The Relationship of Gluteus Medius Strength and Endurance to Stability, Targeting and Agility

by

Lori P. Graumann Stobart

A Thesis submitted to the Faculty of Graduate Studies of
The University of Manitoba
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

School of Medical Rehabilitation
University of Manitoba
Winnipeg

Abstract

Purpose: To examine gluteus medius strength and endurance in relation to lower limb stability, targeting and agility.

Methods: 57 participants performed isometric and dynamic gluteus medius strength and endurance tests of both lower limbs. Lower limb dominance was determined using the Waterloo Footedness Questionnaire-Revised (WFQ-R). Strength and endurance of gluteus medius were compared to single-leg performance of a stork stand, a lateral foot targeting task and a hopping test of agility.

Results: Body mass normalized isometric gluteus medius strength was found to be weakly and inversely correlated to agility score for both dominant limbs (r=-0.262, p=0.026) and non-dominant limbs (r=-0.335, p=0.006) with a lower agility score indicating better agility performance. For non-dominant limbs only, body mass normalized isometric gluteus medius strength correlated negatively to targeting speed (r=-0.229, p=0.045) and isometric gluteus medius endurance measured as percentage drop in strength over time correlated weakly and positively to the amount of body sway demonstrated during a single-leg stork stand task (r=0.253, p=0.030).

Conclusion: Gluteus medius strength may be weakly related to improved agility performance while gluteus medius endurance may weakly relate to improved single-leg static balance performance. It is likely that other factors such as neuromuscular training have a much larger influence on stability, targeting ability and agility than the strength and endurance of the hip abductors alone.

Keywords: hip abductors, functional performance, sex differences, limb dominance, Waterloo Footedness Questionnaire-Revised (WFQ-R)

Acknowledgements

I would like to gratefully acknowledge the University of Manitoba Graduate Fellowship program for financially supporting this research. Thank you as well to all the volunteers who dedicated their free time to participate in this study. Your assistance was genuinely appreciated and this thesis would not have become a reality without you.

I would like to express my sincere gratitude to both of my advisors, Dr. Dean Kriellaars and Dr. Barbara Shay. I consider myself very fortunate to have had access to not one, but two exceptional mentors throughout this research and thesis-writing process. Dr. Dean Kriellaars, I can’t even begin to add up the value of all the things I have learned while working with you over the past few years. Your obvious passion for research is contagious and I can’t thank you enough for all that you invested in this project and in my success. Dr. Barbara Shay, thank you so much for getting me started on this journey and for teaching me the essential research skills that played such a large part in my achievement of this goal. Your guidance and advice kept me grounded from start to finish throughout this process, and your words of encouragement helped so much to keep me motivated along the way.

I would like to thank my committee members, Dr. Brian MacNeil and Dr. Malcolm Doupe, for their valuable contributions to the design and analysis of this research project. You both provided unique perspectives that challenged me to think in different ways and ultimately elevated the final quality of this thesis.

To my family, friends, fellow graduate students, coworkers and colleagues, thank you all for providing endless support and encouragement over the past few years. All of you contributed to my success in so many different ways, and it was so much easier to stay focused on the final goal with such a large group of people cheering me on.

Finally, to my amazing husband Mark, thank you for believing in me and for being my rock during every step of this process. As always, you were my number one supporter in more ways than I could ever count.

Table of Contents

List of Tables

List of Figures

Introduction and Background

A key function of gluteus medius is to stabilize the hip and pelvis during the gait cycle or other weight-bearing activities that involve single-leg stance (Gottschalk et al., 1989; Gray et al., 2005; Magee, 2002; Palastanga et al., 2002). Gluteus medius also contributes to hip abduction in the frontal plane (Gray et al., 2005; Palastanga et al., 2002; Presswood et al., 2008), internal and external hip rotation (Flack et al., 2012) and pelvic rotation (Gottschalk et al., 1989) in the transverse plane, and hip flexion and extension in the sagittal plane (Cutter and Kevorkian, 1999; Presswood et al., 2008).

Gluteus medius weakness has been linked to many different types of lower extremity injury and pathology such as patellofemoral pain syndrome (PFPS) (Bolgla et al., 2011; Dierks et al., 2008; Ferber et al., 2011; Ireland et al., 2003; Nakagawa et al., 2012; Prins and van der Wurff, 2009; Willson and Davis, 2009), iliotibial band syndrome (ITBS) (Fredericson et al., 2000; Powers, 2010), inversion ankle sprain (Friel et al., 2006), hip osteoarthritis (Arokoski et al., 2002), anterior cruciate ligament (ACL) injury (Powers, 2010), and low back pain (Kendall et al., 2010). One prospective study found that athletes who sustained a musculoskeletal injury during the competitive season had significantly weaker hip abductors prior to the start of the season than the athletes who did not get injured (Leetun et al., 2004). However, most literature relating gluteus medius weakness to injury involves cross-sectional or retrospective studies, thus making it difficult to determine whether hip abductor weakness is a cause or an effect of the injury (Arokoski et al., 2002; Bolgla et al., 2011; Dierks et al., 2008; Fredericson et al., 2000; Friel et al., 2006; Ireland et al., 2003; Kendall et al., 2010; Nadler et al., 2000; Nakagawa et al., 2012; Niemuth et al., 2005; Willson and Davis, 2009).

Several authors have proposed that weak hip abductors are unable to eccentrically control hip adduction and internal rotation during functional activities, thus creating increased valgus at the knee (genu valgum), increased external tibial rotation, and consequently, increased risk of ACL injury, PFPS, and damage to other structures of the trunk and lower extremity (Jacobs et al., 2007; Leetun et al., 2004; Powers, 2010). However, there is mixed evidence to support the theory that decreased gluteus medius strength will significantly alter lower extremity biomechanics in ways that will increase risk of injury. Some studies have found that hip abductor weakness in healthy individuals is related to increased lateral trunk bending during single-leg landing (Popovich and Kulig, 2012), increased knee valgus during single-leg landing (Jacobs et al., 2007), and increased hip adduction and knee abduction during stepping (Nakagawa et al., 2012). Other studies have found that hip abductor weakness does not significantly relate to lower extremity biomechanics during double-leg landing (Homan et al., 2012) or running (Dierks et al., 2008). In studies where hip abductor muscle weakness is created experimentally through fatiguing protocols (Geiser et al., 2010; Patrek et al., 2011) or through injection of hypertonic saline (Henriksen et al., 2009), significant alterations in lower extremity mechanics have been shown during cut, jump and run tasks (Geiser et al., 2010), during single-leg landing tasks (Patrek et al., 2011), and during walking (Henriksen et al., 2009), but not in ways that would necessarily increase risk of injury.

Contributing to the debate, it is well-known that individuals with profound weakness of gluteus medius will demonstrate biomechanical changes in the form of a Trendelenburg gait pattern where the pelvis drops towards the side of the swinging leg due to hip abductor weakness on the stance leg (Trendelenburg, 1998). However, in recent studies of individuals who are free of injury and pathology, it has been shown that hip abduction strength is not significantly related to increased hip adduction angle or magnitude of pelvic drop during the Trendelenburg test (DiMattia et al., 2005; Kendall et al., 2010). In addition, Kendall et al. (2010) studied individuals with and without low back pain and found that strengthening the hip abductors did not significantly change maximal pelvic drop during the Trendelenburg test or during walking. These results imply that gluteus medius strength may not be the primary determinant of functional biomechanics in the frontal plane and encourages consideration of other factors that may be more important such as neuromuscular control.

Despite limited evidence of a direct link between gluteus medius weakness and injury-causing biomechanics, gluteus medius strengthening programs are prevalent in the practicing rehabilitation community where clinicians frequently emphasize assessment and treatment of hip abductor weakness during injury prevention and treatment programs (Bolgla and Uhl, 2005; Distefano et al., 2009; Fredericson and Moore, 2005). The clinical popularity of gluteus medius strengthening has clearly been noted by researchers as many recently published articles are dedicated to determining the most effective gluteus medius strengthening exercises and training regimes (Bolgla and Uhl, 2005; Boudreau et al., 2009; Distefano et al., 2009; Krause et al., 2009; O'Sullivan et al., 2010; Presswood et al., 2008; Reiman et al., 2011). Training programs that include gluteus medius strengthening have been shown to significantly decrease pain in pathological conditions such as PFPS (Ferber et al., 2011) and ITBS (Fredericson et al., 2000) and improve performance in single-leg hopping tasks (Baldon et al., 2012). However, the gluteus medius training programs used in the literature often include other components such as stretching and rest

(Fredericson et al., 2000) or core training and guided correction of movement patterns (Baldon et al., 2012), making it difficult to determine whether increasing gluteus medius strength actually played a role in the observed successful outcomes of treatment.

In order to determine whether specific training of gluteus medius can be effective for improving lower extremity biomechanics or preventing injury, it is first necessary to fully understand the role that gluteus medius muscle characteristics play in the function of healthy individuals. However, the role of gluteus medius strength and endurance in the functional performance of healthy individuals is currently unknown. It has been suggested that single-leg stance is the most common posture adopted in daily life because it is the foundation of the gait cycle (Janda, 1983). However, there is a paucity of research that directly explores the relationship between gluteus medius muscle characteristics and static balance performance. It is also unclear if gluteus medius plays an important role in other aspects of lower extremity performance such as directing foot placement during locomotion (Friel et al., 2006; Millard et al., 2009; Sparrow et al., 2003) or targeting the lower limb during “mobilising or manipulating” tasks (Grouios et al., 2009, p. 365) such as kicking a ball. The potential role of gluteus medius strength and endurance in the performance of agility tasks has also not been established, even though high-speed directional changes like cutting and other “side-to-side maneuvers”(Ortiz et al., 2011, p. 14) typically involve foot targeting, momentary single-leg balance, and high levels of torque generated from the lateral musculature of the lower limb.

Establishing the relationship between gluteus medius strength and endurance and functional performance in healthy individuals is an important step towards fully understanding the role of gluteus medius in motion control and ultimately its potential role in injury prevention.

Literature Review

The Role of Gluteus Medius in Human Function

Gluteus medius is a broad, fan-shaped muscle that attaches proximally to the lateral surface of the ilium and converges distally into a flat tendon that attaches to the superolateral surface of the greater trochanter (Gottschalk et al., 1989; Palastanga et al., 2002; Presswood et al., 2008). Cadaver studies have found that the gluteus medius is divided into three distinct parts, each with different fibre orientations and different lines of action (Al-Hayani, 2009; Gottschalk et al., 1989). The anterior, middle and posterior sections of the gluteus medius muscle are also supplied by different branches of the superior gluteal nerve (Al-Hayani, 2009; Gottschalk et al., 1989).

Gottschalk et al. (1989) examined the electromyographic (EMG) activity of gluteus medius in 10 healthy participants during the gait cycle and found that the three segments of gluteus medius tend to activate in sequence from posterior to anterior during ambulation. The authors suggested that the posterior portion of the gluteus medius muscle primarily functions to stabilize the head of the femur during gait from heel strike to midstance when the leg is initially accepting the transfer of body weight. The same study found that the middle part of gluteus medius was active primarily during midstance when the muscle abducts the pelvis on the stance side in order to counteract the downward tilting of the pelvis that occurs on the swing side. It has been suggested that the stance leg gluteus medius muscle may even elevate the opposite side of the pelvis slightly above a neutral position during gait in order to make it easier for the other leg to swing forward for the next step (Gottschalk et al., 1989; Magee, 2002; Palastanga et al., 2002; Presswood et al., 2008). The anterior portion of gluteus medius has been shown to be most active at the end of the stance phase when pelvic rotation is initiated to swing the opposite leg forward, suggesting that the anterior portion of the muscle acts primarily as a pelvic rotator during locomotion (Gottschalk et al., 1989).

Gluteus medius also plays a role in several non-weight-bearing movements of the femur including flexion and extension (Cutter and Kevorkian, 1999; Presswood et al., 2008), internal rotation (Flack et al., 2012; Palastanga et al., 2002) and external rotation (Flack et al., 2012). Much of the literature describes gluteus medius as a primary abductor of the femur that works in conjunction with the tensor fasciae latae (TFL) and gluteus minimus muscles (Gray et al., 2005; Palastanga et al., 2002; Presswood et al., 2008). However, some authors argue that gluteus medius is not mechanically well-positioned to act as a primary abductor of the femur (Al-Hayani, 2009; Gottschalk et al., 1989). Theoretically, gluteus medius is in an ideal position to initiate hip abduction (Al-Hayani, 2009) while TFL has a better mechanical advantage for completing the abduction movement (Al-Hayani, 2009; Gottschalk et al., 1989), making it likely that both muscles play an important role in abducting the femur, albeit during different phases of the motion.

