a suitable test for Gmax onset or activation due to the position of relative insufficiency as a result of the decreased moment arm.

The current study revealed that the dominant and non-dominant SQT displayed ContraES and IpsiES onsets prior to Gmax with IpsiES first at post-testing. This early onset of the ES_{Lumbar} may be an attempt to stabilize the rotation effect inherent to unilateral exercises. In both the non-dominant and the dominant SQT, Gmax was the second to last muscle to display onset with only the Gmed onset occurring later. During the dominant SQT the gluteal training intervention seems to have resulted in earlier onset of the ES_{Lumbar} as well as BicepFem at post-testing; with similar findings for the non-dominant SQT. AS did not agree with that of the suggested ‘ideal’ (Janda, 1991) for the PHE. The Gmax function is believed to be increased in the SQT (Reimann et al., 2012), and with improvements in Gmax function during the PHE, one would expect improved Gmax onset. Gluteal muscle activity is high during the baseline sEMG measurements of the starting position of the SQT. This is especially likely in women who have been shown to have high gluteal activity during a squat (Dwyer et al., 2010). This high level of Gmax activity may make it difficult to display onset which was defined as 5SD above the baseline sEMG activity in the current study. The SQT also only takes place in a range of motion of relative hip flexion with movement ending at neutral hip extension; thus decreased Gmax moment arm. This being said, the Gmax is active during the squat (Dwyer et al., 2010) but may act along with synergists (Kang et al., 2012) to perform the hip extension as opposed to dominating the movement from the outset.

Even though there was an earlier shift in Gmax onset during PHE the same was not seen in the functional SQT movement. The current study also revealed that, although the PHE suggested improved Gmax function, there was no improvement in frontal plane knee valgus at post-testing. Herman et al. (2008) also no improvement in lower extremity alignment during a stop-jump task following gluteal training while Willy and Davis (2011) found no improvements in alignment during running even though there were improvements in alignment during the SQT. Both suggest neuromuscular techniques are needed to ensure transfer if function to a specific task. Other studies have noted improvements in lower extremity alignment following interventions that include gluteal training (Baldon et al., 2012; Earl & Hoch, 2011; Snyder et al., 2009). This lack of improvement in frontal plane knee valgus points to a lack of an output from the suggested improved Gmax function presented by the PHE test. This brings to question the lack of functionality of the PHE and the lack of ability to transfer the results of this test to more functional movements. This is further highlighted by a lack of improvement in knee position relative to the toes. A knee that is positioned past the knee during a squat has been shown to increase anterior knee shear (Fry et al., 2003) and that a more posteriorly positioned knee would be facilitated by improved gluteal function. This seems not to be the case during the squat at post testing again suggesting a false positive 'improved in Gmax function' result during the PHE.

A major study limitation was the small sample size and the loss of the CON group that would have been used for comparison. Another possible limitation is assuming that the AS (Janda, 1991) is the ideal sequence. Various studies have failed to find this proposed pattern (Bullock-Saxton et al., 1994; Kang et al., 2012; Lehman et al., 2012; Lewis and Sahrmann, 2009; Sakamoto et al., 2009; Tateuchi et al., 2012; Vogt and Banzer, 1997). The current study did not account for hip abduction and external rotation which may influence Gmax onset during PHE due to changes in muscle fiber orientation (Kang et al., 2012; Sakamoto et al., 2009). The presence of pre-activation of muscles between repetitions was noted in the study leading to the production of false onsets due to muscle activity not returning to baseline; therefore only the first repetition of each exercise could be used for onset analysis (Lewis and Sahrmann, 2009).

In conclusion, this study endeavoured to determine if it would be possible to achieve the 'ideal' (as set out by Janda, 1991) muscle activation sequence during the hip extension with a gluteal training intervention. Gluteal-specific training did alter the AS during the PHE suggested by Janda (1991). Improvements in the AS during the PHE were not observed during the QALE and SQT, which may indicate that they are not suitable replacements for the PHE in assessing AS's. The lack of improvements in Gmax onset and frontal plane knee valgus during the single limb squat could re-inforce the lack of functionality of the PHE and clinicians should re-think if they can transfer findings from the PHE to more functional movements.

Conflict of interest

The authors declare that they have no conflicts of interest.

Acknowledgements

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Chapter Five

General Discussion and Conclusion

Discussion

Lumbo-pelvic-hip stability plays a vital role in lower limb mechanics, pelvic stability, and lumbar stability with the posterior musculature playing a major role. This study was therefore conducted in order to gain insight into the functioning of the posterior lumbo-pelvic-hip musculature, in terms of muscle onset and activation, and the role of these muscles in lower extremity alignment (LEA) during a single limb squat (SQT).

The primary aim of this study was to determine if the activation sequence during the PHE, if found to not agree with the proposed norm by Janda (1991), can be favourably altered with gluteal training. Gluteal muscles help in ensuring optimal lower limb alignment (Hollman *et al*., 2009) with malalignment of the femur being very common in women (Chumanov *et al*., 2008). This malalignment of the lower extremities and weakness of the gluteal muscles have been associated with increased risk of injury to the lower extremities (Boren *et al*., 2011; Cambridge *et al*., 2012; Distefano *et al*., 2009; Ekstrom *et al*., 2007; Kang *et al*., 2013; Webster & Gribble, 2013; Woodford-Rogers *et al*., 1994). Lehman *et al*. (2004) further suggest that earlier activation of the Gmax could improve lumbo-pelvic stability, and therefore assist in injury prevention. Delayed activation of the Gmax during functional movements in clinically believed to result in lower limb malalignment which is supported by Wilson *et al*. (2012) that found femoral mal-positioning in the presence of delayed Gmax activity during running.

The prone hip extension (PHE) test is used clinically to assess for Gmax recruitment as it is believed to mimic the musculature activation patterns of the hip extensor muscles during typical walking and running (Vogt & Banzer, 1997). The results of the current study into the pre-testing of muscle activation sequences during the PHE (with knee flexion) revealed that bilaterally there were no consistent patterns of muscle onset (See Appendix F: Table i & ii). The mean activation sequence of both the non-dominant and dominant PHE revealed that the movement was initiated by the lumbar erector spinae and that the Gmax was the third muscle to become active with the BicepFem being last. This early activation of the lumbar erector spinae has been noted in previous studies (Lehman *et al*., 2004; Vogt & Banzer, 1997). Early lumbar erector spinae (ES_{Lumbar}) has been proposed as a pre-movement anticipatory stability provision to the trunk (Vogt & Banzer, 1997).. There are however differences between the current study and these studies. For instance, the studies by Lehman *et al*. (2004) and Vogt & Banzer (1997) performed the PHE movement with the knee in extension as opposed to flexed in the current study. Even though both variations are used clinical in practice, it is important to keep in mind that the position of knee flexion may place the hamstrings in active insufficiency (over the knee joint) (Lewis & Sahrmann, 2007); possibly decreasing its contribution in performing hip extension. This decreased optimisation of the hamstrings and poor Gmax recruitment may give rise to the need to produce an anterior pelvic tilt (using the ES_{Lumbar}) in an attempt to improve hamstring and Gmax function (Oh et al., 2015; Tateuchi *et al*., 2012). The current study found the hamstrings to be the last muscle to become active in both dominant and non-dominant PHE. Other studies have found that the PHE movement was initiated by the hamstring muscle (Bullock-Saxton *et al*., 1994; Lewis & Sahrmann, 2009; Sakamoto *et al*., 2009; Tateuchi *et al*., 2012) with all of these studies performing the PHE with the knee in extension. This may possibly ensure improved hamstring efficiency thereby decreasing the demand on the lumbar erector spinae. Earlier hamstring onset than that of the Gmax in the studies by Lewis & Sahrmann (2009) and Tateuchi *et al*. (2012) could be explained by another key methodological difference. In both studies the hip extension movement was started in a position of relative hip flexion whereas in the current study the movement was started in neutral hip position. It was proposed by Tateuchi *et al*. (2012) that the moment arm of the Gmax is decreased in positions of hip flexion while that of the hamstrings is increased. This could indicate that a starting position of hip flexion creates a situation in which the hamstrings would more easily show earlier onset than that of the Gmax. Tightness in hip flexor and quadriceps muscle groups could also play a role in inhibiting Gmax onset; this was not accounted for in the current study.

Achieving the proposed sequence of activation (Janda, 1991) has not yet been assessed leaving room to determine if this sequence is at all relevant. A gluteal training may well have an influence on muscle onset during the PHE. At post-testing there were only seven participants from the experimental group who completed both pre-testing and post-testing. The discussion into the change in activation sequence only involved the results of these participants. Both the non-dominant and the dominant PHE muscle activation sequences did not agree to the proposed ‘ideal’ pattern at pre-testing but did change at post-testing (Appendix F: Table viii & ix). The AS for the non-dominant PHE changed from ContraES→IpsiES→Gmax→ BicepFem→Gmed to IspiES→Gmax→ContraES→Gmed→ BicepFem. It is important to note that the IpsiES onset was only 7.4msec before that of the Gmax at post-testing in comparison with 48.9msec; suggesting improved Gmax onset time relative to that of the IpsiES. Along with the change in order, all the muscles presented with a later onset at post-testing in comparison to that of the Gmax (albeit not significant). The

ContraES presented with a large effect change over time while the IpsiES presented with only a small effect. The BicepFem and the Gmed presented with medium and small changes respectively over time. The dominant PHE AS changed from IspiES→ContraES→Gmax→Gmed→BicepFem to Gmax→ContraES→IpsiES→Gmed→ BicepFem and therefore more closely agreed with the suggested norm. The results for the dominant PHE suggest that all muscle onsets occurred after that of the Gmax at post-testing. There were practically huge (and statistically significant) effect changes over time with later onsets for the lumbar erector spinae while the BicepFem and Gmed showed medium and large effect changes over time. In a study on Gmax activation (amplitude), Kalantari *et al*. (2014) found a significant increase in Gmax activation (amplitude) and a significant decrease in IpsiES activation (amplitude) during the PHE following an intervention including gluteal training. Even though the study did not focus on onset there seems to be similar effects on Gmax activation as was seen on Gmax onset during the current study. The results of the current study indicate that the gluteal training intervention may have had a positive effect of the muscle activation sequence during the PHE. The later onsets observed for the Gmed and the BicepFem may be due to an increased role played by the Gmax during the hip extension. These three muscles act as synergists for hip extension and when more work is performed by one muscle group one could expect decreased load on the remaining synergists (Kang *et al*., 2012). This theory is supported by Cochrane & Barnes (2015) who postulate that weak or inactive Gmax muscles may increase the demands on the hamstrings muscles during functional tasks. Earlier onset of the Gmax may also assist in its function of prevention of anterior pelvic tilt due (Neumann, 2010) preventing a possible lumbar lordosis. A decreased tendency to enter lumbar lordosis may decrease the need for trunk stabilization by the lumbar erector spinae at the start of the PHE movement. What needs to be noted is that the timespan between the first muscle to become active and the last is only 232.76ms for the dominant PHE and 174.38ms at post-testing. The researcher therefore suggest that assessment of the PHE without the use of sEMG cannot be used to asses for onset sequence as the timespan is too short for palpation to be sensitive enough; this is supported by Lehman *et al*. (2004). It may however be possible to assess for contraction quality with manual palpation.

A lack of functionality of the PHE test and the ability to extrapolate the results to functional activities (Lewis & Sahrmann, 2009) is a concern leading to the need to develop other tests to assess Gmax function (Cochrane & Barnes, 2015). Other movements also employ the hip extension movement albeit from a different starting position. The quadruped opposite arm leg extension (QALE) movement employs the hip extension movement similar to that of the PHE but starts in a position of relative flexion. This movement has been shown to recruit the Gmax at a level higher than during the PHE (Boren *et al*., 2011; Ekstrom *et al*., 2007) and could be a more appropriate movement to assess muscle activation sequence during hip extension. To the researcher's knowledge no study has investigated the effects of a gluteal training program on muscle onset during the QALE. At pre-testing (Appendix F: Table xi) the non-dominant QALE had a mean activation sequence of BicepFem→IpsiES→ContraES→Gmed→Gmax which only presented with a slight change at post-testing (Appendix F: Table xi) of BicepFem→IpsiES→Gmed→Gmax→ContraES. All muscles, except the Gmed, displayed a later onset than that at pre-testing. IpsiES onset was significantly later than at onset. What is important to note is that the BicepFem remained the first muscle to become active even though there seemed to be a shift in timing with the Gmax onset earlier than at pre-testing. At pre-testing (Appendix F: Table x) the dominant QALE had a mean AS of IpsiES→BicepFem→Gmed→ContraES→Gmax which changed to BicepFem→IpsiES→ ContraES→Gmax→Gmed at post-testing (Appendix F: Table x). All muscles during the dominant QALE displayed later muscle onsets in comparison to pre-testing indicating that the Gmax onset was improved (earlier) at post-testing. The change in IpsiES onset was significant, resulting in the BicepFem being the first muscle to become active at post-testing. These results may indicate that the gluteal training had a positive impact on the timing of the Gmax during the QALE. As discussed earlier, the position of relative hip flexion may favour hamstring muscle activation (Tateuchi *et al*., 2012) and hence the lack of sequence change as that seen during the PHE (to a condition where the Gmax is the first muscle to display onset). The results indicate that the QALE may not be a suitable replacement for the PHE to assess Gmax onset during hip extension.

Another more functional movement that also employs hip extension and one that is often used clinically in functional assessment is the single limb squat (SQT). The Gmax has been shown to be highly active during the SQT (Boren *et al*., 2011; Distefano *et al*., 2009) with activation levels higher than those seen in the PHE. The SQT may be a more functional movement to assess hip extension activation sequence due to the large role the Gmax will play in both mobilisation and femoral alignment. The non-dominant squat went from an AS of IpsiES→ContraES→Gmax→BicepFem→Gmed at pre-testing (Appendix F: Table xiii) to IpsiES→ContraES→BicepFem→Gmax→Gmed at post testing (Appendix F: Table xiii). All four muscle groups' onset times shifted to earlier at post-testing (IpsiES significantly) indicating that the gluteal training did not have a positive effect on the activation sequence of the non-dominant squat. The dominant squat went from an activation sequence of Gmed→IpsiES→ContraES→Gmax→BicepFem at pre-testing (Appendix F: Table xii) to

IpsiES→ContraES→BicepFem→Gmax→Gmed at post-testing (Appendix F: Table xii). All muscles showed an earlier onset at post-testing with exception of the Gmed onset. One may have expected Gmax onset to improve during the SQT, however this was not the case. Gmax activity may have been at a high level at baseline measurement due to the single leg stance evoking Gmax function; this is very likely in women who display high Gmax activity during a SQT (Dwyer *et al*., 2010). The results of the activation sequence during the SQT movement indicate that it may be more appropriate to use the PHE test to assess hip extension muscle activation sequence (Appendix F: Table vii). It may however still be important to assess gluteal muscle onset during a SQT as Brindle, Mattacola & McCrory (2003) did find delayed Gmed onset during stair climbing in individuals with anterior knee pain.

One would expect that the ‘improved Gmax function noted during the PHE movement would present as an outcome of gluteal function. Sinsurin *et al*. (2013) have stated that a knee that is well aligned is more resistant to injuries during recreational sport participation. The Gmax plays an important role in this LEA, in particular on the alignment of the femur (Boren *et al*., 2009; Hollman, 2009; Struminger *et al*., 2013). Gluteal weakness or recruitment deficits are clinically prevalent in women along with the struggle with lower limb alignment, this is supported by research (Nguyen *et al*., 2009; Trulsson *et al*., 2015; Zeller *et al*., 2003). The current study investigated whether, in the presence of improved Gmax onset, the benefits are seen in improved lower limb alignment during a single limb squat (SQT). To the researchers knowledge this has not previously been investigated. As discussed earlier the study has shown an improved Gmax onset during the PHE which could indicate improved gluteal recruitment, although this was not seen during the squat. Specific attention was placed on pre- and post-testing valgus angles as the gluteal muscles assist in preventing functional knee valgus by resisting femoral adduction and internal rotation (Boren *et al*., 2009; Hollman, 2009; Struminger *et al*., 2013). The gluteal training program seemed to have minimal effect of knee valgus (Appendix F: Figure vi) with only a decrease of 2° (smallest worthwhile change is 1.36°, but low confidence in this value is present) during the dominant SQT and no change during the non-dominant SQT. A decrease in the BicepFem onset time would indicate that the Gmax onset has shifted favourably (Gmax-BicepFem onset interval). There was no significant change in the Gmax-BicepFem onset interval during the dominant SQT (Appendix F: Figure vii; viii) which only presented with a small change over time. There was a significant change in the Gmax-BicepFem interval during the non-dominant SQT with a medium effect over time (Appendix F: Figure vii; viii). This change is a later onset of the Gmax relative to the BicepFem suggesting that the gluteal training intervention had a negative effect on Gmax onset during the non-dominant SQT. There were however medium effect increases in peak activation (amplitude) in both dominant and non-dominant Gmax post intervention. The results of the current study indicate that the gluteal training intervention has minimal effects on the timing of Gmax onset but yet did have a positive effect on activation levels although this seems to not have had a major effect on knee position. What can be noted is that there was a slight decrease in knee valgus angle during the dominant SQT which did not occur in the non-dominant. Non-dominant Gmax onset was significantly worse off at post-testing indicating that a poorer Gmax onset could limit improvements in knee valgus angle. There was however a significant improvement in Gmed onset during the non-dominant SQT and as mentioned earlier this muscle also assists in preventing knee valgus collapse. Other studies also found no improvement in lower limb alignment following the implementation of a gluteal training intervention as was the case in the current study (Herman *et al*., 2008; Sheerin, Hume & Whatman, 2012; Willy & Davis, 2011). The intervention in these studies ranged from six to nine weeks. It is possible that there was no valgus collapse at pre-testing leaving no room for improvement (Sheerin *et al*., 2012). It is also possible that strength training alone is not enough to improve knee position during functional movements and that one needs to ensure transfer of benefits into the functional activities (Herman *et al*., 2008).

Willy & Davis (2011) found improvements in LEA during a SQT but that these benefits did not transfer to running. Baldon *et al*. (2012) found improved lower limb alignment during a SQT following an eight week proximal hip strengthening and stabilization. Improvements were seen in femoral adduction and internal rotation. The study sample of the current study could be a major reason for the lack of improvements in knee valgus. The investigators in the study by Baldon *et al*. (2012) made use of computerized 3D software system to carry out the kinematic assessment of knee valgus where in the current study simple video analysis was carried out. The methodology of measuring knee valgus in the current study left more room for measurement error. The lack of improvements in LEA may also be the result of the type of cues provided. Additional sensory cues, in addition to verbal, may provide extra stimuli to ensure improvements in LEA (Wouters *et al*., 2012). Improvements in LEA have previously been noted with gluteal training (Earl & Hoch, 2011, Nguyen *et al.,* 2011; Snyder *et al.,* 2009). It has also been stated that in the presence of increased strength (as seen in the Gmax torque values of the current study, Appendix F: Figure iv) decreased neural contribution may be required to maintain femoral position (Nguyen *et al.,* 2011). This could be a reason for the lack of change in onset and amplitude of the gluteal muscles. No other relationships existed between knee valgus and Gmax or Gmed (Appendix F: Figures i, ii, iii, v; Table xiv).

The knee-over-toe position during a squatting manoeuvre is a much debated topic with Ariel *et al*. (1974) stating that the knee traveling past the toes increases strain on the knee joint. Study Fry *et al*. (2003) also found that by preventing the knee travelling past the toes one can decrease the shear forces at the knee; however there is a concomitant increase in torque demands on the hip. In the current study there was a medium and small practical decrease in knee-over-toe angle during the dominant and non-dominant SQT, respectively (Appendix F: Figure ix). These non-significant decreases may still be beneficial in clinical practice when looking to decrease shear forces acting out on the knee to decrease the risk of knee injuries. What can be noted is that in the current study there were significant increases in isometric Gmax torque for both dominant and non-dominant Gmax. This increase in torque could help deal with the increase hip torque demands on the hip with a knee that is positioned less in front of the toe (Fry *et al*., 2003). The only significant correlation (negative) was between change in knee-over-toe angle and change in Gmax peak torque, possibly indicating that as Gmax torque increased one can maintain a knee position that positioned less beyond the toes. No other relationships existed between knee-over-toe and Gmax or Gmed (Appendix F: Figures i, ii, iii, v).

The application of the results of the PHE test, which suggested improved gluteal function following gluteal training, becomes questionable with this largely due to alck of improvements in functional movement. Even though there appears to be earlier onset of the Gmax during the PHE, this seems to not have had a positive effect on lower extremity alignment. This questions the usability of the PHE as a means of assessing gluteal function with an apparent inability to extrapolate the results to more functional movments.

In conclusion, it may be possible to alter the activation sequence of the muscles recruited during PHE to more closely resemble that suggested as the golden standard by Janda (1991). Improved Gmax onset was noted relative to the other muscle tested suggested improved Gmax recruitment. The QALE and the SQT appear to not be suitable replacements for assessing muscle onset during hip extension. The improved Gmax onset, as occurred in the PHE, seems to not be transferred into a more functional task (the SQT) with no major improvements noted in lower limb alignment. This suggests that clinicians need to reconsider the use of the PHE test as a means of assessing gluteal function due to the lack of ability to apply the results to more functional movements.

Study limitations & Future studies

The assumption that the AS described by Janda (1991) is the 'ideal' or golden standard to use as references serves as the major limitation of the study. This even though evidence suggests that such a sequence does not exist (Bullock-Saxton *et al*., 1994; Kang *et al*., 2012; Lehman *et al*., 2012; Lewis *&* Sahrmann, 2009; Sakamoto *et al*., 2009; Tateuchi *et al*., 2012; Vogt *&* Banzer, 1997). There were a number of additional limitations to this study. Other multi-joint muscles that may act as synergists to hip extension were excluded from the assessment, such as the adductor magnus and the semitendinosus (Neumann, 2010). The BicepFem was isolated as a hamstring muscle for assessment due to its connection to the Gmax through the sacrotuberous ligament (Leinonen at al., 2000) and it was believed this may increase the role of the BicepFem in the AS during hip extension. Future studies should include other synergists to hip extension. Gmax activation is also largely effected by the position of the femur in terms of abduction and external rotation (Kang *et al*., 2012; Sakamoto *et al*., 2009). These movements should be negated or accounted for in the future.

Studies investigating muscle onset should also record each repetition in isolation. Considering that measures of continuous repetitions gives rise to an improper return to baseline following each repetition (Lewis *&* Sahrmann, 2009). This unfortunately occurred in the current study and therefore only the first repetition could you used for onset assessment.

The participant number following post-testing dropped to seven in the control group and only three in the experimental group; thereby increasing the possibility of type one error. Consequently, the current study could not compare results to a control group.

The use of a more sophisticated 3D movement analysis system would be beneficial to increase the accuracy of the measurements of lower limb alignment. The current study used a video analysis system with software that increases the risk for measurement error. Financial limitations on the study prevented the use of a more sophisticated system.

Finally, netball is a dynamic sport that involves many jumping and landing movements. Landing from a jump has been proposed as a major risk factor for injury in netball (Sinsurin *et al*., 2013). Accordingly, it may be beneficial in future studies to include a jumping and landing task to make the assessment results more applicable to the sport.

Implications for practice/research

The PHE test seems to be the most ideal test to assess for activation sequence of the hip extensors when compared to the QALE and the SQT. The results of the current study also suggest that therapists could use the pattern suggested by Janda (1991) as the golden standard that individuals should achieve during the PHE as it appears possible to improve Gmax onset with focused gluteal training. This appears to be only true for the PHE movement and the researchers suggest that therapists need to reconsider the application of the results of the PHE to functional movements.