Although the basic activity patterns of gluteus medius are well-described in the literature, it is unclear whether a predictive relationship exists between gluteus medius characteristics and the biomechanics of healthy individuals during complex, multi-joint movements. Kendall et al. (2010) found that there were no significant correlations between hip abduction strength and the magnitude of pelvic drop during the Trendelenburg test or between hip abduction strength and mean maximum frontal plane pelvic excursion during walking in healthy individuals. Gluteus medius strength has also been shown to have very little effect on running biomechanics (Dierks et al., 2008). A study that included twenty uninjured male and female runners found that hip abduction strength and hip external rotation strength decreased significantly over the course of a prolonged run while peak hip adduction angle and peak hip internal rotation angle did not change significantly over time (Dierks et al., 2008).The participants in this study were able to continue adequately controlling the femur in both the frontal and transverse planes throughout the run despite progressive gluteus medius fatigue, but in the absence of EMG measurements it is not possible to determine whether this was due to progressive increases in gluteus medius activation or due to other factors such as the assistance of other muscles.

Although some research shows evidence of a relationship between gluteus medius strength and lower extremity biomechanics, often this association is found to exist among female participants only (Geiser et al., 2010; Jacobs and Mattacola, 2005a; Jacobs et al., 2007; Nakagawa et al., 2012; Popovich and Kulig, 2012). Inverse relationships have been shown between peak knee valgus angles in women during single-leg landing and peak hip abductor torque measured both isometrically (Jacobs et al., 2007) and eccentrically (Jacobs and Mattacola, 2005a). However, the same studies that reported this relationship among females also found that there was no relationship between hip abductor strength and peak knee valgus angle during single-leg landing among males (Jacobs and Mattacola, 2005a; Jacobs et al., 2007). In a different study of single-leg landing biomechanics, a fatiguing protocol that reduced the hip abduction strength of females by an average of 63% caused a significant increase in mean internal knee adduction moment (7.3 Nm) and movement into a slightly larger range of knee abduction (0.4°) and hip adduction (0.5°) (Geiser et al., 2010). Women with lower hip abductor strength have also exhibited increased lateral trunk bending and greater peak angular velocity of lateral trunk bending during single-leg landing (Popovich and Kulig, 2012). Another study compared a group of males and females and found that the females displayed less hip abductor strength than the males along with significantly greater hip adduction, knee abduction, ipsilateral trunk lean, and contralateral pelvic drop during the downward and upward phases of a stepping task (Nakagawa et al., 2012). Although participants with and without patellofemoral pain syndrome participated in this study, the authors found that the differences observed between the sexes were not related to pain levels (Nakagawa et al., 2012).

Other research has found that hip abductor weakness may affect the lower extremity biomechanics of females in ways that are unexpected based on traditional knowledge of gluteus medius anatomy and muscle actions (DiMattia et al., 2005; Hollman et al., 2009; Patrek et al., 2011). One study found weak positive correlations between hip abduction strength and hip adduction angle during both the Trendelenburg test (r=0.22) and the single-leg squat test (r=0.21) (DiMattia et al., 2005) while another study found a moderate positive correlation between hip abduction strength and knee valgus during a step-down test (r=0.455) (Hollman et al., 2009). Similarly, Patrek et al. (2011) analyzed the single-leg drop landing performance of women before and after a fatiguing protocol that reduced peak hip abduction strength by an average of 43% and found that the participants demonstrated a small but statistically significant increase in hip abduction (0.8°) at initial contact and a small but statistically significant decrease in knee abduction (0.4°) at the time period 60 milliseconds after landing.

There is some evidence to suggest that weaker hip abductor muscles may be able to compensate for strength deficits by increasing activation levels during functional activities (Homan et al., 2012; Nguyen et al., 2011), thus providing a possible explanation for the inconsistencies seen in the literature regarding the relationship between gluteus medius strength and lower extremity biomechanics. A study of 60 healthy men and women found an inverse relationship between hip abduction strength and gluteus medius activation during a single-leg squat, suggesting that weaker individuals may activate gluteus medius to a greater extent in order to maintain efficient biomechanics (Nguyen et al., 2011). Another study divided physically active male and female participants into tertiles based on hip strength and found that the hip and knee kinematics of the high strength and low strength groups did not differ significantly during double-leg landing from a height, but the low strength group exhibited more EMG activity of the glutei medii than the high strength group (Homan et al., 2012). This again shows that individuals with less hip abductor strength may be able to compensate for weakness by increasing gluteus medius activation.

With mixed evidence presented within a body of literature that employs a variety of different research models, it is difficult to draw any meaningful conclusions about the effects of gluteus medius strength on the functional biomechanics of either males or females. More studies that simultaneously employ EMG recording, biomechanical measurements and strength assessments are necessary to further examine whether gluteus medius strength or gluteus medius muscle activation have a larger influence on the functional biomechanics of the lower extremities.

Gluteus Medius Weakness in Relation to Musculoskeletal Injury

Despite limited evidence of a significant relationship between gluteus medius strength and functional biomechanics, it is commonly believed that weak or inefficient gluteus medius muscles will lead to biomechanical changes that increase injury risk. Powers (2010) reviewed the body of literature on the subject and summarized the different ways that abnormal hip mechanics can theoretically contribute to injury development. According to Powers (2010), weak hip abductors can alter biomechanics in ways that increase either knee valgus or varus, thus contributing to a number of issues including increased strain on the anterior cruciate ligament (ACL), medial collateral ligament (MCL) or lateral collateral ligament (LCL), greater lateral patellar pressure that increases the risk of PFPS, or increased tension on the iliotibial band. Additionally, Friel et al. (2006) discussed the possibility that inversion ankle sprains may occur when ineffective muscular control of the hip causes errors in foot placement during walking and running, or when weak gluteus medius muscles are unable to counteract the increased lateral sway that occurs when balance is challenged at a level that the ankle and foot muscles cannot correct alone.

Partially supporting the theorized relationship between gluteus medius weakness and injury, individuals with an injured lower limb have been found to demonstrate side-to-side imbalances in hip abductor strength (Fredericson et al., 2000; Friel et al., 2006; Niemuth et al., 2005). One study compared a group of runners who had recently suffered a unilateral lower limb overuse injury to a group of healthy controls and found that the injured runners had significantly weaker hip abductors on the affected leg compared to the unaffected leg while runners in the control group demonstrated a lack of significant side-to-side differences (Niemuth et al., 2005). However, this study utilized a cross-sectional design, thus making it impossible to tell whether the muscular imbalances observed in the injured runners were pre-existing or whether limbs became weaker after sustaining an injury due to pain and deconditioning. Decreased hip abductor strength on the affected side compared to the unaffected side has also been found in people with a history of unilateral chronic ankle sprains (Friel et al., 2006) and in runners with iliotibial band syndrome (ITBS) (Fredericson et al., 2000), but it is again unclear whether these observed side-to side strength differences are a cause or an effect of the injuries.

When investigating the relationship between gluteus medius strength and injury, many authors favour a study design that compares the hip abductor strength of injured lower limbs to the hip abductor strength of healthy controls. Fredericson et al. (2000) compared runners with ITBS to a control group of healthy runners and found that the affected leg of the injured athletes demonstrated less hip abductor strength than the randomly selected test leg of the uninjured athletes. Individuals with low back pain have also been found to exhibit less gluteus medius strength than pain-free controls (Arab and Nourbakhsh, 2010; Kendall et al., 2010), and both males and females with PFPS have been shown to present with decreased hip abductor strength when compared to individuals without an injury (Bolgla et al., 2011; Dierks et al., 2008; Ferber et al., 2011; Ireland et al., 2003; Nakagawa et al., 2012; Robinson and Nee, 2007; Souza and Powers, 2009; Willson and Davis, 2009).

The association between hip abductor weakness and injury has not been reported consistently, as some studies have found that asymptomatic individuals do not demonstrate significantly better hip abductor strength than individuals with ITBS (Grau et al., 2008) or PFPS (Cowan et al., 2009). In addition, a large study of 210 male and female college athletes compared a group of uninjured athletes to a group of athletes who had experienced a lower extremity injury or lower back pain in the previous year and found that side-to-side asymmetries in hip abductor strength did not differ significantly between the groups (Nadler et al., 2000).

Even when an injured limb does present with gluteus medius weakness, studies present varying results regarding the association between decreased gluteus medius strength in an injured limb and biomechanical changes during function. Individuals with PFPS have been shown to exhibit less hip abductor torque than healthy controls while demonstrating increased hip adduction, contralateral pelvic drop, ipsilateral trunk lean and knee valgus during both the downward and upward phases of a stepping task (Nakagawa et al., 2012). Confirming these results, Willson and Davis (2009) compared women with PFPS to asymptomatic controls and reported that the PFPS group exhibited decreased hip abductor strength and increased hip adduction excursion when landing from a single-leg jump. However, the authors also reported a negative correlation between hip abduction strength and hip adduction excursion among both the PFPS group and the asymptomatic group (Willson and Davis, 2009), indicating that hip abductor weakness may not have been the cause of the increased hip adduction excursion observed in the PFPS group. Another study compared a group of females with PFPS to a control group during running, drop jump and step-down tasks and found that even though the PFPS group demonstrated weaker hip abductors and greater peak hip internal rotation during the tasks, the groups did not demonstrate significantly different peak hip adduction angles during the same tasks (Souza and Powers, 2009). In regards to running biomechanics, Ferber et al. (2011) observed that peak knee valgus angles during running did not differ between individuals with and without PFPS, despite the existence of weaker hip abductors in the PFPS group.

Taking a different approach to investigating the relationship between gluteus medius and lower extremity injury, one study recruited a sample of twenty-one females with PFPS and compared hip strength to self-reported levels of function as measured by the Anterior Knee Pain Questionnaire and self-reported levels of pain during a single-leg squat (Long-Rossi and Salsich, 2009). The authors found that gluteus medius strength had no relationship to pain levels or to self-reported functional levels in females with PFPS (Long-Rossi and Salsich, 2009).

Most studies that investigate the relationship between gluteus medius characteristics and musculoskeletal injury are either retrospective or cross-sectional in nature, making it difficult to discern whether any gluteus medius weakness observed in an injured limb came before or after the onset of injury and pain. However, gluteus medius strength measurements have been included in several prospective studies that aim to determine whether a predictive relationship exists between muscular weakness and the development of injury. One prospective study evaluated 80 female and 60 male college athletes and found that athletes who sustained a back or lower extremity injury during their competitive season demonstrated significantly less hip abduction strength and less hip external rotation strength during the pre-season assessments than athletes who did not get injured (Leetun et al., 2004). In contrast to these findings, a study by Thijs et al. (2011) evaluated the strength of hip flexors, extensors, abductors, adductors, internal rotators and external rotators in novice female runners prior to the beginning of an organized running program and found that there were no significant strength differences between the women who developed PFPS and the women who did not develop an injury. In another prospective study, Marshall et al. (2011) concluded that hip abductor strength cannot predict whether or not a healthy individual will develop lower back pain during prolonged standing. However, the same authors observed that the people who developed lower back pain during prolonged standing demonstrated lower side-bridge endurance times than the people who did not develop pain (Marshall et al., 2011), thus indicating that hip abductor endurance may be more useful than hip abductor strength in predicting the risk of experiencing low back pain.

Based on the varying evidence presented by both retrospective and prospective studies, it can be concluded that there is no clear causal relationship between gluteus medius weakness and the development of injury.

Effects of Gluteus Medius Strengthening Programs

Even though there is not enough evidence to support the theory that hip abductor weakness leads to injury, gluteus medius strengthening programs are often utilized in clinical practice with the intention of correcting faulty biomechanics, improving function, or decreasing pain. It has been shown that rehabilitation programs consisting solely of gluteus medius strengthening exercises can significantly decrease pain and increase hip abductor strength in persons with PFPS after a training period of 8 weeks (Khayambashi et al., 2011) or a treatment period as short as 3 weeks (Ferber et al., 2011). A study by Earl and Hoch (2010) also reported that an 8 week treatment program for PFPS involving gluteus medius strengthening was effective to increase hip abduction and external rotation strength, decrease pain, improve self-reported function and decrease peak internal knee abduction moment during running. However, the rehabilitation program used in this study included many other elements such as ice for pain, flexibility exercises, core strengthening exercises, and feedback regarding proper lower extremity alignment during weight-bearing activities (Earl and Hoch, 2010). When a similar multimodal treatment program was administered to patients with PFPS over the course of 6 weeks, improvements in hip abduction strength were found to be unrelated to decreases in pain (Tyler et al., 2006). Another study also found that a 6 week gluteus medius training program was effective to reduce pain and increase hip abductor strength in male and female runners with ITBS, but again the treatment program included other elements such as stretches, ultrasound, and non-steroidal anti-inflammatories that may have confounded the impact of the strengthening exercises on pain levels (Fredericson et al., 2000).