Conclusion

Pre-testing revealed no consistent AS during the PHE, the QALE, and the SQT with all three movements not agreeing with the proposed 'ideal' AS (Janda, 1991). The implementation of the gluteal training program favourably altered the AS during the PHE so that the Gmax shifted earlier in the order; suggesting improved Gmax function. This change in the AS more closely resembled that of the proposed 'ideal' AS suggesting that this AS can be used as a reference standard during clinical testing. The AS during the QALE and SQT did not change favourably and therefore might not be suitable replacements for the assessment of AS during hip extension; this in spite of the fact that they are more functional in nature. The position of hip flexion in these movements seems to favour earlier activation of the hamstrings. The improved Gmax onset seen in PHE did not transfer into your more functional movements and there was no improvement in LEA following the gluteal training; suggesting an inability to transfer results of the PHE to improved gluteal function during more functional movements.

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Figures:

Figure 2.2: https://www.kenhub.com/en/atlas/musculus-gluteus-maximus

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Figure 2.3: https://www.kenhub.com/en/atlas/musculus-gluteus-medius

Permission granted by Kenhub©

Figure 2.4: http://www.sports-injury-info.com/pulled-hamstring.html

Permission granted by Sport-injury-info©

Figure 2.5: http://www.myweightlifting.com/erector-spinae-muscles.html

Permission requested (no response)

Appendices

Appendix A: Ethical Clearance

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Approval Notice
Amendment

17-Jul-2015 Rainsford, Ian IG

Proposal #: HS941/2013
Title: The Role of the Gluteus Maximus During the Prone Hip Extension

Dear Mr. Ian Rainsford,

Your **Amendment** received on **10-Jun-2015**, was reviewed by members of the **Research Ethics Committee: Human Research (Humanities)** via Expedited review procedures on **10-Jul-2015** and was approved.
Sincerely,

Clarissa Graham
REC Coordinator
Research Ethics Committee: Human Research (Humanities)

Appendix B: Informed Consent form

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CONSENT TO PARTICIPATE IN RESEARCH

The Role of the Gluteus Maximus During the Prone Hip Extension

You are asked to participate in a research study conducted by Ian Rainsford (B.Hons Sport Science: Biokinetics) from the Sport Science Department at Stellenbosch University. The results of the study will contribute to a Master's thesis as well as a honours project. You were selected as a possible participant in this study because of your participation in netball and because you are of appropriate age and injury status for the study.

PURPOSE OF THE STUDY

The purpose of the research is to evaluate hip function, in terms of muscle activation and balance, following an exercise intervention. Proper hip function can ensure a decrease in risk of injury to the lower extremities as well as to the pelvic and lumbar regions; this type of research is thus very useful.

1. PROCEDURES

This is a double blind study, in which the principle researcher(s) involved with the testing is not aware of the grouping of the individuals that participate in the study, and the expected outcomes will not be revealed to you (the participant) until after the project has been completed. However any possible risks will be truthfully explained to you.

If you volunteer to participate in this study, we would ask you to do the following things:

Pre-participation screening:

You will fill in a pre-participation screening form which will help us gather important data; this data will be kept confidential. This data will be useful in helping describe the study population and help identify important aspects, such as leg dominance.

Grouping and initial testing:

You will be randomly divided into one of two groups (control and experimental). Each group will undergo the same initial testing procedures; which are as follows:

Electromyography (EMG) testing during certain exercise positions will be carried out of which one will also be videotaped to assess improvements in form. The EMG electrodes (electrodes pick up signals from activated muscles) will be placed on the skin surface above certain muscle groups surrounding the hip region. Excessive hair may need to be shaved from the skin surface to ensure optimal attachment of the electrodes. The muscles include the lumbar Erector Spinae (lower back muscles), the Hamstring muscle group (posterior thigh), the gluteus medius muscles, and the Gluteus Maximus muscles (buttocks). Balance testing will also be carried out on both legs during the testing sessions.

Intervention:

The intervention will cover a ten week period during which three training sessions per week will be required that will last for up to one hour each. During the intervention, normal netball training can continue and all activity will be requested to be logged during the 10 week period.

Post-intervention:

Following the intervention a post-intervention testing will take place, once again following the same setup as the initial testing.

Summary:

You will be involved in the study for approximately 12 weeks, involving 30 training sessions and two testing occasions.

POTENTIAL RISKS AND DISCOMFORTS

The possible risks are muscle soreness/discomfort following exercise sessions and possibly, although unlikely, skin reaction to electrode adhesive. In the unlikely case of injury a referral to Campus Health Services of Stellenbosch University where a doctor (J-A. Kirby, 021 – 808 3494) will be able to assess severity of injury will be made; physiotherapist services are also available through the same clinic. For any further rehabilitation, a referral to Stellenbosch Biokinetics Centre, where rehabilitation services are offered, will be made.

2. POTENTIAL BENEFITS TO SUBJECTS AND/OR TO SOCIETY

The possible benefits of participation in the research are improvements in lower extremity strength, a better understanding of hip function, and improved exercise technique.

The study can also make a contribution to the clinical field when it comes to understanding and assessing hip function. The research could make a valuable contribution to the academic field in the understanding of hip function and muscle recruitment in and around the hip. This research could also act as a stepping stone for further research into the understanding and management of injury prevention and rehabilitation of lower back pain and numerous lower extremity injuries.

3. PAYMENT FOR PARTICIPATION

There will be no compensation for participation in the study. Results of your tests and the findings of the study will be made available to you upon request. The exercise intervention program will made accessible to you after completion of the study upon request; particularly if the results of the study show particular benefits to you as netball player. A debriefing will be held following the completion of the study during which all results will be discussed and any questions you may have will be answered.

4. CONFIDENTIALITY

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. Confidentiality will be maintained by means of assigning codes to the data. All results of the tests will be stored under a code with a list linking the names and the codes being kept separate and only available to the researcher (Ian Rainsford). All results of the tests will only be made available to Dr Karen Welman and Dr Ranel Venter (study supervisors and lecturers at Sport Science Department of Stellenbosch University) as well as students for honour's thesis work (at this point no names will be linked to the data).

The participant has the right to review any and all video recordings; these video recording will only be used in the study and will not be used for any other purposes. Following thesis and/or article publication the video recording will be kept on a password protected computer for three years and then destroyed.

The results of the study will be published as a Master's Thesis and possibly in a scientific peer-reviewed journal at a later stage; at this point the results will not be linked to any names.

5. PARTICIPATION AND WITHDRAWAL

You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so; these circumstances include injury, sickness, and failure to adhere to exercise intervention.

6. IDENTIFICATION OF INVESTIGATORS

If you have any questions or concerns about the research, please feel free to contact the following individuals:

Name	Email Address	Contact number
Mr Ian Rainsford (principle investigator)	irainsford@sun.ac.za	+27 76 176 3290
Dr Karen Welman (study supervisor)	welman@sun.ac.za	+27 21 808 4733
Dr Ranel Venter (study supervisor)	rev@sun.ac.za	+27 21 808 4721

Above individuals can be found at the Department of Sport Science, Stellenbosch University, Noordwalwes street, Coetzenberg, Stellenbosch.

7. RIGHTS OF RESEARCH SUBJECTS

You may withdraw your consent at any time and discontinue participation without penalty. You are not waiving any legal claims, rights or remedies because of your participation in this research study. If you have questions regarding your rights as a research subject, contact Ms Maléne Fouché [mfouche@sun.ac.za; 021 808 4622] at the Division for Research Development.

SIGNATURE OF RESEARCH PARTICIPANT

The information above was described to me by Ian Rainsford in English and I am in command of this language or it was satisfactorily translated to me. I was given the opportunity to ask questions and these questions were answered to my satisfaction.

I hereby consent voluntarily to participate in this study and I have been given a copy of this form.

____

Name of Participant

____ ______________

Signature of Participant Date

SIGNATURE OF INVESTIGATOR

I declare that I explained the information given in this document to ______________________________. She was encouraged and given ample time to ask me any questions. This conversation was conducted in English and no translator was used.

____ ______________

Signature of Investigator Date

Ian Rainsford

Appendix C: Medical screening questionnaire

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UNIVERSITEIT STELLENBOSCH

<u>Subject Screening Form</u>

Screening Code: _____ Subject Code: _____

(For office use only) *(For office use only)*

This form is to be used as a gathering of important information relevant to the study. It is important that the questions be answered with accuracy and care so as to ensure optimal study conditions and parameters.

Many thanks for your willingness to partake in the study as your involvement will help make a valuable contribution to the field of Sport Science and Biokinetics.

1. What is your date of birth?	YYYY / MM / DD			
2. Which is your dominant leg? (i.e. which leg would you most likely use to kick a ball)	Left		Right	
3. How many hours per week are you engaged in physical activity? (Circle applicable)	0-2	3-4	5-6	≥ 7
4. What type/s of physical activity are you engaged in (Circle all applicable)	Netball	Running	Gym	Cycling
5. If you circled Running, Gym, or Cycling in question 4, please specify the frequency				
6. If you circled gym in question 4, please circle all that are applicable.	Toning	Muscle Building	Plyometric/ Power	Cardio
7. Are you currently suffering with a back injury or have you injured your back in the last 12 months?	Yes		no	
	If yes, describe:			
8. Are you currently suffering from any lower extremity injury or have you suffered an injury to the lower extremities in the last 12 months?	Yes		no	
	If yes, describe:			
9. Are you currently suffering with a muscle injury or have you injured a muscle in the last 12 months?	Yes		no	
	If yes, describe:			
10. Are you aware of any reason why you should not participate in the study?(If yes please specify in the space provided)	Yes	No		

For researcher use: Lumbar spine assessment				
11. Duration of pain	< 12 weeks		≥ 12 weeks	
12. Cause of pain	Acute	Chronic	Surgical	
13. Postural Deviation	Kyphosis	Lordosis	Scoliosis	
14. Pain Scale (out of 10)	Pre:		Post:	
15. ROM limitation (left and right active straight leg raise)	Pre:		Post:	
	R:	L:	R:	L:
16. Faber Test	Pre:		Post:	
17. Slump Test	Pre:		Post:	
18. Modified Stork Test	Pre:		Post:	

Owestry Pain Questionnaire

Section 1 – Pain Intensity		Section 2 – Personal Care (Washing, Dressing, etc)	
0	I can tolerate the pain I have without having to use pain killers	0	I can look after myself normally without causing extra pain
1	The pain is bad but I manage without taking pain killers	1	I can look after myself normally but it causes extra pain
2	Pain killers give complete relief from pain	2	It is painful to look after myself and I am slow and careful
3	Pain killers give moderate relief from pain	3	I need some help but manage most of my personal care
4	Pain killers give very little relief from pain	4	I need help every day in most aspects of self-care
5	Pain killers have no effect on the pain and I do not use them	5	I do not get dressed, I wash with difficulty and stay in bed
Section 3 – Lifting		**Section 4 - Walking**	
0	I can lift heavy w8s without extra pain	0	Pain does not prevent me walking any distance
1	I can lift heavy w8s but it gives extra pain	1	Pain prevents me from walking more than 2 kilometres
2	Pain prevents me from lifting heavy w8s off the floor, but I can manage if they are conveniently placed eg. on a table	2	Pain prevents me from walking more than 1 kilometre
3	Pain prevents me from lifting heavy w8s, but I can manage light to medium w8s if they are conveniently positioned	3	Pain prevents me from walking more than 500 metres
4	I can lift very light w8s	4	I can only walk using a stick or crutches

5	I cannot lift or carry anything at all	5	I am in bed most of the time
Section 5 – Sitting		**Section 6 - Standing**	
0	I can sit in any chair as long as I like	0	I can stand as long as I want without extra pain
1	I can only sit in my favourite chair as long as I like	1	I can stand as long as I want but it gives me extra pain
2	Pain prevents me sitting more than one hour	2	Pain prevents me from standing for more than 1 hour
3	Pain prevents me from sitting more than 30 minutes	3	Pain prevents me from standing for more than 3 minutes
4	Pain prevents me from sitting more than 10 minutes	4	Pain prevents me from standing for more than 10 minutes
5	Pain prevents me from sitting at all	5	Pain prevents me from standing at all
Section 7–Sleeping		**Section 8–Sex Life**	
0	My sleep is never disturbed by pain	0	My sex life is normal and causes no extra pain
1	My sleep is occasionally disturbed by pain	1	My sex life is normal but causes some extra pain
2	Because of pain I have less than 6 hours sleep	2	My sex life is nearly normal but is very painful
3	Because of pain I have less than 4 hours sleep	3	My sex life is severely restricted by pain
4	Because of pain I have less than 2 hours sleep	4	My sex life is nearly absent because of pain
5	Pain prevents me from sleeping at all	5	Pain prevents any sex life at all
Section 9–Social Life		**Section 10–Travelling**	
0	My social life is normal and gives me no extra pain	0	I can travel anywhere without pain
1	My social life is normal but increases the degree of pain	1	I can travel anywhere but it gives me extra pain
2	Pain has no significant effect on my social life apart from limiting my more energetic interests eg, sport	2	Pain is bad but I manage journeys over two hours
3	Pain has restricted my social life and I do not go out as often	3	Pain restricts me to journeys of less than one hour
4	Pain has restricted my social life to my home	4	Pain restricts me to short necessary journeys under 30 minutes
5	I have no social life because of pain	5	Pain prevents me from travelling except to receive treatment

PAR-Q and You

Common sense is your best guide when you answer the following questions. Please read the questions carefully and answer each one.