The literature also presents mixed results regarding the efficacy of gluteus medius strengthening programs for improving biomechanics and preventing development of injury. One study reported that a 6 week gluteus medius training program significantly increased the hip abductor and external rotator strength of uninjured females and significantly decreased external knee abduction moment, ankle inversion moment, and foot eversion range of motion during running (Snyder et al., 2009). The authors concluded that increasing hip abductor and external rotator strength can alter running biomechanics in a way that may reduce the risk of injury (Snyder et al., 2009). However, the study participants also demonstrated a small but significant increase in hip adduction range of motion after completion of the training program and the researchers were unable to fully explain this unexpected observation (Snyder et al., 2009). In contrast, a study by Willy and Davis (2011) found that the running biomechanics of uninjured females did not change significantly after the completion of a 6 week program involving gluteus medius strengthening and single-leg squat movement training, even though the participants demonstrated significant increases in both hip abductor and hip external rotator strength. However, the program did result in decreased hip adduction, decreased hip internal rotation and decreased contralateral pelvic drop during single-leg squat performance, suggesting that hip strengthening and movement training will only alter biomechanics when the training is specific to the activity (Willy and Davis, 2011). A similar study of healthy females also showed that a training program designed to improve hip abduction strength can significantly decrease hip adduction, hip internal rotation and contralateral pelvic drop during a single-leg squat (Baldon et al., 2012). However, the training program used in this study once again included verbal feedback regarding functional lower limb alignment (Baldon et al., 2012), making it impossible to determine whether the observed changes in biomechanics were due to improved strength, improved neuromuscular control, or a combination of other factors.

In summary, the mixed results presented in the literature suggest that improving hip abductor strength does not necessarily decrease the pain of certain conditions or improve functional biomechanics. When studies do report that increased hip abductor strength is associated with improvements in pain or biomechanics, often the training programs used include other treatment modalities in addition to gluteus medius strengthening exercises. Therefore, based on currently available evidence, it is difficult to draw any strong conclusions regarding the best use of hip abductor strengthening in clinical practice.

Gluteus Medius Strength in Relation to Functional Performance

Much of the literature surrounding gluteus medius focuses on its role in biomechanics and the development or treatment of injuries, but very little research has been published regarding the role of gluteus medius strength in functional task performance.

One study of males and females with a history of recent total knee arthroplasty assessed the performance of participants on the Figure-of-8 Walk Test, a self-selected walking speed test, the Stair Ascend/Descend Test and the 5-Chair Rise Test and found that functional performance on all tasks was better predicted by hip abductor strength than by quadriceps strength, demographic variables or anthropometric measures (Piva et al., 2011). Increases in the strength of the hip abductors, hip internal rotators and hip external rotators have also been associated with significant improvements in performance of a single-leg triple hop for distance and in a timed 6-metre single-leg hop task, but the observed increases in hip strength were the result of a functional stabilization program that simultaneously trained other neuromuscular structures as well (Baldon et al., 2012).

It is possible that greater gluteus medius strength may also be related to superior sports performance. Callaway et al. (2012) noted that gluteus medius strength correlates significantly with peak pelvic rotation speed in golfers and reported that low handicap golfers display significantly greater gluteus medius strength than high handicap golfers. However, the study included athletes with a wide variety of skill levels, so it is not clear whether increased gluteus medius strength actually plays a role in improving golf performance or whether playing golf more often simply improves both gluteus medius strength and peak pelvic rotation speed simultaneously (Callaway et al., 2012).

Other research has investigated the relationship between gluteus medius strength and postural stability. Salavati et al. (2007) reported that fatigue of the hip muscles creates greater deterioration of stability than fatigue of the ankle muscles. Another study found that men and women who completed an eccentric hip abduction fatiguing protocol performed significantly worse on a single-leg static balance test and on the Star Excursion Balance Test (SEBT) for dynamic single-leg balance (McMullen et al., 2011). However, it is important to consider that fatiguing regimes are likely to affect multiple muscles simultaneously, thus the balance changes observed in these gluteus medius fatiguing studies may be at least partially due to the fatigue of other structures.

Using a study design that involved strengthening rather than fatiguing, Leavey (2006) placed healthy college students into a control group or one of three different exercise groups. After a 6 week time period, the group that performed only gluteus medius strengthening exercises demonstrated the largest gains in hip abduction strength while the group that practiced a combination of proprioceptive training and gluteus medius strengthening exercises demonstrated the greatest improvements on the Star Excursion Balance Test (Leavey, 2006). Notably, the study group with the largest gluteus medius strength gains was not the group that displayed the greatest improvements on the Star Excursion Balance Test (Leavey, 2006), thus indicating that gluteus medius strength may not be the most important factor in determining dynamic balance performance.

With very little scientific evidence available regarding the relationship between gluteus medius characteristics and functional task performance, it is clear that further research is necessary to determine whether improved gluteus medius strength and endurance provide a functional advantage.

Research Question

Do the strength and endurance of gluteus medius relate to lower limb stability, targeting and agility performance?

Objectives

1) To determine if the strength and endurance of gluteus medius in the dominant and non-dominant limbs are related to single-limb performance of:
    a. a stability task
    b. a targeting task
    c. an agility task
2) To determine if there are a) sex-dependent or b) side-dependent differences in gluteus medius strength or endurance.
3) To determine if there are a) sex-dependent or b) side-dependent differences in stability, targeting or agility task performance.

Hypotheses

Objective #1:

a. Performance on a single-leg stability task will be related to gluteus medius endurance.

b. Performance on a foot targeting task will be related to gluteus medius strength and endurance.

c. Performance on an agility task will be related to gluteus medius strength and endurance.

Objective #2:

a. Males will have better gluteus medius strength and endurance than females in both the dominant and non-dominant limbs.

b. The gluteus medius muscles of non-dominant limbs will demonstrate greater strength and endurance than the gluteus medius muscles of dominant limbs.

Objective #3:

a. Males will perform better than females on stability, targeting and agility tasks with both the dominant and non-dominant limbs.

b. The non-dominant limbs will perform better than the dominant limbs on the stability task, while the dominant limbs will display superior performance on the targeting and agility tasks.

Methodology

Experimental Design

A cross-sectional observational study design was used.

Participants

Recruitment

Fifty-seven participants were recruited from the local community by word of mouth.

Inclusion/Exclusion Criteria

Males and females between the ages of 18 and 39 were recruited for the study. All participants were required to have a good understanding of written and spoken English and be in good general health. Participants were excluded if they had a history of lower extremity surgery or lower back surgery, or if they had experienced a lower extremity injury or back injury within the past 12 months that affected walking ability or caused pain for longer than one week. Potential participants were also excluded from the study if they had a neurological condition or a circulatory condition that affected lower limb motor or sensory function. Pregnant and lactating females were also excluded from the study.

A Priori Sample Size Determination

A power calculation was performed a priori to determine the sample size required to detect a statistically significant correlation between two continuous variables in a single group. It has been established through previous calculations that a moderate r-value of 0.5 is sufficient to observe a large effect size for the correlation of any two chosen variables (Cohen, 1992). Using the value of r=0.5 in a formula presented by Dell, Holleran and Ramakrishnan (2002), it was determined that a sample size of 30 participants was necessary to detect a significant moderate correlation of 0.5.

A second sample size calculation was necessary in order to ensure that the study would be adequately powered to compare the gluteus medius strength and endurance differentials between the dominant and non-dominant limbs of males and females. A previous study determined that the average within-subject difference in peak torque between the dominant and non-dominant hip abductors was 11.6 % with a standard deviation of 8.31% (Jacobs et al., 2005b). It has been suggested that a large effect size for an unpaired t-test is equal to 0.8 times the standard deviation (Motulsky, 2010). Therefore, 0.8x8.31=6.648% was estimated to represent a large effect size in peak torque between a group of male participants and a group of female participants. The value of 6.648% was inserted into a formula presented by Hassard (1991) and it was found that the sample size needed to detect a significant difference in hip abductor torque between a group of males and a group of females was 25 participants per group.

It was therefore determined that a total sample size of 50 participants (25 males and 25 females) was required to ensure that the study was adequately powered for all study objectives.

Protocol

Each participant attended a 1.5-2 hour session at the University of Manitoba's Human Performance Laboratory in Winnipeg, Manitoba. Participants were asked to bring running shoes, athletic shorts and a shirt that allowed access to the upper part of the sternum. All experimental sessions took place between the hours of 7:00 a.m. and 10:00 p.m. and tests were conducted by one researcher.

Prior to beginning the experiment, all participants were required to read and sign the informed consent document (Appendix A) that was approved by the University of Manitoba Research Ethics Board (Ethics File Number H2012:026). The body mass (kg) of each participant was measured with a digital scale and the height (cm) of each participant was assessed with the measuring rod attached to a column scale. The length of both legs was measured in supine from the largest prominence of the greater trochanter to the centre of the lateral malleolus (LL1 in cm), and also from the anterior superior iliac spine to the centre of the lateral malleolus (LL2 in cm). All anthropometric data was then recorded in a spreadsheet along with birth date, age and sex.

All participants completed the Waterloo Footedness Questionnaire-Revised (WFQ-R) (Elias et al., 1998). Participants also used descriptive five-level scales to rate the amount of physical activity required by their current occupation (school, work, etc.), to rate their current level of participation in exercise and sport, and to indicate the highest level of participation in exercise and sport that they had achieved during the past five years (Appendix B).

Participants then performed six assessments with each leg (Table 1): an isometric gluteus medius strength test, an isometric gluteus medius endurance test, a dynamic gluteus medius strength and endurance test, a test of single-leg stability, a single-leg targeting task, and a single-leg agility task.

Table 1: Testing protocol of the "R" group that started each task with the right leg. (The "L" group of participants completed the same protocol but started each task with the left leg.)

Task		Leg Tested	# of Repetitions	Rest between Repetitions
Isometric gluteus medius strength (3 second maximum contraction)		Right	3	15 seconds
		REST x 2 minutes		
		Left	3	15 seconds
Isometric gluteus medius endurance (40 second maximum contraction)		Right	1	--
		REST x 5 minutes		
		Left	1	--
REST x 5 minutes				
Balanced Order Design (STA, TAS, AST)	**Single-Leg Stork Stand**	Alternating repetitions between Right and Left	4 repetitions each leg x 30 seconds	10 seconds
	REST x 2 minutes			
	Targeting	Right	10 each target (#1 & #2) in a standardized order	5 seconds to hit target and re-set foot at start
		REST x 2 minutes		
		Left	10 each target (#1 & #2) in a standardized order	5 seconds to hit target and re-set foot at start
	REST x 2 minutes			
	Agility	Right	10 hops small gap 10 hops large gap	10 second rest between gaps
		REST x 2 minutes		
		Left	10 hops small gap 10 hops large gap	10 second rest between gaps
REST x 2 minutes				
Dynamic gluteus medius strength & endurance		Plank on left side, leg lifts with Right	Leg lifts to fatigue or failure	No rest allowed between reps
		REST x 2 minutes		
		Plank on right side, leg lifts with Left	Leg lifts to fatigue or failure	No rest allowed between reps

The stability (S), targeting (T) and agility (A) tests were performed using a balanced order design in an attempt to control for order effects. As participants arrived for their study session, they were assigned to the next task order from the list of STA, TAS and AST as determined by the order that was performed by the previous participant of the same sex. In addition, the first 13 males and the first 13 females were assigned to the “R” group that started each task with the right leg and the next 13 males and 13 females were assigned to the “L” group that started each task with the left leg. All male and female participants recruited in addition to the first 52 were assigned to the “R” and “L” groups in an alternating fashion based on the group assignment of the previous same-sex participant.

Limb Dominance

All participants in this study completed the Waterloo Footedness Questionnaire-Revised (WFQ-R) (Elias et al., 1998) which includes a question about preferred kicking limb along with nine other questions that evaluate foot preference for both stability and manipulation tasks. On each question, participants are asked to consider which lower limb they typically use to perform the described task and answers are recorded on a 5-point scale ranging from left always (score of -2) to right always (score of +2). The total WFQ-R score can be used to categorize a respondent as left-footed (score of -7 or less), mixed-footed (score of -6 to +6), or right-footed (score of +7 or higher) (Grouios et al., 2009).

Although total WFQ-R score indicates limb dominance for a wide variety of tasks, some studies have shown that lower limb dominance may actually change for different tasks, depending on whether the activity requires skill in manipulation or stability (Grouios et al., 2009; Wang and Newell, 2013). The common definition of footedness is the lower limb that is preferentially selected to manipulate objects (Peters, 1988). Furthermore, in the literature reviewed on the topic of gluteus medius function, the most frequently used method of determining limb dominance is asking participants which limb they prefer to use for kicking a ball. Thus, for the purposes of comparing results of this study to other literature regarding gluteus medius characteristics, lower limb dominance was determined using preference for manipulation tasks. Participant answers to the 5 manipulation questions from the WFQ-R were added up and scored to determine lower limb dominance. Participants with scores less than 0 were categorized as left-footed, those with scores equal to 0 were considered to be mixed-footed, and those with scores higher than 0 were considered to be right-footed.

Instruments and Assessments

Isometric Strength and Endurance Testing

Isometric strength and endurance were tested in standing using a force transducer (Sensortronics 6001 tension-compression load cell) connected to a data acquisition system (Data Translation, USB 9800 Series, 16-bit resolution). The force signal was acquired at a sampling rate of 50 Hz. The force transducer was calibrated using three weight plates with known mass. Static calibration method was used to determine the best fit equation ($y=391.39x-6.7709$ with $R^2=0.9999$), and the calibration process was performed again halfway through the study in order to ensure that calibration remained repeatable. The mid-study static weight calibration test produced a best fit equation of $y=351.44x+9.868$ with $R^2=1$.

Gluteus medius isometric strength and endurance were tested in standing using a procedure that combined the methods described by Inman (1947) and Dwyer et al. (2010). Two vertically-oriented wooden boards were firmly attached to the front legs of a standard wooden plinth and a piece of stainless steel with multiple holes was attached to each board (Figure 1). This allowed the force transducer to be attached to either board at different heights. A nylon rope connected the force transducer to an ankle cuff that each participant wore centered over the lateral malleolus of the test leg. The participant faced the plinth and stood on the non-test leg at the edge of a 3.81 cm block such that the test leg itself was unsupported when the pelvis was held in a level position. The force transducer was connected to the board on the plinth leg closest to the non-test leg at a height that allowed the rope to remain parallel to the ground throughout testing. The rope length was adjusted to ensure that the leg remained perpendicular to the ground when the participant attempted hip abduction. Two stable vertical pipes with foam grip were attached to the upper part of the plinth at approximately shoulder-width apart, and the participant was allowed to hold the grips to assist with stabilization of the upper trunk throughout testing.

Figure 1: Body position during isometric strength and endurance testing of gluteus medius.

The participant was instructed to stand with the pelvis level and the test leg slightly off the ground while performing isometric abduction of the test leg against the resistance of the force transducer. During testing, the participant was required to keep the knees straight, the toes pointing forwards, the ankle of the test leg dorsiflexed to 90^o, and the trunk, pelvis, hips and leg in neutral. The test position was explained and demonstrated along with common undesirable movements such as dropping the pelvis in the frontal plane, leaning sideways with the trunk, rotating the pelvis or trunk in the transverse plane, and externally or internally rotating the test leg. In order to familiarize the participant with the test procedure, at least one and up to three submaximal test repetitions were allowed with each leg while the researcher provided verbal feedback and physical cueing to ensure correct body positioning.

In order to determine gluteus medius torque produced during testing, the resultant joint moment about the hip (RJM_{HIP}) was calculated using the following formula:

$$RJM_{HIP}(Nm) = M_{FT} + M_{W_{LL}}$$

where M_{FT}=*moment about the hip due to force applied to the force transducer* and M_{WLL}=*moment about the hip due to weight of the lower limb*.

Because the test position was such that the leg was perpendicular to the ground, the moment about the hip due to the weight of the lower limb was negligible. Therefore, as shown in Figure 2:

$$RJM_{HIP}(Nm) = M_{FT} = F_T * d_1 * sin\theta = F_T * d_1 * \sin(90) = F_T * d_1$$

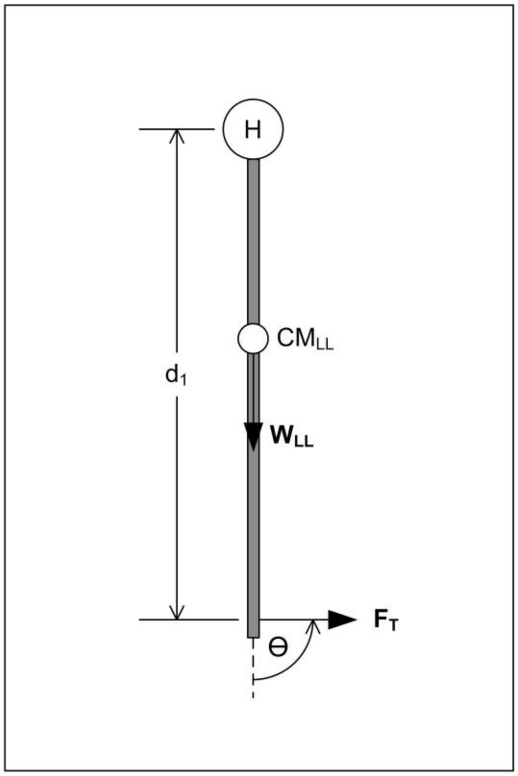

Figure 2: Forces acting on the leg during isometric hip abduction testing. H=hip joint axis of motion. CM_{LL}=centre of mass of the lower limb. d_1=distance from hip joint axis to point of application of force against the transducer (i.e. leg length). W_{LL}= weight of the lower limb. F_T=force applied to the force transducer. Θ=angle between the vector of F_T and the vector of d_1.

STRENGTH: Three maximal isometric hip abduction contractions were performed with a 1 second ramp-up and a 3 second hold (Figure 3). The instructions to participants were: “Ramp up to max, hold at max, push as hard as you can, and down.” When the participant heard the word “down” they were allowed to rest the test foot on the ground for 15 seconds between repetitions. The researcher stood behind the participant during testing and provided verbal encouragement during the maximal contraction in order to enhance effort (Johansson et al., 1983; McNair et al., 1996). If the participant performed a compensatory movement during a trial, the researcher provided a verbal reminder of correct test positioning during the 15 second rest and the trial was repeated. Contractions that were achieved using compensatory motions were discarded.

RJM_{HIP} (Nm) for all three trials was plotted and the 1 second time period with the highest torque was visually identified for each trial. Any unsustained sharp peaks in torque that occurred at the start of a trial were discounted as they were considered to represent initial acceleration-dependent motion rather than true isometric torque. Average torque over the chosen 1 second time period was calculated for each trial and the mean of all three averages was used as a measure of absolute isometric gluteus medius strength for the test leg. Body mass normalized isometric gluteus medius strength (Nm/kg) was calculated by dividing absolute torque by body mass (Jaric et al., 2005; Jaric et al., 2002).

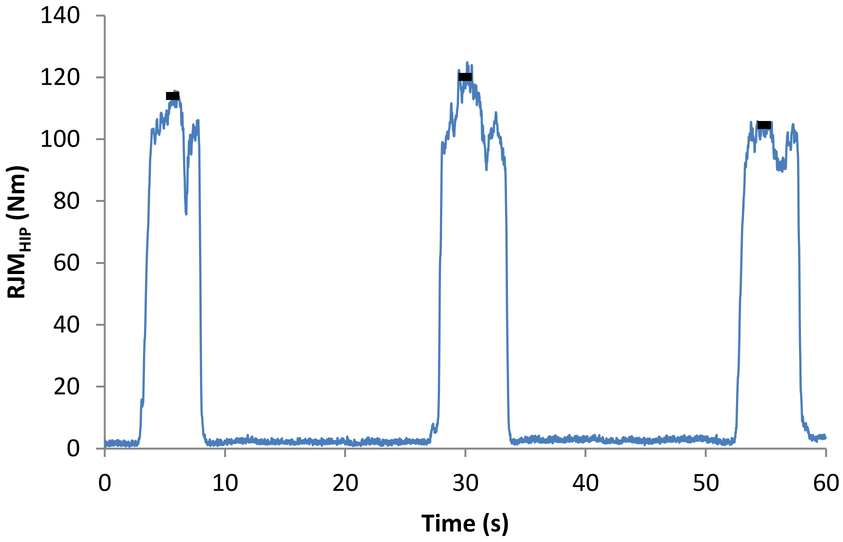

Figure 3: Raw data from isometric gluteus medius strength testing of a study participant. The black bars represent the 1 second time period with the highest average torque for each trial.

ENDURANCE: Each participant performed a 40 second maximal isometric hip abduction contraction with a 1 second ramp-up to maximum effort (Figure 4). The participant was told that the test would have to be repeated if maximum effort was not exerted from the beginning or if undesirable compensatory movements were used. The instructions given at the start of the trial were: “Ramp up to max and hold at max.” The researcher provided consistent verbal encouragement throughout the trial using the standardized statements of “Keep pushing at max. You’re doing great” at 10 seconds, “Keep pushing. You’re halfway there” at 20 seconds and “You’re almost there” at 35 seconds. At 40 seconds the researcher stated “and down” to end the trial. If the participant began using compensatory movements during the trial, the researcher provided verbal reminders of correct test positioning.

Sharp peaks in torque that could not be sustained were visually identified and eliminated from analysis. Isometric gluteus medius endurance was calculated as percentage drop in strength over the course of the trial using the following formula:

$$\%\ drop = \frac{(\bar{y}_1 - \bar{y}_2)}{\bar{y}_1} * 100$$

where $\bar{y}_1$=*mean torque over the first 5 seconds of the trial* and $\bar{y}_2$=*mean torque over the last 5 seconds of the specified 40 second time period.*

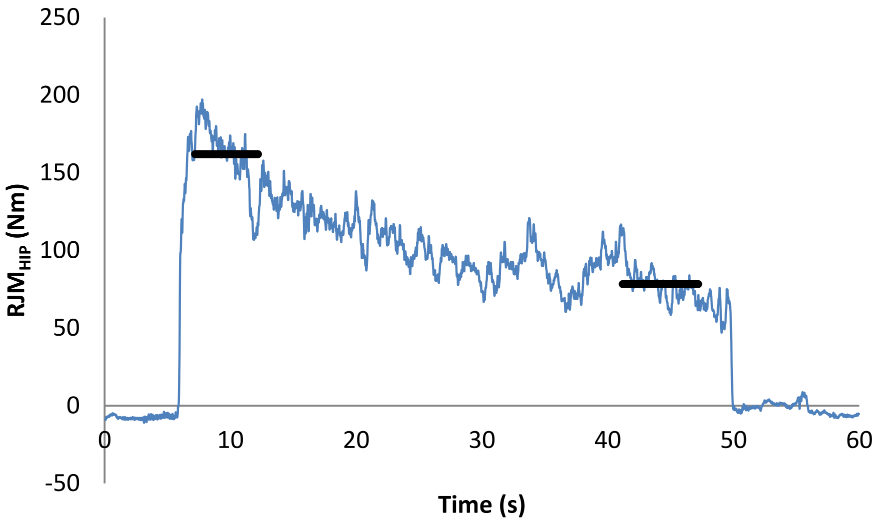

Figure 4: Raw data from isometric gluteus medius endurance testing of a study participant. The black lines represent the 5 second time periods used to evaluate percentage drop in strength over the course of the 40 second endurance trial.

Dynamic Strength and Endurance Testing

Dynamic gluteus medius strength and endurance were measured using the number of repetitions of hip abduction performed to fatigue in the side plank position. A similar method of fatiguing the hip abductors was used by Patrek et al. (2011) in the sidelying position. However, the side plank position was chosen for this study because it has been shown that hip abduction in a side plank position elicits a greater percentage of maximal voluntary isometric contraction from gluteus medius than the same exercise performed in sidelying (Boren et al., 2011). In the testing position, the body was supported only by the lateral edge of the foot and the forearm/elbow with the test leg stacked on top of the support leg and the body held in a straight line with the toes, hips and shoulders facing forward in a neutral position (Figure 5). The shoulder and elbow of the support arm were positioned at 90° and the other hand was placed on the hip with the elbow at 90°. From this side plank position, participants were instructed to keep the knee locked at 180°, the ankle flexed to 90°, and the toes facing forward while lifting the top leg until the heel touched the bottom edge of a zip tie attached to a metal pole. The desired leg raise height for each participant was set by passively abducting the test leg to shoulder height and moving the zip tie to the height of the heel.

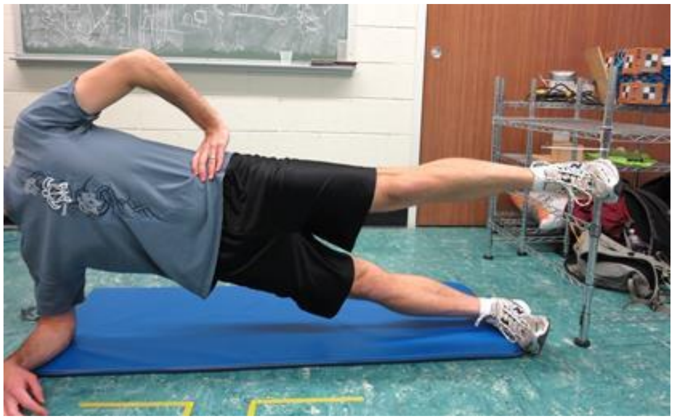

Figure 5: Body position during side plank hip abduction.