ڤ	Yes	ڤ	No	Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?
ڤ	Yes	ڤ	No	Do you feel pain in your chest when you do physical activity?
ڤ	Yes	ڤ	No	In the past month, have you had chest pain when you were not doing physical activity?
ڤ	Yes	ڤ	No	Do you lose your balance because of dizziness or do you ever lose consciousness?
ڤ	Yes	ڤ	No	Do you have a bone or joint problem that could be made worse by a change in your physical activity?
ڤ	Yes	ڤ	No	Is your doctor currently prescribing drugs (for example water pills for blood pressure or heart conditions)? If yes, Please specify and dosage: ______________________________
ڤ	Yes	ڤ	No	Do you know of any other reason why you should not do physical activity?

Should your answers to any of the above questions change during the time of the study, please inform the researcher.

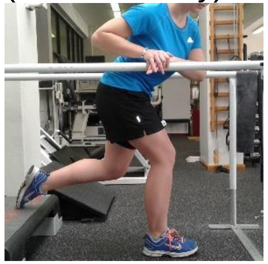
Subject name and surname: ____________________________

Subject Signature: _________________ Date: ________________

Researcher Signature: _________________ Date: ________________

Appendix D: Exercise depictions

Standing glute activation
(used clinically)



Single limb squat (with cable pull)
(Ayotte *et al*., 2007; Simenz *et al*., 2012)

Side plank (modified with clam)
(Boren *et al*., 2011)

Unilateral wall squat
(Ayotte *et al*., 2007; Simenz *et al*., 2012)

Single limb stiff leg deadlift
(Distefano *et al*., 2009)

Quadruped arm/lower extremity lift
(Ekstrom *et al*., 2007)

Frontal step up
(Ayotte *et al*., 2007; Simenz *et al*., 2012)

Single limb glute thrust
(used clinically)

Appendix E: Exercise progressions

			Progression weeks								
Exercises	**Sets**	**Reps**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Standing glute activation	1	1min	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Unilateral wall squat	2	10	OBW	2kg	4kg	6kg	8kg	10kg	12kg	14kg	16kg
Frontal step up	2	12	OBW	2kg	4kg	6kg	8kg	10kg	12kg	14kg	16kg
Single limb squat	2	12	OBW *	OBW **	OBW **	3kg ***	3kg ***	4kg ***	4kg ***	5kg ***	6kg ***
Single limb stiff leg deadlift	2	10	OBW	OBW	2kg	4kg	6kg	8kg	10kg	12kg	14kg
Single limb glute thrust	2	10	OBW	2.5kg	2.5kg	5kg	5kg	10kg	10kg	10kg	10kg
Side plank with clam	2	Time	20 sec	25 sec	30sec	35sec	40sec	45sec	50sec	55sec	60sec
Quadruped arm/lower extremity lift	2	10	OBW	OBW	1kg^	1kg^	2kg^	2kg^	3kg^	3kg^	3kg^

* Supported
** Free standing
*** With opposite arm cable pull
^ With ankle weights

Appendix F: Additional data analysis and representation

Article 1:

Table i: Pre-testing Dominant PHE muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-59.3	-54.0	47.3	0.0	-320.7	368.0	12543
2	-94.7	-115.3	488.0	0.0	43.3	603.3	21453
3	36.0	-56.0	60.7	0.0	-24.7	116.7	25413
4	7.3	47.3	210.0	0.0	-4.0	214.0	14123
5	-8.7	-156.7	154.7	0.0	180.0	336.7	21435
6	-72.0	-83.3	59.3	0.0	4.0	142.7	21453
7	19.3	17.3	500.7	0.0	371.3	500.7	42153
8	255.3	14.0	146.7	0.0	74.0	255.3	42531
9	6.0	29.3	76.7	0.0	35.3	76.7	41253
10	134.0	20.0	2.7	0.0	58.0	134.0	43521
11	-93.3	-100.7	175.3	0.0	182.0	282.7	21435
12	89.3	32.0	422.7	0.0	118.7	422.7	42153
13	-22.0	-83.3	38.7	0.0	102.7	186.0	21435
14	-58.7	-56.0	148.0	0.0	238.0	296.7	12435
15	12.7	24.7	30.7	0.0	88.0	88.0	41235
16	37.3	-78.0	7.3	0.0	262.7	340.7	24315
17	-267.3	-275.3	-194.0	0.0	-210.7	275.3	21534
18	-27.3	-40.7	322.7	0.0	234.0	363.3	21453
Mean	-5.9	-50.8	149.9	0.0	79.6	278.0	21453
S.D	107.5	81.8	182.3	0.0	164.9	144.4	

Table ii: Pre-testing non-dominant PHE muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IspiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-36.7	-44.0	254.7	0.0	14.0	298.7	12453
2		52.7	216.7	0.0	40.7		
3	-694.7	-694.7	339.3	0.0	29.3	1034.0	12453
4	538.7	79.3	349.3	0.0	20.0	538.7	45132
5	-108.7	-142.0	390.0	0.0	-6.7	532.0	12543
6	-764.0	-803.3	245.3	0.0	71.3	1048.7	12453
7							
8	2.7	-176.7	75.3	0.0	47.3	252.0	14253
9	-2.7	-62.7	4.7	0.0	22.0	84.7	12435
10	696.7	-119.3	33.3	0.0	6.0	816.0	14532
11	-58.7	-106.7	1212.7	0.0	266.7	1319.3	12453
12	195.3	-10.0	846.0	0.0	258.7	856.0	14253
13	-116.0	-129.3	124.0	0.0	87.3	253.3	21453
14	-374.0	-432.7	-239.3	0.0	28.0	460.7	12345
15	11.3	260.0	-23.3	0.0	120.7	283.3	34251
16	-142.7	-168.0	-78.7	0.0	153.3	321.3	12345
17	36.7	18.7	58.0	0.0	81.3	81.3	41235
18	-247.3	-268.0	-135.3	0.0	-194.7	268.0	12534
Mean	-66.5	-161.6	216.0	0.0	61.5	528.0	12453
S.D	370.8	267.9	359.0	0.0	104.8	375.9	

Table iii: Pre-testing Dominant QALE muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-36.0	17.3	110.7	0.0	119.3	155.3	14235
2	-529.3	-624.0	-132.0	0.0	-305.3	624.0	21534
3	-55.3	-292.7		0.0	-276.0		
4	-300.0	-150.0	318.7	0.0	-210.7	618.7	15243
5	-412.0	-636.0	-602.7	0.0	-296.7	636.0	23154
6	-262.0	-356.0	-846.0	0.0	-753.3	846.0	35214
7	-425.3	-514.7	-570.7	0.0	38.0	608.7	32145
8	32.0	-162.7	-306.0	0.0	54.7	360.7	32415
9	-266.0	-278.0	-39.3	0.0	19.3	297.3	21345
10	22.0	4.7	-35.3	0.0	-8.7	57.3	35421
11	139.3	6.0	334.0	0.0	-36.7	370.7	54213
12	-522.7	-581.3	-526.7	0.0	-304.7	581.3	23154
13	-371.3	-372.0	-472.0	0.0	177.3	649.3	32145
14	95.3	21.3	47.3	0.0	125.3	125.3	42315
15	25.3	-14.0	-563.3	0.0	17.3	588.7	32451
16	13.3	-500.0	28.0	0.0	-93.3	528.0	25413
17	-82.0	-822.7	-436.0	0.0	-744.7	822.7	25314
18	-290.7	-233.3	-438.0	0.0	162.7	600.7	31245
Mean	-179.2	-304.9	-242.9	0.0	-128.7	498.3	23154
S.D	219.6	263.8	348.5	0.0	278.8	232.3	

Table iv: Pre-testing non-dominant QALE muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-120.0	-229.3	-156.7	0.0	102.0	331.3	13245
2	-34.7	-84.0	-26.0	0.0	44.7	128.7	12345
3	-359.3	-595.3	-458.7	0.0	-559.3	595.3	15324
4	-106.7	-210.0	-99.3	0.0	-14.7	210.0	12354
5	-604.0	-628.7	-235.3	0.0	-453.3	628.7	12534
6	-401.3	-432.7	-756.7	0.0	-380.0	756.7	31254
7	-317.3	-362.7	-130.7	0.0	-258.0	362.7	12534
8	163.3	36.0	-378.0	0.0	-197.3	541.3	35412
9	-358.0	-404.0	-244.0	0.0	154.0	558.0	12345
10	140.7	5.3	-14.0	0.0	172.7	186.7	34125
11							
12	656.0	421.3	449.3	0.0	848.0	848.0	41325
13	-128.7	-154.0	-312.0	0.0	244.7	556.7	32154
14	283.3	-293.3	-452.7	0.0	-65.3	736.0	31542
15	-350.7	-310.0	-382.0	0.0	-179.3	382.0	32154
16	-564.0	-611.3	-224.7	0.0	2.0	613.3	12345
17	162.0	-292.7	-84.0	0.0	-52.7	454.7	13542
18	-463.3	472.0	-601.3	0.0	-275.3	1073.3	32541
Mean	-141.3	-216.1	-241.6	0.0	-51.0	527.3	31254
S.D	337.9	317.1	270.4	0.0	324.4	248.6	

Table v: Pre-testing Dominant SQT muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-43.3	-301.3	28.0	0.0	449.3	750.7	21435
2	-510.0	-514.7	-232.7	0.0	-550.7	550.7	52134
3	-3.3	-192.0	-306.0	0.0	-2.0	306.0	32154
4	-241.3	-387.3	-454.0	0.0	-158.7	454.0	32154
5	120.0	66.7	141.3	0.0	653.3	653.3	42135
6	137.3	124.0	-85.3	0.0	177.3	262.7	34215
7		94.0	-46.7	0.0			
8	70.0	212.7	368.0	0.0	239.3	368.0	41253
9	-188.0	-170.7	-398.0	0.0	1123.3	1521.3	31245
10	-233.3	-240.7	-54.0	0.0	1923.3	2164.0	21345
11	33.3	-9.3	10.0	0.0			
12	-175.3	-145.3		0.0	896.7		
13	198.7	-3.3	205.3	0.0	-2.0	208.7	25413
14	-34.7	90.0	370.7	0.0	-178.0	548.7	51423
15	626.7	670.0	704.7	0.0	82.0	704.7	45123
16	-232.0	-178.0		0.0	401.3		
17	-468.7	-476.0	-224.7	0.0	-30.0	476.0	21354
18	-889.3	-294.0	127.3	0.0	-289.3	1016.7	12543
Mean	-107.8	-92.0	9.6	0.0	296.0	713.2	12435
S.D	333.5	284.3	307.9	0.0	616.1	538.8	

Table vi: Pre-testing non-dominant SQT muscle onset relative to Gmax for each subject

Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
1	-237.3	-121.3	-131.3	0.0	651.3	888.7	23145
2	-152.7	-463.3	-77.3	0.0	58.7	522.0	12345
3	-419.3	-702.7	-807.3	0.0	-38.7	807.3	31254
4	-80.7	-304.7	98.0	0.0	253.3	558.0	12435
5	-220.0	-220.0	-61.3	0.0	-7.3	220.0	12354
6	107.3	322.7	-101.3	0.0	150.7	424.0	34251
7	230.0	204.0	401.3	0.0	1296.0	1296.0	41235
8	450.0	172.7	-358.7	0.0	447.3	808.7	34152
9	71.3	114.7	42.0	0.0		114.7	
10	50.7	-54.0	2.0	0.0		104.7	
11	110.7	-302.7	-458.0	0.0	344.0	802.0	31425
12	-224.7	-216.7		0.0	282.7		
13	262.7	42.7	343.3	0.0	694.7	694.7	41235
14	-145.3	80.0	592.7	0.0	-52.7	738.0	25413
15	-322.7	-324.0	76.7	0.0	682.7	1006.7	12435
16	33.3	40.0		0.0	870.7		
17	-367.3	-513.3	-296.0	0.0	-184.7	513.3	12354
18	38.0	-440.0	-443.3	0.0	-346.7	481.3	31542
Mean	-45.3	-149.2	-73.7	0.0	318.9	623.8	13245
S.D	235.4	283.4	353.3	0.0	434.4	323.0	

Table vii: Comparison of the activation sequences of the PHE, QALE, and SQT

Movement	Muscle used to initiate movement											
	ContrES		IspiES		BicepFem		Gmax		Gmed		Not assessed	
	#	%	#	%	#	%	#	%	#	%	#	%
RPHE	3.0	16.7	9.0	50.0	0.0	0.0	6.0	33.3	0.0	0.0	0.0	0.0
LPHE	12.0	66.7	1.0	5.6	1.0	5.6	2.0	11.1	0.0	0.0	2.0	11.1
RQALE	2.0	11.1	6.0	33.3	7.0	38.9	1.0	5.6	1.0	5.6	1.0	5.6
LQALE	9.0	50.0	0.0	0.0	7.0	38.9	1.0	5.6	0.0	0.0	1.0	5.6
RSQT	1.0	5.6	4.0	22.2	4.0	22.2	3.0	16.7	2.0	11.1	4.0	22.2
LSQT	5.0	27.8	2.0	11.1	5.0	27.8	2.0	11.1	0.0	0.0	4.0	22.2

Article 2:

Table viii: Pre- and post-testing Dominant PHE muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1	-94.67	-115.33	488.00	0.00	43.33	603.33	2143
Pre	2	-72.00	-83.33	59.33	0.00	4.00	142.67	2143
Pre	3	6.00	29.33	76.67	0.00	35.33	76.67	4123
Pre	4	-22.00	-83.33	38.67	0.00	102.67	122.00	2143
Pre	5	-58.67	-56.00	148.00	0.00	238.00	206.67	1243
Pre	6	12.67	24.67	30.67	0.00	88.00	30.67	4123
Pre	7	-267.33	-275.33	-194.00	0.00	-210.67	275.33	2134
Pre	**Mean**	**-70.86**	**-79.90**	**92.48**	**0.00**	**42.95**	**208.19**	**21453**
Pre	**SD**	**-95.39**	**-102.40**	**-203.98**	**0.00**	**-135.12**	**-192.00**	
Post	1	81.33	-88.67	322.67	0.00	52.00	411.33	2413
Post	2	8.00	54.67	71.33	0.00	190.00	71.33	4123
Post	3	7.33	244.67	55.33	0.00	316.00	244.67	4132
Post	4	51.33	-24.00	16.67	0.00	56.67	75.33	2431
Post	5	224.67	224.00	420.00	0.00	20.67	420.00	4213
Post	6	124.67	74.00	238.00	0.00	166.00	238.00	4213
Post	7	7.33	22.00	168.67	0.00	87.33	168.67	4123
Post	**Mean**	**72.10**	**72.38**	**184.67**	**0.00**	**126.95**	**232.76**	**41253**
Post	**SD**	**80.68**	**122.98**	**150.18**	**0.00**	**103.81**	**142.63**	

Table ix: Pre- and post-testing non-dominant PHE muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1		52.67	216.67	0.00	40.67		
Pre	2	-764.00		245.33	0.00	71.33		
Pre	3	-2.67	-62.67	4.67	0.00	22.00	67.33	1243
Pre	4	-116.00	-129.33	124.00	0.00	87.33	253.33	1243
Pre	5	-374.00	-432.67	-239.33	0.00	28.00	432.67	1234
Pre	6	11.33	260.00	-23.33	0.00	120.67	283.33	3421
Pre	7	36.67	18.67	58.00	0.00	81.33	58.00	4123
Pre	**Mean**	**-201.44**	**-48.89**	**55.14**	**0.00**	**64.48**	**218.93**	**12435**
Pre	**SD**	**314.65**	**229.89**	**164.54**	**0.00**	**35.85**	**158.03**	
Post	1	-14.00	0.67	395.33	0.00	-6.00	409.33	2413
Post	2	76.00	9.33	43.33	0.00	152.67	76.00	4132
Post	3	-13.33	-21.33	71.33	0.00	22.00	92.67	1243
Post	4	42.67	-64.67	159.33	0.00	40.00	224.00	1423
Post	5	-99.33	-112.67	-28.00	0.00	93.33	112.67	1234
Post	6	63.33	13.33	16.00	0.00	68.67	63.33	4132
Post	7	167.33	123.33	242.67	0.00	158.67	242.67	4123
Post	**Mean**	**31.81**	**-7.43**	**128.57**	**0.00**	**75.62**	**174.38**	**24153**
Post	**SD**	**84.43**	**73.51**	**148.80**	**0.00**	**63.25**	**125.71**	

Table x: Pre- and post-testing Dominant QALE muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1	-529.33	-624.00	-132.00	0.00	-305.33	624.00	2134
Pre	2	-262.00	-356.00	-846.00	0.00	-753.33	846.00	3214
Pre	3	-266.00	-278.00	-39.33	0.00	19.33	278.00	2134
Pre	4	-371.33	-372.00	-472.00	0.00	177.33	472.00	3214
Pre	5	95.33	21.33	47.33	0.00	125.33	95.33	4231
Pre	6	25.33	-14.00	-563.33	0.00	17.33	588.67	3241
Pre	7	-82.00	-822.67	-436.00	0.00	-744.67	822.67	2314
Pre	**Mean**	**-198.57**	**-349.33**	**-348.76**	**0.00**	**-209.14**	**532.38**	**23514**
Pre	**SD**	**222.83**	**304.13**	**320.34**	**0.00**	**399.36**	**274.94**	
Post	1	-576.67	-357.33	-153.33	0.00	39.33	576.67	1234
Post	2	127.33	168.67	146.00	0.00	298.67	168.67	4132
Post	3	-253.33	-86.67	-250.00	0.00	-109.33	253.33	1324
Post	4	-27.33	-67.33	-62.67	0.00	94.00	67.33	2314
Post	5	-5.33	-16.67	74.00	0.00	397.33	90.67	1243
Post	6	164.00	244.67	-399.33	0.00	-118.67	644.00	3412
Post	7	413.33	-434.67	-326.67	0.00	-20.00	848.00	2341
Post	**Mean**	**-22.57**	**-78.48**	**-138.86**	**0.00**	**83.05**	**378.38**	**32145**
Post	**SD**	**318.30**	**249.72**	**203.28**	**0.00**	**198.16**	**308.10**	

Table xi: Pre- and post-testing non-dominant QALE muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (2)	IspiES (1)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1	-34.67	-84.00	-26.00	0.00	44.67	84.00	1234
Pre	2	-401.33	-432.67	-756.67	0.00	-380.00	756.67	3124
Pre	3	-358.00	-404.00	-244.00	0.00	154.00	404.00	1234
Pre	4	-128.67	-154.00	-312.00	0.00	244.67	312.00	3124
Pre	5	283.33	-293.33	-452.67	0.00	-65.33	736.00	3142
Pre	6	-350.67	-310.00	-382.00	0.00	-179.33	382.00	3214
Pre	7	162.00	-292.67	-84.00	0.00	-52.67	454.67	1342
Pre	**Mean**	**-118.29**	**-281.52**	**-322.48**	**0.00**	**-33.43**	**447.05**	**32154**
Pre	**SD**	**270.35**	**125.30**	**244.97**	**0.00**	**208.71**	**236.48**	
Post	1	-430.67	-565.33	-616.00	0.00	-487.33	616.00	3124
Post	2	90.00	45.33	97.33	0.00	164.67	97.33	4123
Post	3	42.00	112.67	-174.00	0.00	230.00	286.67	3421
Post	4	276.00	-2.67	-37.33	0.00	214.00	313.33	3142
Post	5	225.33	-14.00	-88.67	0.00	-42.00	314.00	3142
Post	6	-134.67	14.00	-119.33	0.00	-273.33	148.67	2341
Post	7	-11.33	10.00	242.00	0.00	-122.00	253.33	2413
Post	**Mean**	**8.10**	**-57.14**	**-99.43**	**0.00**	**-45.14**	**289.90**	**32541**
Post	**SD**	**238.08**	**228.03**	**268.35**	**0.00**	**270.92**	**166.26**	

Table xii: Pre- and post-testing Dominant SQT muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (1)	IpsiES (2)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1	-510.00	-514.67	-232.67	0.00	-550.67	514.67	2134
Pre	2	137.33	124.00	-85.33	0.00	177.33	222.67	3421
Pre	3	-188.00	-170.67	-398.00	0.00		398.00	3124
Pre	4	198.67	-3.33	205.33	0.00	-2.00	208.67	2413
Pre	5	-34.67	90.00	370.67	0.00	-178.00	405.33	1423
Pre	6	626.67	670.00	704.67	0.00	82.00	704.67	4123
Pre	7	-468.67	-476.00	-224.67	0.00	-30.00	476.00	2134
Pre	**Mean**	**-34.10**	**-40.10**	**48.57**	**0.00**	**-83.56**	**418.57**	**52143**
Pre	**SD**	**399.83**	**404.50**	**393.68**	**0.00**	**257.72**	**171.96**	
Post	1	-491.33	-495.33	484.00	0.00	734.00	979.33	2143
Post	2	-102.00	-3.33	10.67	0.00	46.00	112.67	1243
Post	3	-202.00	-115.33	-165.33	0.00	203.33	202.00	1324
Post	4	11.33	10.00	227.33	0.00	590.00	227.33	4213
Post	5	-102.00	-208.00	-1092.00	0.00	-251.33	1092.00	3214
Post	6	-496.00	-385.33	-483.33	0.00		496.00	1324
Post	7	555.33	65.33	702.00	0.00	529.33	702.00	4213
Post	**Mean**	**-118.10**	**-161.71**	**-45.24**	**0.00**	**308.56**	**544.48**	**21345**
Post	**SD**	**355.89**	**212.81**	**607.99**	**0.00**	**374.82**	**391.66**	

Table xiii: Pre- and post-testing non-dominant SQT muscle onset relative to Gmax for each subject

Group	Subject #	ContraES (2)	IspiES (1)	Bicep Fem (3)	Gmax (4)	Gmed (5)	Time Span (ms)	Order
Pre	1	-152.67	-463.33	-77.33	0.00	58.67	463.33	1234
Pre	2	107.33	322.67	-101.33	0.00	150.67	424.00	3421
Pre	3	71.33	114.67	42.00	0.00		114.67	4321
Pre	4	262.67	42.67	343.33	0.00	694.67	343.33	4123
Pre	5	-145.33	80.00	592.67	0.00	-52.67	738.00	2413
Pre	6	-322.67	-324.00	76.67	0.00	682.67	400.67	2143
Pre	7	-367.33	-513.33	-296.00	0.00	-184.67	513.33	1234
Pre	**Mean**	**-78.10**	**-105.81**	**82.86**	**0.00**	**224.89**	**428.19**	**21435**
Pre	**SD**	**233.23**	**324.11**	**297.93**	**0.00**	**376.34**	**187.41**	
Post	1	-485.33	-383.33	146.67	0.00	7.33	632.00	2143
Post	2	0.00	164.00	202.67	0.00	218.67	202.67	2413
Post	3	-178.00	-217.33	-116.00	0.00	189.33	217.33	1234
Post	4	140.00	-14.67	614.00	0.00	505.33	628.67	1423
Post	5	446.00	-200.67	-628.67	0.00		1074.67	3142
Post	6	-567.33	-726.67	-537.33	0.00	-298.00	726.67	1234
Post	7	-781.33	-866.67	-136.00	0.00	-559.33	866.67	1234
Post	**Mean**	**-203.71**	**-320.76**	**-64.95**	**0.00**	**10.56**	**621.24**	**21345.00**
Post	**SD**	**433.51**	**369.80**	**433.20**	**0.00**	**384.73**	**320.28**	