Prior to testing, hip abduction technique was demonstrated along with undesirable compensatory motions. Participants were instructed to avoid dropping the hip of the support leg towards the floor, dropping the ankle of the support leg to the floor, rotating the pelvis forwards or backwards, bending the knee of the test leg, or externally rotating the test leg. The goal of the task was to abduct the test leg as many times as possible until one of three "stop" conditions occurred:

1) the participant fatigued and stopped voluntarily
2) the heel failed to hit the zip tie twice in a row
3) the researcher indicated that the participant was using compensatory motions.

A minimum of two practice hip abduction motions were performed with verbal and physical cueing provided in order to ensure proper positioning and technique. The participant then rested on the ground in sidelying for 30 seconds before returning to the side plank position for testing. The number of hip abduction repetitions performed by the test leg was recorded as a measure of dynamic hip strength and endurance.

Stability Task

Stability was assessed by measuring trunk acceleration during a single-leg stork stand using a wireless triaxial accelerometer (G-link model, LORD MicroStrain, +/- 10g range, 10mg measurement resolution) attached to the sternum of the participant. Factory calibration settings of the accelerometer were used in conjunction with Node Commander Wireless Sensing Software (version 2.4.0, LORD MicroStrain) and acceleration data was acquired at a sampling rate of 617 Hz. It has been shown that accelerometry is a valid measure of balance performance when compared to centre of pressure measurements

(Whitney et al., 2011) or compared to clinical tests such as the Berg Balance Scale or Timed Up and Go test (O'Sullivan et al., 2008).

The goal of the stability task was to remain as steady as possible in single-leg stance for 30 seconds without intentionally shifting the foot or arm position (Figure 6). While in single-leg support, the participant was asked to fold the arms across the chest, hook the dorsum of the opposite foot just below the back of the knee on the stance leg and keep the eyes looking straight ahead at a patterned blue screen. The screen lacked vertical and horizontal lines in order to minimize visual cues that would indicate a shift in body position. Stork stand technique was demonstrated once, and the participant was allowed to practice the task twice for five seconds on each leg before the start of testing. Verbal feedback was provided during practice trials in order to ensure proper technique.

Figure 6: Single-leg stork stand position. A wireless triaxial accelerometer was attached to the sternum of the participant to measure trunk acceleration as an indicator of stability.

Four trials of the stork stand were performed on each leg alternately with only 10 seconds of rest allowed in double-leg stance between trials. Each trial began with verbal instruction to “lift your (right/left) leg now” which cued the participant to obtain the test position. After 30 seconds had passed, the verbal instruction “and down” indicated to the participant that they could return to double-leg stance. No verbal feedback on technique was provided during the trials.

Time required for the researcher to state which leg to lift and time required for the participant to assume a stable test position were both included in the 30 second recording period, therefore the first 8 seconds of recorded data were discarded for each trial. The 20 second time period after the initial 8 seconds was used for analysis. None of the participants completely lost balance or touched the ground with the opposite foot during a trial.

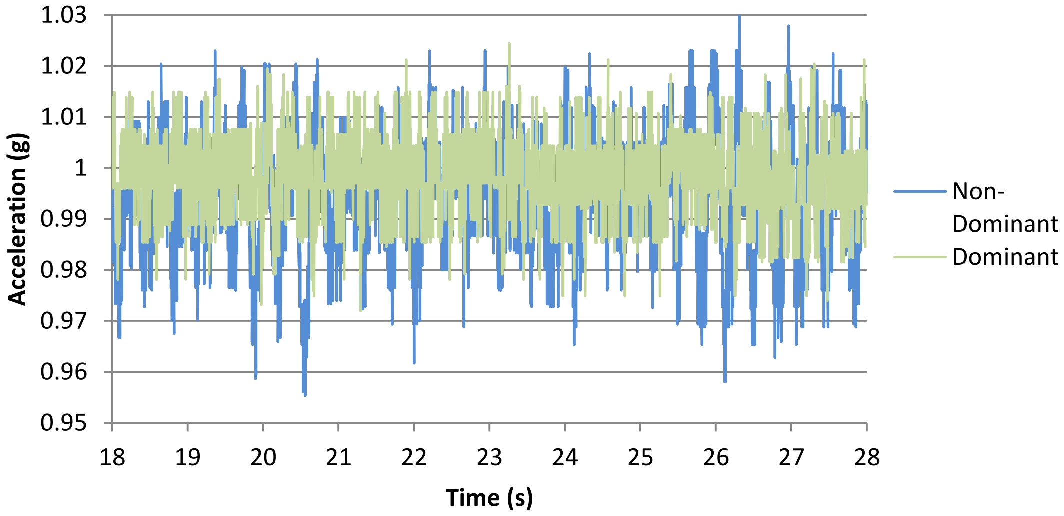

Figure 7: 10 second time excerpts of resultant acceleration data recorded during bilateral single-leg balance trials of a study participant.

Data recorded by the accelerometer in the mediolateral, vertical, and anteroposterior directions was combined by calculating the instantaneous resultant acceleration vector (Figure 7). Mean resultant acceleration was calculated over the 20 second time period and “sway” was calculated as the average variation from that mean during each trial. Sway averaged over all four trials represented the stability performance of each leg. A higher sway value indicates worse balance performance.

Targeting Task

The foot targeting task was recorded using hi-speed digital video (120 frames per second, 640x480 resolution, Casio Exilim EX-FH100). In order to bias the test towards gluteus medius involvement, targets were oriented in the frontal plane and a weight shift was required during each targeting attempt. Two different target distances were utilized in accordance with the typical practice of using multiple movement amplitudes during upper and lower limb targeting studies (Hoffmann and Hui, 2010; Hoffmann, 1991; Rohr, 2006).

Tape was used to outline a box on the floor as the starting position or “docking” position for the test, and corners of tape labeled #1 and #2 were placed at horizontal distances 15 cm and 30 cm from the docking position in both directions (Figure 8). The entire task included 10 attempts at each target distance and the standardized order of the targeting sequence was determined using a random number generator. The sequence of target numbers was read aloud at five second intervals and recorded on a digital audio file that was used for all participants.

The starting position for the targeting task was standardized as an erect stance with the knees locked and both feet flat on the floor inside the docking box. The participant was asked to line up the toes and lateral edge of the test foot as close as possible to the corner of the docking box without actually touching the tape itself. Upon hearing the number “1” or “2” on the digital audio file, the participant was instructed to laterally move the test foot to the requested target as quickly and as accurately as possible with the goal of landing the lateral and front aspects of the foot as close as possible to the target corner without actually contacting the tape. Once the test foot had fully landed at the target, the participant was required to immediately lift the opposite foot and tap it against the medial side of the test foot in order to ensure a complete transfer of body weight to the test leg. In between targeting attempts, the participant was allowed 5 seconds to return the test foot to the starting position in the docking box.

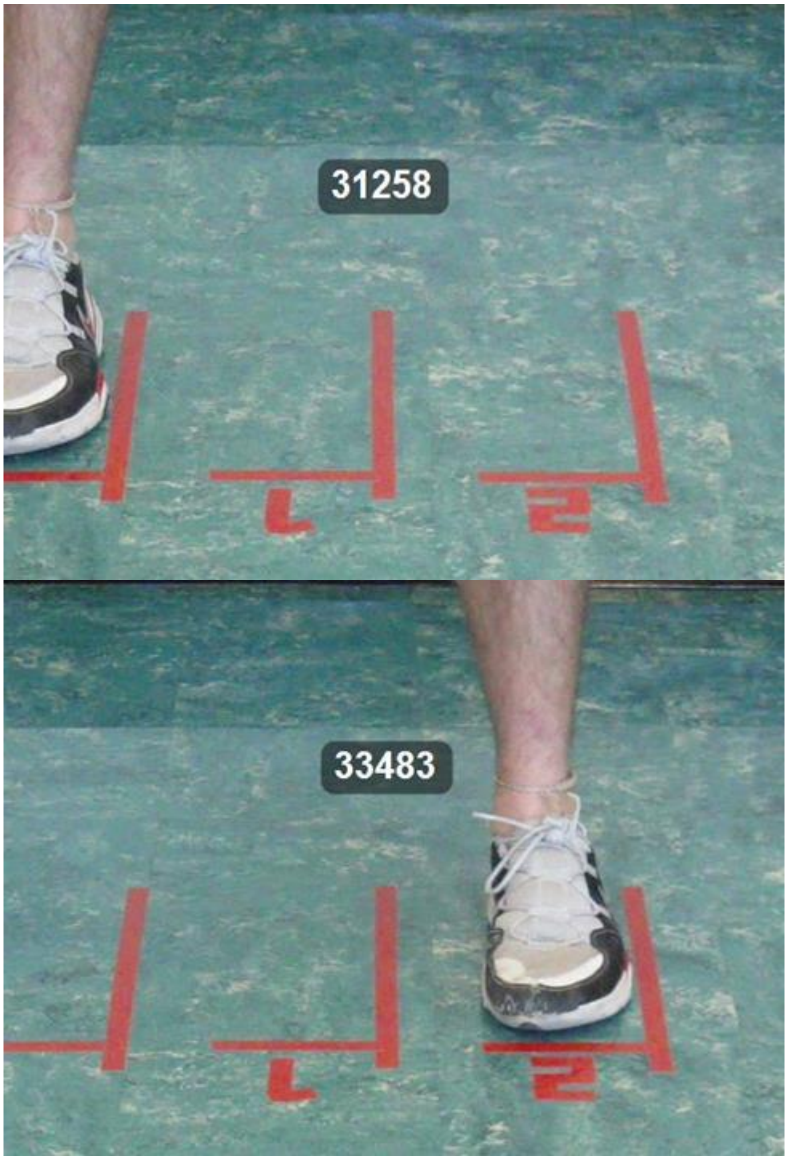

Figure 8: Targeting test layout showing the starting position of the foot (top panel) and the foot placed at target #2 (bottom panel). The numbers inset into the images represent the time (ms) from the start of the entire targeting trial.

The researcher demonstrated the targeting task and the participant performed a minimum of three practice attempts for each target while receiving verbal feedback from the researcher regarding technique. It was made clear to all participants that both speed and accuracy would be tested and it was explained that jumping from the docking position to the target position was not allowed. When the participant was ready for testing, the digital audio recording started with the phrase: “The test will begin in 5 seconds.” The participant then aimed for each of the 20 targets in the order stated on the digital audio file. Completion of the test was marked by the phrase: “The test is now complete.”

Targeting accuracy was evaluated using video motion analysis software (Kinovea 0.8.15). The horizontal distance between the intended target and the lateral edge of the foot upon landing was recorded as horizontal error (mm). Horizontal error was then divided by the intended target distance and expressed as percentage error (%). Average percentage error over all 20 targeting attempts (10 for each of the two target distances) was calculated as a measure of targeting accuracy for each limb. In order to determine movement speed (m/s), the distance of horizontal foot movement (mm) was divided by the total time (ms) from initial lift-off of the foot at the docking box to initial touch-down of the foot at the intended target. Speed (m/s) was averaged for each leg over all 20 targeting attempts. To account for the trade-off between movement speed and accuracy as per Fitts’ law (Fitts, 1954), a targeting score was derived for each leg by dividing horizontal error (mm) by movement speed (m/s). A lower targeting score indicates better combined speed and accuracy during the task.

Agility Task

Lower extremity agility was assessed using a single-leg lateral hopping test. Lateral hopping movements in the frontal plane have been shown to elicit moderately high gluteus medius EMG activation (Distefano et al., 2009) and similar lateral hop test designs have been used to assess the functional abilities of individuals with ACL injury (Itoh et al., 1998; Ortiz et al., 2011). Task performance was recorded using hi-speed digital video (120 fps, 640x480, Casio Exilim EX-FH100).

Two pieces of yellow tape were placed in parallel on the floor at a distance of 15 cm apart to form the “small gap” while two blue pieces of tape were placed on either side of the yellow tape lines at a distance of 30 cm apart to form the “large gap” (Figure 9). Two pieces of green tape were laid down 45 cm apart and parallel to the blue tape lines in an effort to control for any performance effects that could result from the perception of hopping outside the lines when traveling back and forth over the large gap. Pink tape was placed across the middle point of all tape lines in order to visually cue participants to stay in the centre of the tape grid while hopping.