Article 3:

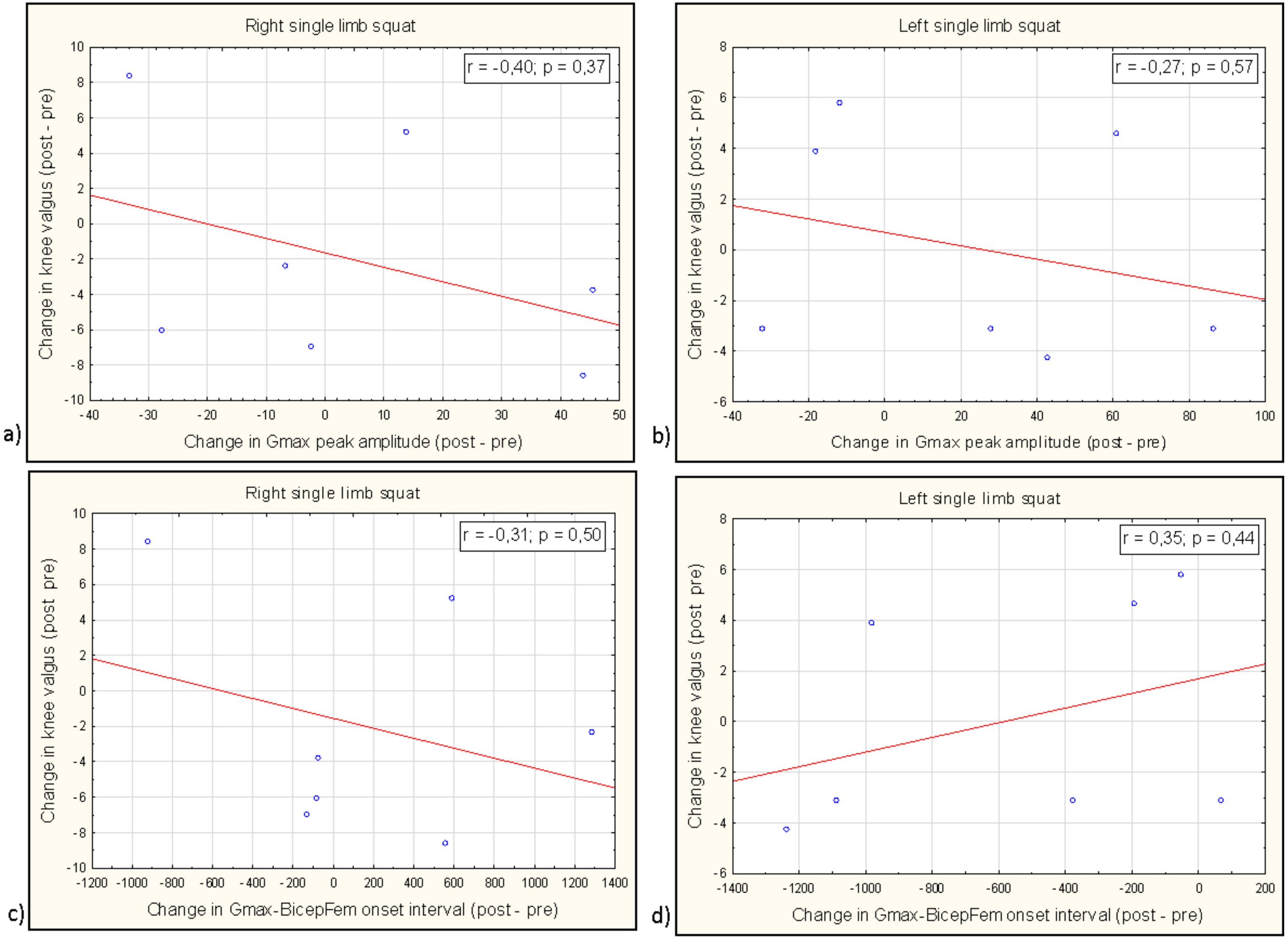


Figure i: Gmax: Valgus angle and Onsets and amplitudes

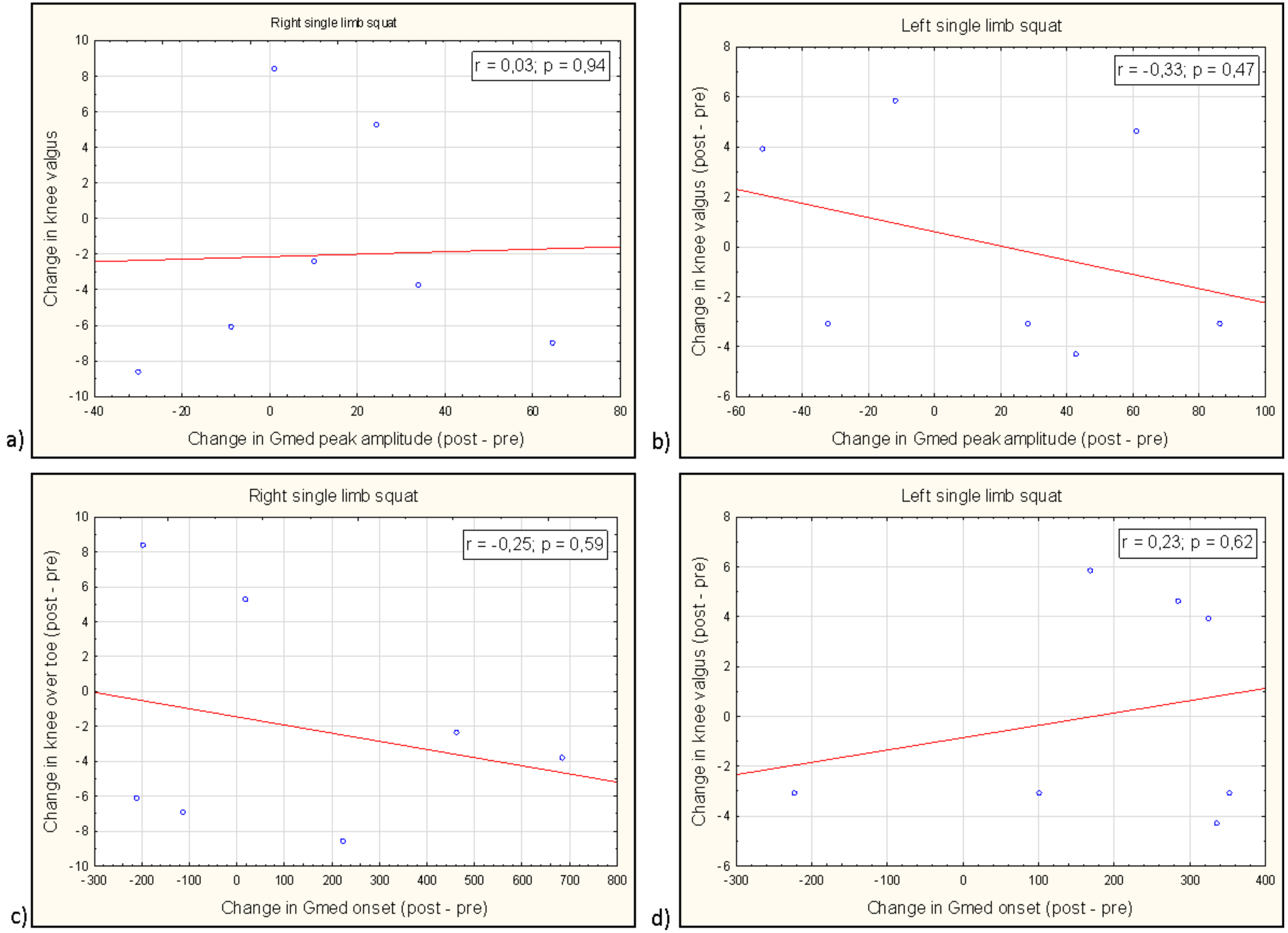


Figure ii: Gmed: Valgus angle and Onsets and amplitudes

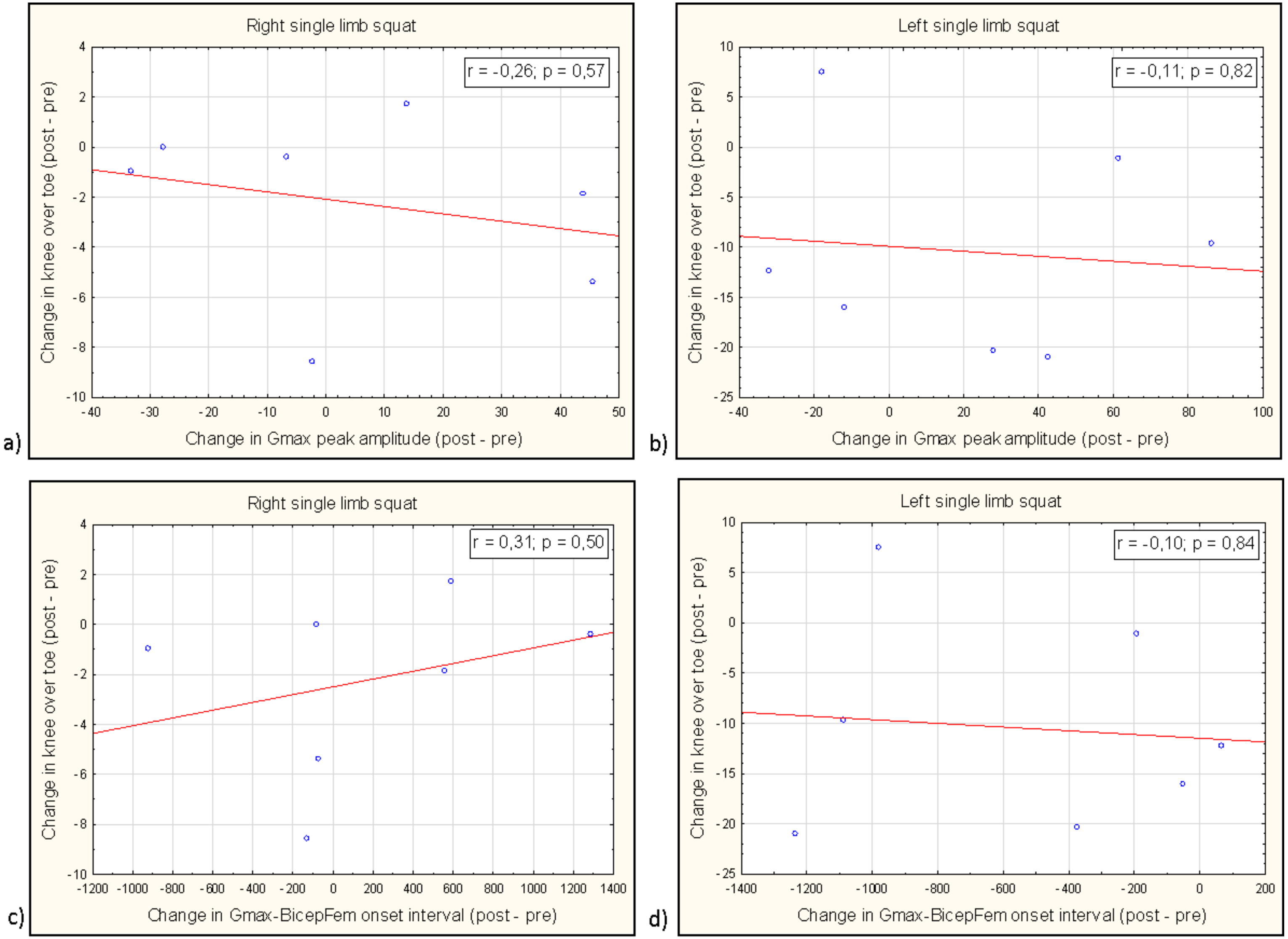


Figure iii: Gmax: Valgus and knee-over-toe and valgus and peak torque