The participant was instructed to stand with the lateral border of the test foot lined up against the outer edge of the yellow tape line. The goal was to hop back and forth on one leg over the small gap while moving as quickly as possible and staying as close to the outer edge of the tape lines as possible without actually landing on them. It was explained that both speed and accuracy would be evaluated and the participant was told to independently determine the combination of speed and accuracy that would achieve the best score. When step-downs with the opposite foot occurred due to loss of balance, participants were instructed to immediately pick up the opposite foot and continue hopping without taking time to reposition the test foot.

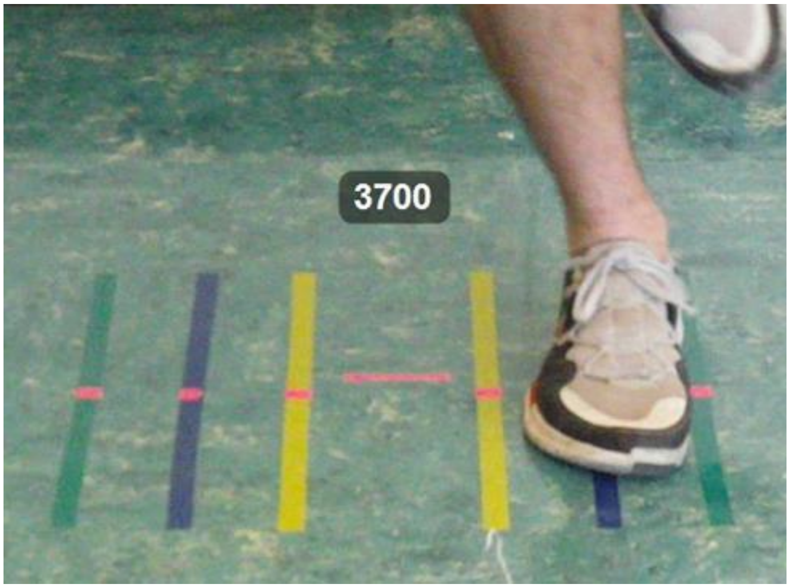

Figure 9: Agility test layout showing the small yellow gap (inner lines), the large blue gap (middle lines) and the additional green outer lines. The foot is positioned at the start of a hop over the small gap. The number inset into the image represents the time (ms) from the start of the entire agility trial.

One hop was defined as a complete trip from one side of the gap to the other side and back. The researcher demonstrated 3 hops over the small gap and 3 hops over the large gap before allowing the participant to perform a minimum of 3 practice hops over each gap with the test leg. Verbal feedback was provided during practice hops to ensure that the participant understood the task. Agility testing for each leg included 10 hops over the small gap and 10 hops over the large gap in sequence with an enforced 10 second rest between gaps. During the rest period, the participant lined up the lateral border of the test foot against the outer edge of the large gap. A trial was stopped and repeated when the participant performed the task incorrectly due to a misunderstanding of the instructions, or when a complete loss of balance caused the participant to take several steps with both feet between hops. A minimum two minute rest was enforced between the agility task trials of the right and left leg.

Agility task accuracy and movement time were determined using video motion analysis software (Kinovea 0.8.15). For each hop, the foot landed once on either side of the gap resulting in a total of 40 footfalls during the test, 38 of which involved rapid direction changes. Using methods similar to those described for targeting analysis, percentage error (%), speed (m/s) and agility score were calculated for all 40 footfalls and averaged to represent the agility performance of each limb.

Statistical Analysis

Data was analyzed using Microsoft Excel (2010) and SPSS statistical software (Version 16). Test-retest reliability of the isometric strength testing method and the single-leg stork stand testing method were evaluated using coefficient of variation. The validity of the isometric endurance testing protocol was evaluated using a two-tailed paired t-test that compared the peak torque values achieved during isometric endurance testing to those measured during isometric strength testing.

One-tailed independent t-tests were used to compare males and females in regards to demographic characteristics, gluteus medius strength and endurance measures, and performance on stability, targeting and agility tasks. Two-tailed paired t-tests were used to evaluate potential differences in leg length between dominant and non-dominant limbs, while one-tailed paired t-tests were used to compare dominant and non-dominant limbs in regards to gluteus medius strength and endurance measures and performance on stability, targeting and agility tasks.

Pearson’s correlation coefficients with one-tailed significance tests were used to evaluate the relationships between all gluteus medius strength and endurance characteristics and all measurements of stability, targeting and agility performance for both the dominant and non-dominant limbs. Pearson’s correlation coefficients with two-tailed significance tests were used to explore the inter-relationships between gluteus medius strength and endurance characteristics as well as the inter-relationships between all measures of stability, targeting and agility performance.

The significance level for all statistical tests was set a priori at 0.05.

All measures of gluteus medius strength, gluteus medius endurance, and stability, targeting and agility performance were assessed for the existence of outliers that differed from the mean by greater than three standard deviations. No consistent outliers were detected.

Results

Description of Participants

A total of 57 participants were recruited and tested. One participant failed to follow instructions during the testing session and the data collected from that participant was eliminated from analysis. A summary of participant characteristics can be found in Table 2. The ages of participants ranged from 21-38 years and body mass index (BMI) ranged from 18.6 to 36.4. 52% of participants had a BMI value of less than 25 and were considered to be normal weight, 43% of participants had a BMI between 25 and 30 and were considered to be overweight, and 5% of participants had a BMI higher than 30 which indicates obesity.

Table 2: Description of participants.

	All Subjects *n=56* *Mean (SD)*	**Males** *n=28* *Mean (SD)*	**Females** *n=28* *Mean (SD)*	**T-test (M vs. F)** *p-value*
Age (y)	27.9 (3.8)	28.9 (4.1)	26.9 (3.4)	**.025**
Height (cm)	171.6 (10.5)	178.2 (9.7)	165.1 (6.4)	**<.001**
Body mass (kg)	72.84 (13.84)	82.24 (11.35)	63.44 (8.83)	**<.001**
BMI (kg/m^2)	24.62 (3.51)	25.95 (3.52)	23.29 (2.99)	**.002**
Dominant leg length (cm)	83.01 (6.23)	86.34 (5.74)	79.68 (4.80)	**<.001**
Non-dominant leg length (cm)	83.01 (6.03)	86.30 (5.58)	79.71 (4.52)	**<.001**

Independent t-tests were used to compare males and females in terms of age, height, body mass, BMI, and leg length. Statistically significant differences ($p<0.05$) were found between males and females in all demographic categories as the male participants were found overall to be older and taller with greater body mass, higher BMI values and longer legs than the female participants. Paired t-tests showed that dominant leg lengths were not significantly different than non-dominant leg lengths within the group of male (p=0.872) or female (p=0.827) participants.

Self-reported activity level data is summarized in Table 3. Participants varied widely in self-reported physical activity levels with 11% participating in exercise less than once a week, 29% exercising moderately 2 to 3 times per week, 41% exercising moderately greater than 3 times per week, 18% exercising intensely on a daily basis, and 2% rating themselves as elite competitive athletes.

Table 3: Self-reported physical activity levels of participants. Participants reported their current level of participation in exercise and sport as well as the highest level of participation in exercise and sport that they had achieved in the past 5 years.

	Exercise <1x/week (Score=1)	**Moderate Exercise 2-3x/week (Score=2)**	**Moderate Exercise >3x/week (Score=3)**	**Intense Exercise Almost Daily (Score=4)**	**Elite Athlete (Score=5)**	**Average Score of All Subjects** *n=56*
	Count (%)	*Count (%)*	*Count (%)*	*Count (%)*	*Count (%)*	*Mean (SD)*
Current Physical Activity	6 (10.7%)	16 (28.6%)	23 (41.1%)	10 (17.9%)	1 (1.8%)	2.7 (0.9)
Highest Physical Activity	2 (3.6%)	9 (16.1%)	20 (35.7%)	24 (42.9%)	1 (1.8%)	3.2 (0.9)

Reliability and Validity of Strength and Endurance Testing Methods

The isometric testing method used to assess gluteus medius strength showed high test-retest reliability with an average between-trial coefficient of variation of 6.6%. The testing method used to evaluate single-leg stork stand performance also had a high level of repeatability with an average between-trial coefficient of variation of 6.9%.

In order for the isometric gluteus medius endurance testing method to be valid, participants needed to exert maximum effort at the start of the test. The peak torque achieved during the initial phase of isometric gluteus medius endurance testing was not significantly different than the average maximum 1 second torque achieved during isometric gluteus medius strength trials for either the dominant limbs ($p=0.490$) or the non-dominant limbs ($p=0.430$) of participants.

Strength and Endurance Characteristics of Gluteus Medius

The gluteus medius strength and endurance measurements of all participants are presented in Table 4. One participant performed an altered testing protocol of the dynamic gluteus medius strength and endurance test during the early stages of the study, and another participant could not perform the plank position on the left side due to a history of recent left forearm surgery. The dynamic gluteus medius strength and endurance test results of these two participants were excluded from analysis.

Sex-Dependent Strength and Endurance Differences

The gluteus medius characteristics of all male and female participants are presented in Table 4. Males demonstrated significantly greater absolute isometric gluteus medius strength (Nm) than females with both the dominant and non-dominant limbs ($p<0.001$). When isometric strength measures were normalized for body mass (Nm/kg), the difference between males and females remained significant at a level of $p<0.05$. Males also performed a significantly greater number of leg lifts than females with both the dominant and non-dominant limbs ($p<0.01$). Any differences observed in isometric gluteus medius endurance between males and females were not found to be statistically significant.

Table 4: Dominant vs. non-dominant gluteus medius characteristics.

	Dominant Limb				Non-dominant Limb				All Subjects
	All Subjects *Mean (SD) [Range]*	**Males** *Mean (SD) [Range]*	**Females** *Mean (SD) [Range]*	**T test (M vs. F)** *p-value*	**All Subjects** *Mean (SD) [Range]*	**Males** *Mean (SD) [Range]*	**Females** *Mean (SD) [Range]*	**T test (M vs. F)** *p-value*	**T test (D vs. ND)** *p-value*
Absolute Isometric Strength (Nm)	110.451 (37.792) [51.163-217.868]	136.887 (32.750) [59.075-217.868]	84.015 (19.680) [51.163-115.421]	**<.001**	112.069 (39.531) [40.121-214.553]	135.511 (38.022) [45.650-214.553]	88.628 (24.451) [40.121-134.036]	**<.001**	.239
Normalized Isometric Strength (Nm/kg)	1.51 (0.41) [0.70-2.72]	1.68 (0.42) [0.70-2.72]	1.34 (0.32) [0.70-2.03]	**<.001**	1.54 (0.46) [0.54-2.81]	1.67 (0.50) [0.54-2.81]	1.41 (0.39) [0.55-2.12]	**.016**	.159
Isometric Endurance (% Drop)	43.635 (16.656) [1.724-76.117]	42.203 (13.263) [18.749-69.902]	45.066 (19.620) [1.724-76.117]	.263	44.993 (16.119) [4.731-87.357]	46.494 (14.481) [26.562-79.338]	43.493 (17.745) [4.731-87.357]	.246	.195
Dynamic Strength & Endurance (# of leg lifts)	10.6 (9.0) [0-34]	14.1 (9.1) [0-34]	7.1 (7.7) [0-27]	**.002**	10.6 (9.4) [0-39]	13.4 (10.1) [0-39]	7.8 (7.7) [0-26]	**.009**	.478

Dominance-Dependent Strength and Endurance Differences

The gluteus medius characteristics of all dominant and non-dominant limbs are presented in Table 4. No significant differences between the dominant and non-dominant limbs were identified for any of the strength and endurance measures of gluteus medius. Performances of the dominant limbs were found to be strongly correlated with performances of the non-dominant limbs on all gluteus medius strength and endurance tests at a significance level of $p<0.001$ for measures of absolute isometric strength ($r=0.905$), body mass normalized isometric strength ($r=0.865$), isometric endurance ($r=0.743$), and dynamic strength and endurance ($r=0.859$).

Inter-Relationships between Strength and Endurance Measures

The inter-relationships between strength and endurance measures are presented in Table 5. Performance on the dynamic gluteus medius strength and endurance test was significantly correlated to absolute isometric gluteus medius strength and to body mass normalized isometric gluteus medius strength among both dominant and non-dominant limbs. Moderate but significant negative correlations were also found to exist between dynamic gluteus medius strength and endurance test results and isometric gluteus medius endurance percentage drop for both dominant and non-dominant limbs.

Stability, Targeting and Agility Performance

The stability, targeting and agility task performance results of all participants are presented in Table 6.

Table 5: Correlations between strength and endurance measures.

	Dominant Limb				Non-dominant Limb			
	Absolute Isometric Strength (Nm) *r (p-value)*	**Normalized Isometric Strength (Nm/kg)** *r (p-value)*	**Isometric Endurance (% Drop)** *r (p-value)*	**Dynamic Strength & Endurance (# of Leg Lifts)** *r (p-value)*	**Absolute Isometric Strength (Nm)** *r (p-value)*	**Normalized Isometric Strength (Nm/kg)** *r (p-value)*	**Isometric Endurance (% Drop)** *r (p-value)*	**Dynamic Strength & Endurance (# of Leg Lifts)** *r (p-value)*
Absolute Isometric Strength (Nm)	--	**.832 (<.001)**	-.021 (.879)	**.504 (<.001)**	--	**.847 (<.001)**	-.013 (.926)	**.476 (<.001)**
Normalized Isometric Strength (Nm/kg)	--	--	-.021 (.877)	**.601 (<.001)**	--	--	-.128 (.349)	**.588 (<.001)**
Isometric Endurance (% Drop)	--	--	--	**-.397 (.003)**	--	--	--	**-.397 (.003)**

Table 6: Performance of dominant and non-dominant limbs on the stability, targeting and agility tasks.

	Dominant Limb				**Non-dominant Limb**				**All Subjects**
	All Subjects *Mean (SD) [Range]*	**Males** *Mean (SD) [Range]*	**Females** *Mean (SD) [Range]*	**T test (M vs. F)** *p-value*	**All Subjects** *Mean (SD) [Range]*	**Males** *Mean (SD) [Range]*	**Females** *Mean (SD) [Range]*	**T test (M vs. F)** *p-value*	**T test (D vs. ND)** *p-value*
Stability Task Sway (g)	83.01 (12.12) [64.94-124.36]	84.11 (12.41) [66.83-124.36]	81.91 (11.94) [64.68-109.07]	.251	83.73 (13.08) [64.68-142.34]	86.90 (15.09) [66.96-142.34]	80.56 (9.99) [64.68-109.07]	**.035**	.256
Targeting Accuracy (% Error)	4.3 (1.3) [2.1-9.5]	4.4 (1.5) [2.1-9.5]	4.2 (1.0) [2.9-6.9]	.307	4.5 (1.5) [2.1-10.5]	4.7 (1.7) [2.1-10.5]	4.4 (1.3) [2.3-8.4]	.260	.117
Targeting Speed (m/s)	0.64 (0.10) [0.37-0.85]	0.64 (0.12) [0.37-0.84]	0.64 (0.07) [0.48-0.77]	.396	0.64 (0.09) [0.39-0.84]	0.65 (0.10) [0.39-0.82]	0.64 (0.09) [0.51-0.84]	.260	.384
Targeting Score	14.2 (3.7) [9.0-27.8]	14.6 (4.2) [9.2-27.8]	13.8 (3.1) [9.0-21.0]	.236	14.9 (4.7) [8.5-34.9]	15.0 (4.9) [9.9-34.9]	14.7 (4.5) [8.5-27.7]	.432	.182
Agility Accuracy (% Error)	17.0 (6.4) [8.8-36.3]	17.0 (7.0) [8.8-36.3]	17.0 (5.9) [10.0-32.0]	.498	15.9 (5.4) [7.3-38.5]	17.0 (5.9) [9.1-38.5]	14.8 (4.8) [7.3-28.5]	.067	**.035**
Agility Speed (m/s)	1.57 (0.21) [1.11-2.31]	1.58 (0.24) [1.22-2.31]	1.56 (0.19) [1.11-2.06]	.319	1.52 (0.19) [1.12-2.11]	1.55 (0.19) [1.29-2.11]	1.49 (0.18) [1.12-1.79]	.115	**.013**
Agility Score	23.0 (6.3) [13.0-39.9]	22.6 (6.2) [13.0-32.9]	23.4 (6.5) [13.3-39.9]	.310	23.1 (8.5) [11.3-55.0]	24.2 (9.3) [14.1-55.0]	21.9 (7.6) [11.3-44.7]	.157	.470

Sex-Dependent Performance Differences

Females performed better on the static single-leg balance task than males with both dominant and non-dominant limbs, but the difference was statistically significant for non-dominant limbs only (p=0.035). No significant differences between males and females were found for any of the targeting or agility measures.

Dominance-Dependent Performance Differences

Dominant limbs performed the agility task at a significantly higher speed (p=0.013) but with a significantly higher percentage of error (p=0.035) than non-dominant limbs. However, the overall agility scores of the dominant and non-dominant limbs were not found to be significantly different (p=0.470). There were no significant differences between the dominant and non-dominant limbs on performances of either the stability task or the targeting task.

Inter-Relationships between Stability, Targeting and Agility Measures

The inter-relationships between stability, targeting and agility performance measures are shown in Table 7 and Table 8. Among both dominant and non-dominant limbs, targeting accuracy (percentage error) was significantly and positively correlated to targeting speed and targeting score, while agility accuracy (percentage error) was found to be significantly and positively correlated to agility speed and agility score. No other significant correlations were found between any measures of stability, targeting and agility performance.

Table 7: Correlations between stability, targeting and agility performance of dominant limbs.

	Dominant Limb						
	Stability Task Sway (g) *r (p-value)*	**Targeting Accuracy (% Error)** *r (p-value)*	**Targeting Speed (m/s)** *r (p-value)*	**Targeting Score** *r (p-value)*	**Agility Accuracy (% Error)** *r (p-value)*	**Agility Speed (m/s)** *r (p-value)*	**Agility Score** *r (p-value)*
Stability Task Sway (g)	--	-.101 (.460)	-.165 (.226)	-.022 (.873)	.025 (.857)	.229 (.089)	-.134 (.324)
Targeting Accuracy (% Error)	--	--	**.360** **(.006)**	**.839** **(<.001)**	.109 (.426)	.106 (.438)	.047 (.728)
Targeting Speed (m/s)	--	--	--	-.175 (.197)	.060 (.659)	-.001 (.992)	.129 (.342)
Targeting Score	--	--	--	--	.082 (.548)	.100 (.463)	-.006 (.964)
Agility Accuracy (% Error)	--	--	--	--	--	**.698** **(<.001)**	**.762** **(<.001)**
Agility Speed (m/s)	--	--	--	--	--	--	.180 (.185)

Table 8: Correlations between stability, targeting and agility performance of non-dominant limbs.

	Non-Dominant Limb						
	Stability Task Sway (g) *r (p-value)*	**Targeting Accuracy (% Error)** *r (p-value)*	**Targeting Speed (m/s)** *r (p-value)*	**Targeting Score** *r (p-value)*	**Agility Accuracy (% Error)** *r (p-value)*	**Agility Speed (m/s)** *r (p-value)*	**Agility Score** *r (p-value)*
Stability Task Sway (g)	--	-.004 (.979)	-.131 (.337)	.028 (.837)	.010 (.941)	.205 (.129)	-.001 (.995)
Targeting Accuracy (% Error)	--	--	**.392 (.003)**	**.897 (<.001)**	-.149 (.127)	-.225 (.095)	.012 (.932)
Targeting Speed (m/s)	--	--	--	-.028 (.840)	-.015 (.911)	-.106 (.435)	.135 (.323)
Targeting Score	--	--	--	--	-.122 (.368)	-.198 (.143)	-.024 (.858)
Agility Accuracy (% Error)	--	--	--	--	--	**.440 (.001)**	**.705 (<.001)**
Agility Speed (m/s)	--	--	--	--	--	--	-.134 (.323)

Table 9: Correlations between gluteus medius characteristics and performance on stability, targeting and agility tasks.

	Dominant Limb				**Non-dominant Limb**			
	Absolute Isometric Strength (Nm) *r (p-value)*	**Normalized Isometric Strength (Nm/kg)** *r (p-value)*	**Isometric Endurance (% Drop)** *r (p-value)*	**Dynamic Strength & Endurance (# of Leg Lifts)** *r (p-value)*	**Absolute Isometric Strength (Nm)** *r (p-value)*	**Normalized Isometric Strength (Nm/kg)** *r (p-value)*	**Isometric Endurance (% Drop)** *r (p-value)*	**Dynamic Strength & Endurance (# of Leg Lifts)** *r (p-value)*
Stability Task Sway (g)	-.054 (.346)	.016 (.452)	.156 (.126)	.007 (.480)	.032 (.408)	.058 (.336)	**.253** **(.030)**	-.047 (.366)
Targeting Accuracy (% Error)	-.014 (.460)	-.087 (.263)	-.051 (.355)	-.017 (.451)	.168 (.108)	.075 (.291)	.173 (.101)	.102 (.230)
Targeting Speed (m/s)	-.162 (.117)	-.217 (.054)	.047 (.367)	-.147 (.145)	-.145 (.143)	**-.229** **(.045)**	.196 (.074)	-.182 (.092)
Targeting Score	.079 (.282)	.018 (.447)	-.086 (.265)	.056 (.345)	.217 (.054)	.158 (.123)	.100 (.232)	.156 (.128)
Agility Accuracy (% Error)	-.170 (.106)	-.196 (.074)	-.069 (.306)	-.027 (.423)	-.033 (.404)	-.123 (.184)	-.077 (.286)	-.117 (.197)
Agility Speed (m/s)	-.004 (.488)	.071 (.303)	-.048 (.363)	.171 (.109)	.113 (.204)	.109 (.212)	-.002 (.495)	.089 (.258)
Agility Score	-.206 (.064)	**-.262** **(.026)**	.064 (.320)	-.175 (.102)	-.220 (.052)	**-.335** **(.006)**	.086 (.264)	-.195 (.077)

Relationships between Functional Performance Measures and Gluteus Medius Characteristics

The relationships between stability, targeting and agility task performance measures and gluteus medius strength and endurance measures are shown in Table 9. Among dominant limbs, only 1 out of the 28 correlations evaluated between these variables was found to be significant, while only 3 of the 28 correlations calculated among non-dominant limbs were found to be significant.

A statistically significant weak positive correlation (Figure 10) was found to exist between the isometric gluteus medius endurance of non-dominant limbs and the amount of sway exhibited during the single-leg static balance task.

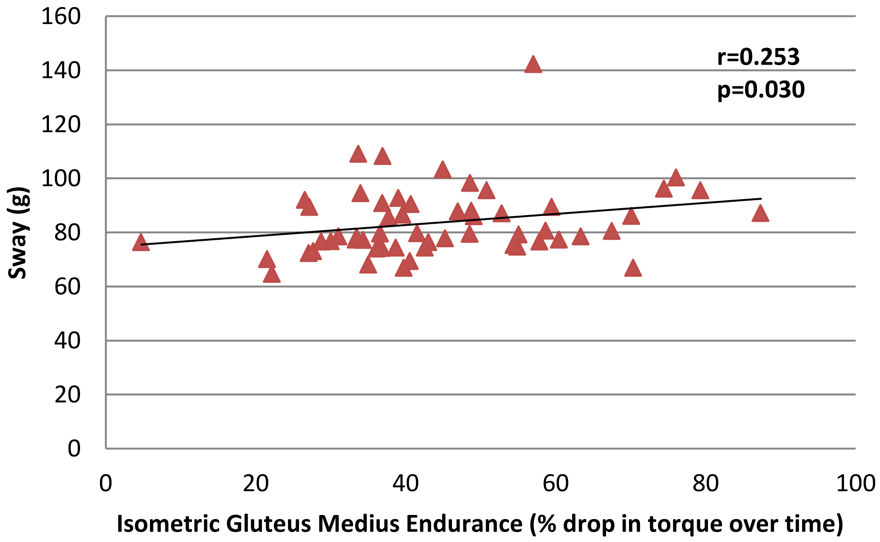

Figure 10: Relationship between the isometric gluteus medius endurance of non-dominant limbs and the amount of sway (g) exhibited during the single-leg stability task.

A statistically significant but weak negative correlation (Figure 11) was found to exist between targeting speed and body mass normalized isometric gluteus medius strength among non-dominant limbs only. The weak positive correlation (r=0.217) between targeting score and absolute isometric gluteus medius strength of non-dominant limbs nearly approached significance (p=0.054), as did the weak negative correlation (r=-0.217) between targeting speed and body mass normalized isometric gluteus medius strength of dominant limbs (p=0.054). However, none of the other targeting performance measures correlated significantly with any of the gluteus medius strength and endurance measures.