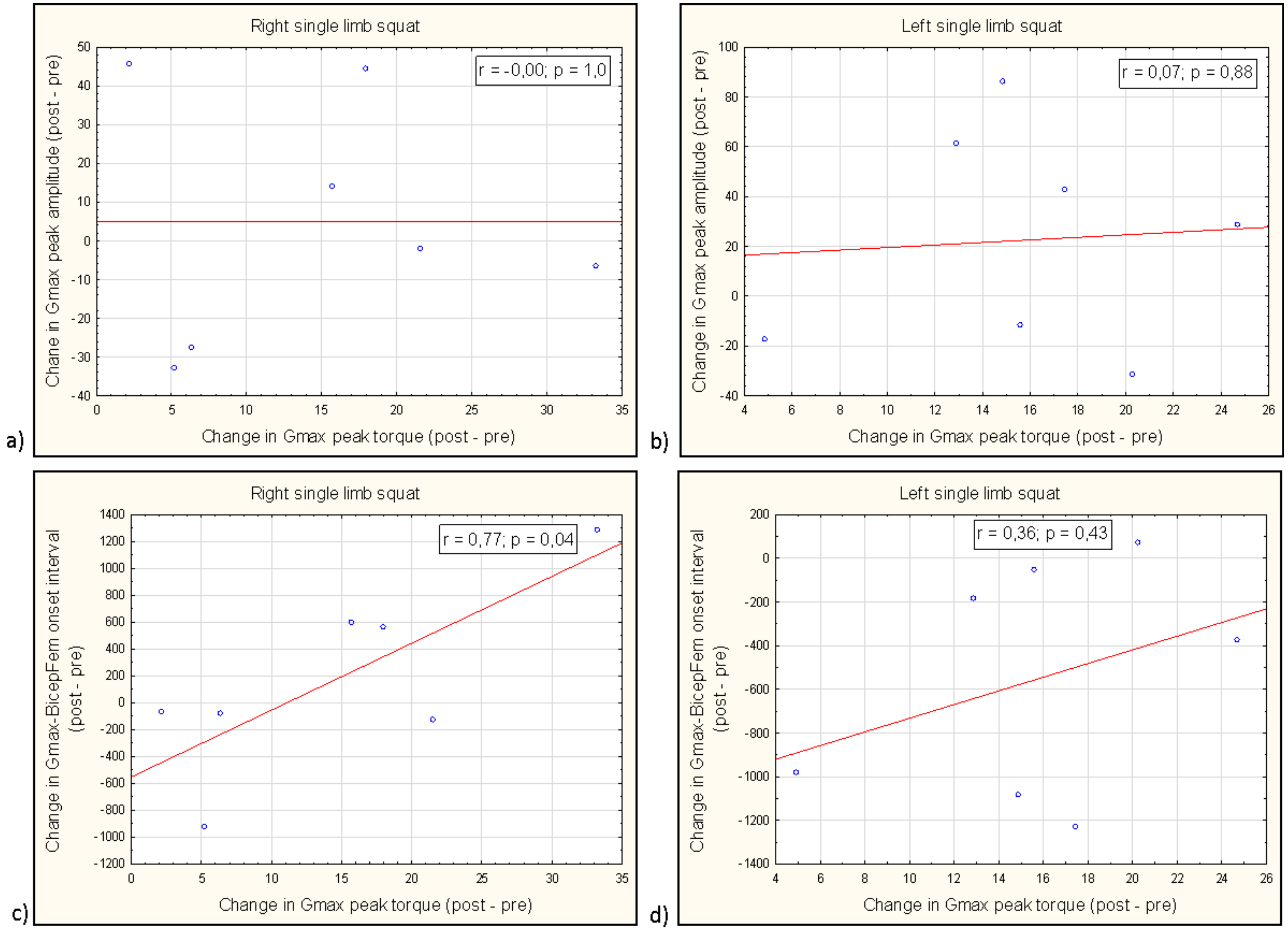


Figure iv: Gmax: Onset and amplitude and peak torque

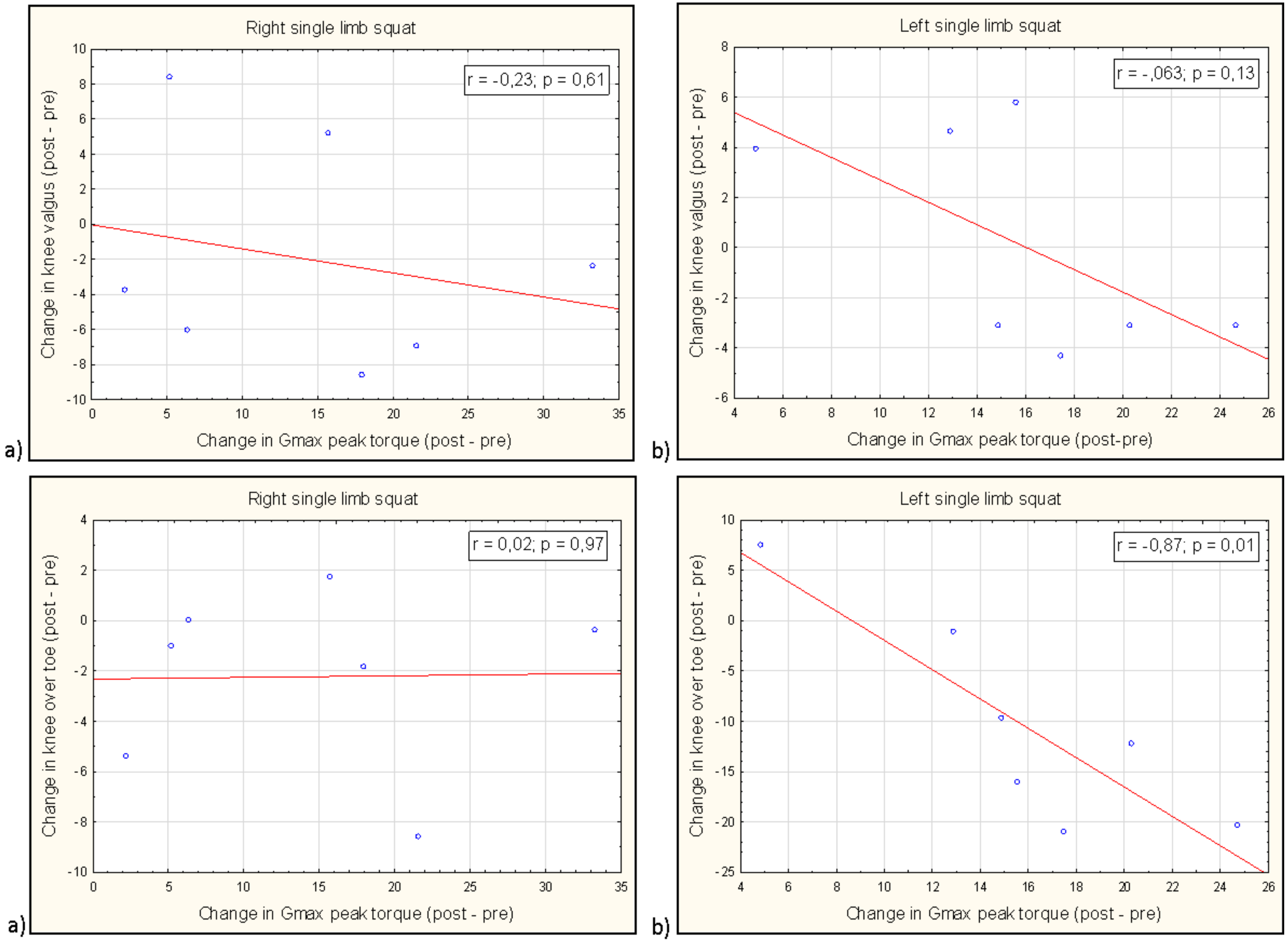


Figure v: Gmax: Peak torque and knee valgus and knee-over-toe angles

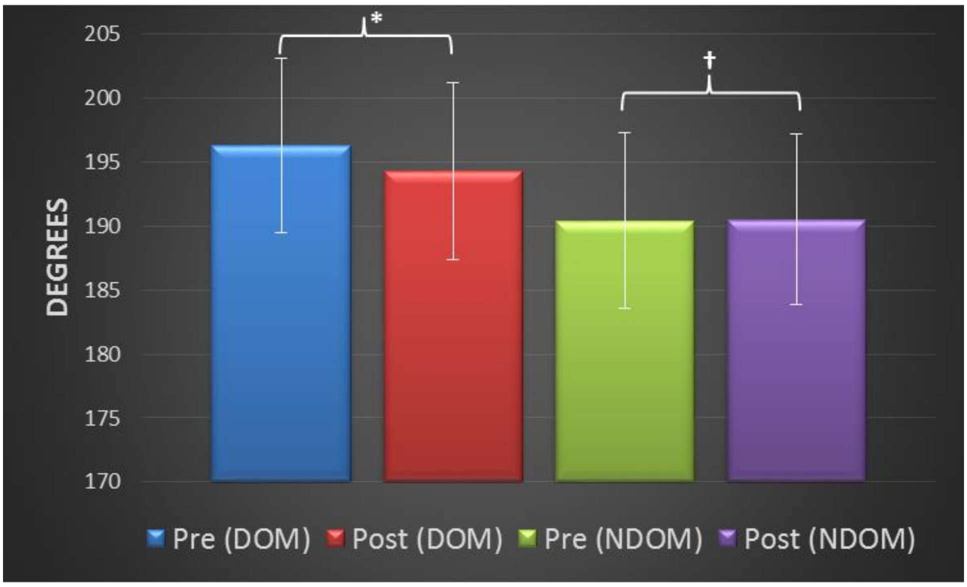
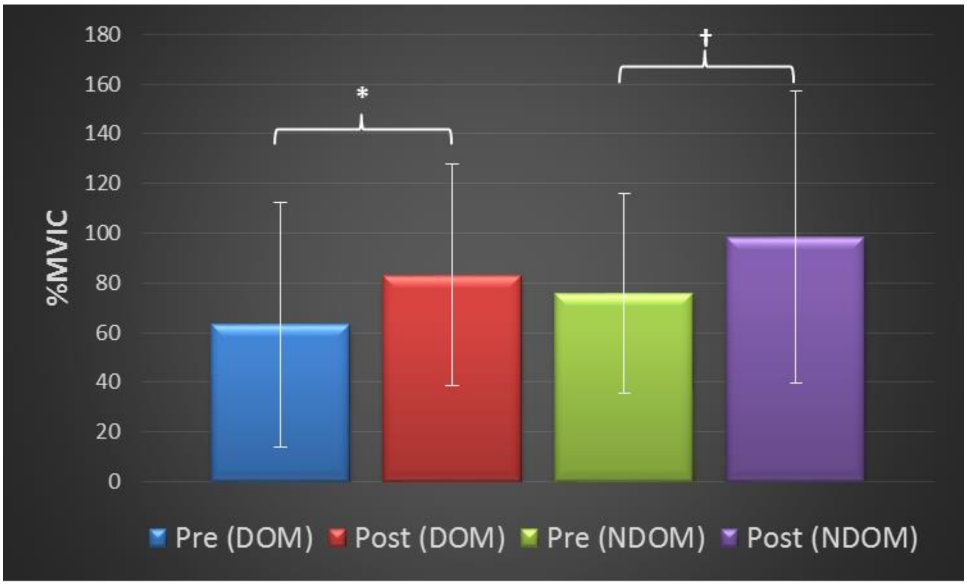


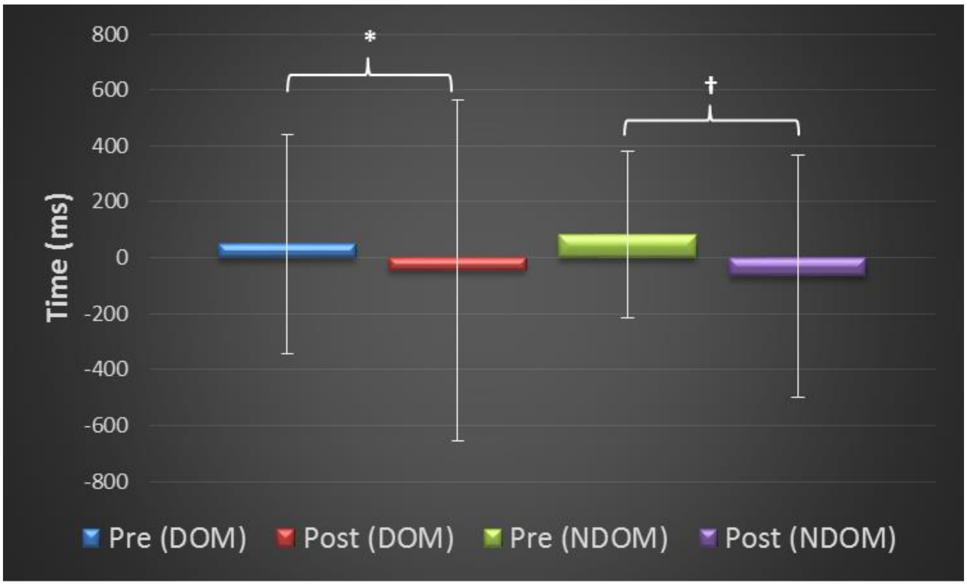
Figure vi. Change in knee valgus angle over time

Pre, Pre-testing; Post, Post-testing; DOM, Dominant; NDOM, Non-dominant, *d*, Cohen's effect size

* *d*=0.32: small effect; † *d*=0.02: negligible effect



a)

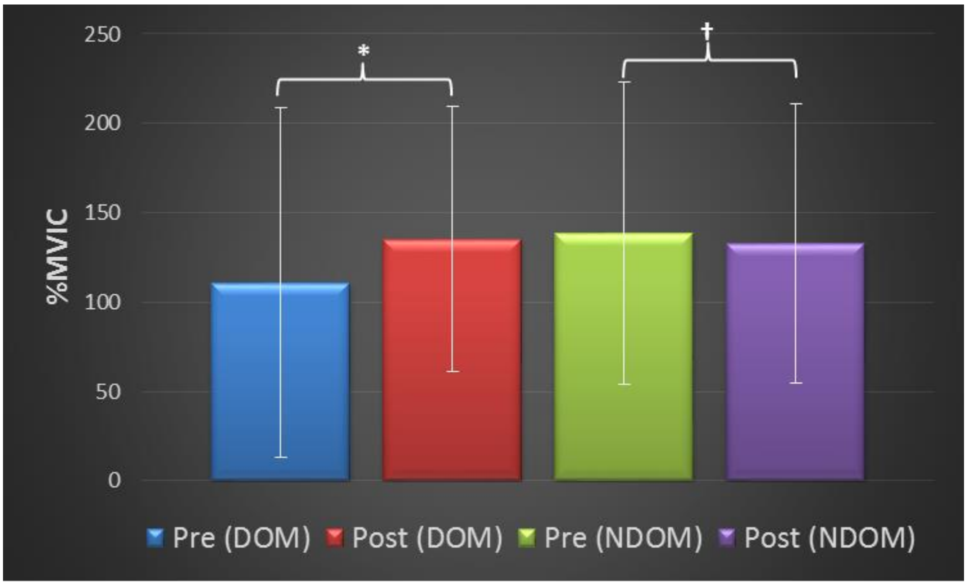


b)

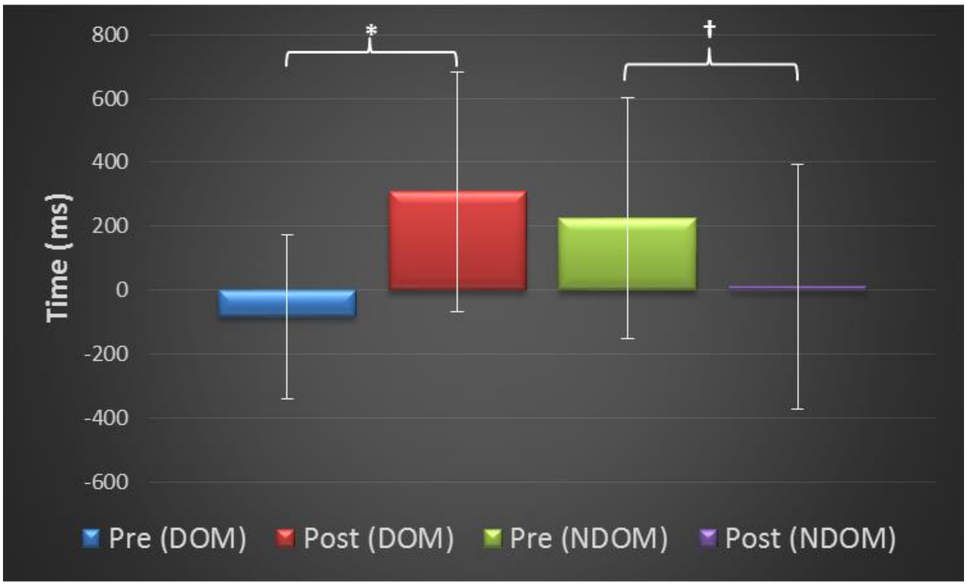
Figure vii. Change in Gmax variables: a) Amplitude b) Gmax-BicepFem onset interval

Pre, Pre-testing; Post, Post-testing; DOM, Dominant; NDOM, Non-dominant, *d*, Cohen's effect size

a) * *d*=0.45: medium effect; † *d*=0.48: medium effect
b) * *d*=0.20: small effect; † *d*=0.43: medium effect



a)



b)

Figure viii. Change in Gmed variables: a) Amplitude b) Onset

Pre, Pre-testing; Post, Post-testing; DOM, Dominant; NDOM, Non-dominant, *d*, Cohen's effect size

a) * *d*=0.30: small effect; † *d*=0.07: negligible effect
b) * *d*=1.32: very large effect; † *d*=0.61: medium effect

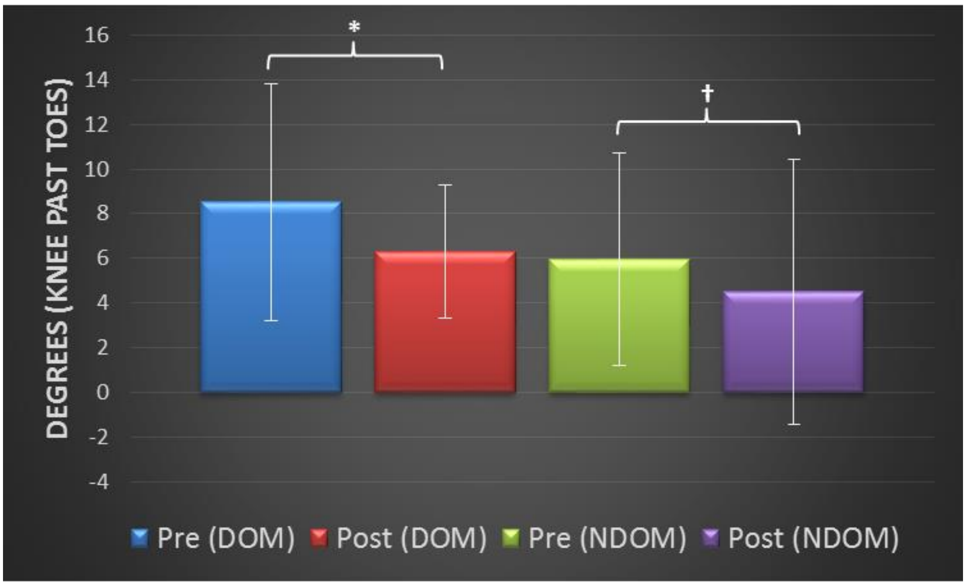


Figure ix. Change in knee-over-toe angle

Pre, Pre-testing; Post, Post-testing; DOM, Dominant; NDOM, Non-dominant, *d*, Cohen's effect size

* *d*=0.56: medium effect; † *d*=0.29: small effect

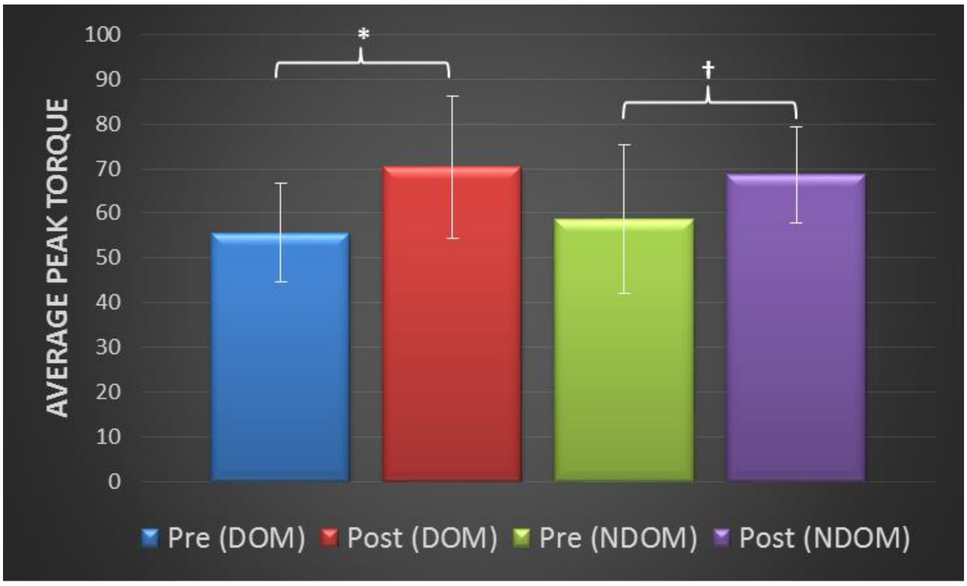


Figure x. Change in Gmax torque

Pre, Pre-testing; Post, Post-testing; DOM, Dominant; NDOM, Non-dominant, *d*, Cohen's effect size

* *d*=1.14: very large effect; † *d*=0.78: large effect

Table xiv. Relationship between changes in the outcome variables

	Dominant		Non-dominant	
Variables (Δ in variable vs Δ variable)	**rho**	**p**	**rho**	**p**
Gmax peak torque vs. knee valgus	-0.23	0.61	-0.63	0.13
Gmax amplitude vs. knee valgus	-0.40	0.37	-0.27	0.57
Gmax-BicepFem onset interval vs. knee valgus	-0.31	0.50	0.35	0.44
Gmed amplitude vs. knee valgus	0.03	0.94	-0.33	0.47
Gmed onset vs. knee valgus	-0.25	0.59	0.23	0.62
Gmax peak torque vs. knee-over-toe	0.02	0.97	-0.87	0.01*
Gmax amplitude vs. knee-over-toe	-0.26	0.57	-0.11	0.82
Gmax-BicepFem onset interval vs. knee-over-toe	0.31	0.50	-0.10	0.84
Gmed amplitude vs. knee-over-toe	-0.66	0.11	-0.25	0.54
Gmed onset vs. knee-over-toe	-0.16	0.73	0.07	0.87
Gmax amplitude vs. Gmax peak torque	0.00	1.00	0.07	0.88
Gmax-BicepFem onset interval vs Gmax peak torque	0.77	0.04*	0.36	0.43

Abbreviations: Δ, Change; Gmax, Gluteus maximus; BicepFem, Bicep femoris; Gmed, Gluteus medius; rho, correlation coefficient; p, alpha level, *p<0.05

Appendix G: Turnitin plagiarism check