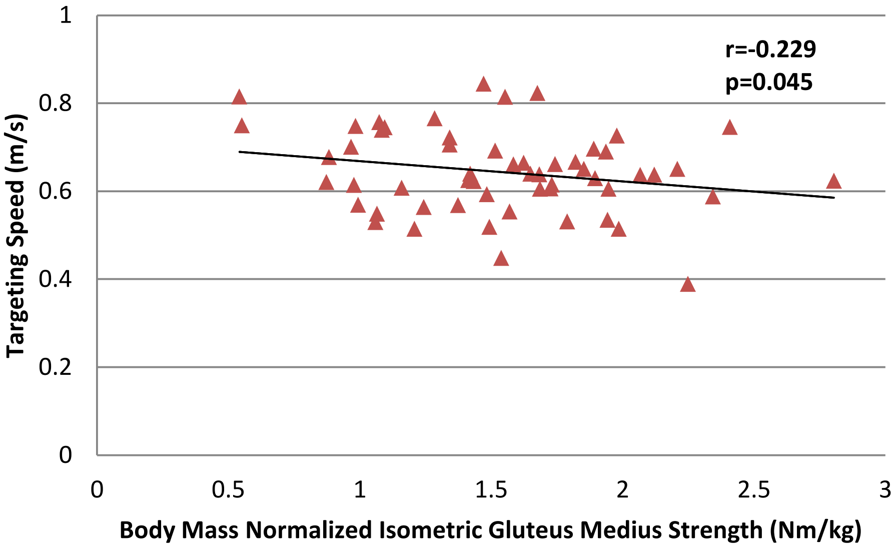

Figure 11: Relationship between the body mass normalized isometric gluteus medius strength (Nm/kg) and the targeting task speed of movement (m/s) of non-dominant limbs.

Weak to moderately strong inverse correlations were found to exist between agility score and body mass normalized isometric gluteus medius strength at a significance level of 0.026 for dominant limbs (Figure 12) and 0.006 for non-dominant limbs (Figure 13). Although the weak negative correlations between absolute isometric gluteus medius strength and agility score approached significance for both dominant and non-dominant limbs (p=0.064, p=0.052), ultimately none of the other agility measures correlated significantly with any measures of gluteus medius strength and endurance.

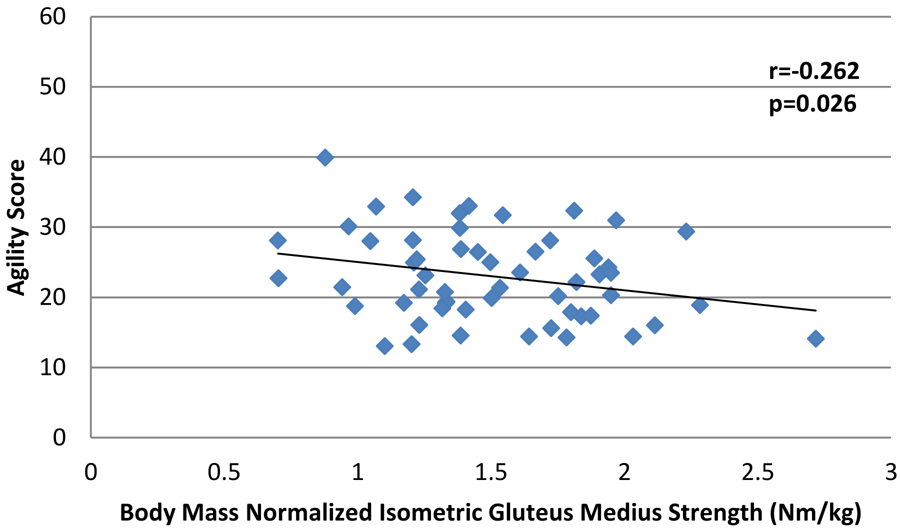

Figure 12: Relationship between the body mass normalized isometric gluteus medius strength (Nm/kg) of dominant limbs and agility task performance expressed as agility score (an aggregate score of speed and accuracy). A lower agility score indicates better performance.

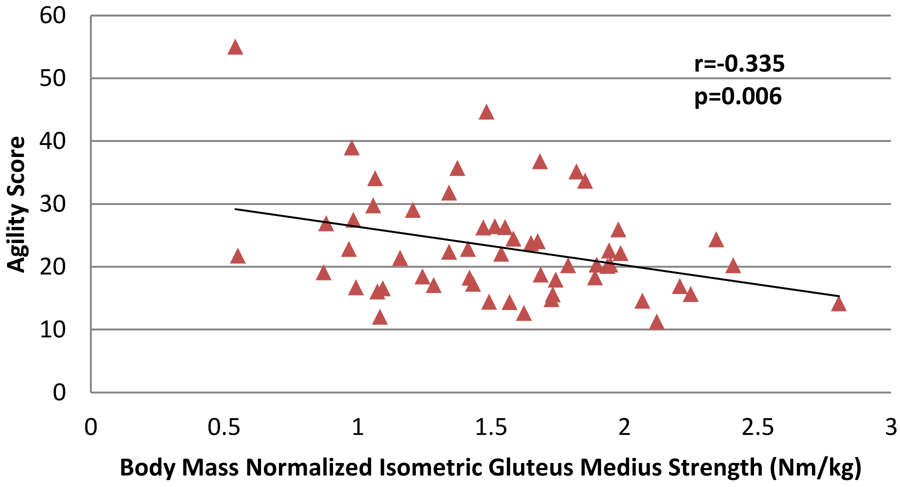

Figure 13: Relationship between the body mass normalized isometric gluteus medius strength (Nm/kg) of non-dominant limbs and agility task performance expressed as agility score (an aggregate score of speed and accuracy). A lower agility score indicates better performance.

Discussion

The primary objective of this study was to determine whether the strength and endurance of gluteus medius relate to the performance of lower limb stability, targeting and agility tasks. Unexpectedly, there was only weak evidence showing that gluteus medius strength may be related to agility performance and gluteus medius endurance may be related to single-leg stork stand performance. Contrary to the anticipated results, higher gluteus medius strength was also weakly associated with slower movement speeds during the targeting task.

Evidence of high gluteus medius activation during midstance of the gait cycle (Gottschalk et al., 1989) and conventional wisdom regarding the role of endurance in maintaining posture led to the hypothesis that gluteus medius endurance would be related to stability task performance. However, this theory was challenged by the study results as gluteus medius endurance was only weakly correlated to stability task performance and this relationship was significant only among non-dominant limbs. It could be argued that a more challenging balance task would have brought gluteus medius closer to fatigue, thus increasing the influence of gluteus medius endurance on stability performance and resulting in a more significant relationship between these variables. In fact, Salavati et al. (2007) and McMullen et al. (2011) showed that gluteus medius fatiguing protocols can negatively affect both static and dynamic stability performance. However, fatiguing protocols can also fatigue other neuromuscular structures, making it difficult to determine whether gluteus medius fatigue was the main cause of the observed effects on balance in these studies (McMullen et al., 2011; Salavati et al., 2007). In addition, Krause et al. (2009) reported that although single-leg dynamic exercises challenge gluteus medius to a greater extent than static exercises, single-leg balance activities performed on an unstable surface do not elicit significantly greater gluteus medius activation than performance of the same activities on a stable surface. This shows that increasing the difficulty of a stability task does not necessarily increase gluteus medius activation; therefore, choosing a different balance task for the current study may not have significantly altered the results. The data presented by the current study shows that gluteus medius strength and endurance may not play a major role in static single-leg stability, thus implying that other factors such as gluteus medius activation, proprioception, or strength of other muscles may be more important than gluteus medius strength and endurance in maintaining single-leg balance.

The hypothesis that targeting performance would be related to gluteus medius strength and endurance was not supported by the results. Body mass normalized isometric strength of gluteus medius was found to be significantly but weakly and negatively correlated to targeting speed for non-dominant limbs. In fact, all measures of gluteus medius strength were negatively correlated to targeting speed and positively correlated to targeting score for both dominant and non-dominant limbs, and two of these correlations nearly approached statistical significance. According to these results, participants with better gluteus medius strength demonstrated decreased movement speed and overall worse performance during the targeting task. As a means of explaining this unanticipated outcome, it is logical to consider that participants may have chosen a strategy of accuracy over speed during the targeting task. However, the correlations between strength measures and targeting accuracy were weakly negative for dominant limbs and weakly positive for non-dominant limbs, making it very likely that gluteus medius strength simply had no clinically meaningful effect on performance of the targeting task selected for this study. Isometric gluteus medius endurance also did not correlate significantly with any aspects of targeting performance.

It is possible that the targeting task was merely not challenging enough to sufficiently activate gluteus medius and elicit an inferior performance from participants with weaker gluteus medius muscles. Supporting this theory, Dierks et al. (2008) suggested that hip abductor strength may need to fall below a certain threshold before lower limb control is negatively affected. However, it should also be considered that the current study revealed a lack of relationship between gluteus medius characteristics and targeting performance because motor control of gluteus medius and activation of other muscles may be more important than strength of the hip abductors in determining the speed and accuracy of foot placement.

Body mass normalized gluteus medius strength demonstrated weak to moderate inverse correlations with agility score at a statistically significant level for both the dominant and non-dominant limbs in this study. In addition, the inverse correlations found to exist between absolute isometric gluteus medius strength and agility score approached significance for both the dominant and non-dominant limbs. These outcomes provide some evidence to support the hypothesis that gluteus medius strength is related to agility. It may be that gluteus medius strength demonstrated a more consistent relationship with agility performance than with performance on the targeting or stability tests because the agility task was the most challenging activity of the three. The importance of gluteus medius in lateral hopping is confirmed by the research of Distefano et al. (2009) who found that the EMG activity measured in gluteus medius during a sideways hopping motion was equivalent to 57% of the EMG activity measured during a maximum voluntary isometric contraction of the hip abductors. Although endurance of gluteus medius did not factor into the agility performance of participants in the current study, it is reasonable to predict that endurance may have played a larger role in both agility speed and accuracy if the hopping task was longer, and consequently even more fatiguing.

As anticipated, the males in this study demonstrated better gluteus medius strength than the females. However, it was found that the sexes did not differ significantly in gluteus medius endurance. These results are confirmed by previous studies where males have been found to have greater gluteus medius strength than females (Cowan and Crossley, 2009; Jacobs et al., 2007; Leetun et al., 2004; Nakagawa et al., 2012) and the sexes have demonstrated similar hip abduction endurance (Jacobs et al., 2007). Despite the presence of superior gluteus medius strength, males in the current study did not perform significantly better than females on the stability, targeting, or agility tasks. In fact, females performed better than males on the single-leg static balance task with both the dominant and non-dominant limbs, even though the difference between the sexes was found to be statistically significant for non-dominant limbs only. These results are consistent with the results of other authors who have found that females perform better than males on the Star Excursion Balance Test for dynamic single-leg stability (Gribble et al., 2009) and on double-leg balance tests (Greve et al., 2013). The sex-dependent differences in stork stand performance found in the current study may be explained by the fact that the male group had a significantly higher mean height, body mass, and BMI than the female group, as an increase in any one of these factors has been shown to negatively affect postural control (Greve et al., 2013). However, it is also possible that the females had simply developed better neuromuscular control for balance tasks prior to study enrolment, potentially due to the habit of wearing high heels as suggested by Greve et al. (2013).

It was hypothesized that non-dominant limbs would demonstrate better gluteus medius strength and endurance than dominant limbs, but the results of this study found a lack of significant side-to-side differences in gluteus medius strength and endurance measures among both the male and female groups of participants. Confirming these findings, Niemuth et al. (2005) also observed a lack of significant side-to-side differences in hip abductor strength in both males and females, and Jacobs et al. (2005b) reported that dominant and non-dominant limbs do not differ significantly in hip abductor endurance. In contrast, the same study by Jacobs et al. (2005b) found that dominant limbs demonstrate significantly stronger hip abductors than non-dominant limbs in both males and females while Brophy et al. (2009) reported that a side-to-side gluteus medius strength differential exists in women but not in men. However, Jacobs et al. (2005b) and Brophy et al. (2009) do not appear to have excluded athletes with history of a recent injury as was done in the current study, thus making it possible that the side-to-side strength differences observed in these studies (Brophy et al., 2009; Jacobs et al., 2005b) were due to injury-related atrophy.

The original hypothesis that non-dominant limbs would have stronger gluteus medius muscles was based on the notion that the non-dominant limb often stabilizes the body in single-leg stance while the dominant limb manipulates objects. However, when the stork stand performances of dominant and non-dominant limbs were compared in the current study, no significant differences were found. These results are confirmed by the research of Greve et al. (2007) who found that dominant and non-dominant limbs did not show any statistically significant differences in dynamic balance performance on the Star Excursion Balance Test. The hypothesis that dominant limbs would perform better than non-dominant limbs on the agility and targeting tasks was also challenged by the results of this study. During the agility task, the dominant limbs did demonstrate some superiority in speed of movement but the non-dominant limbs displayed better accuracy of foot placement. This suggests that participants may have favoured a different strategy for success depending on whether the agility task was performed with the dominant or non-dominant limb. Considering that limb dominance was determined by subjective preference via questionnaire, it is possible that participants simply felt more confident performing the agility task at higher speeds with the limb that they perceived to be "dominant". However, when speed and accuracy were both accounted for, the overall agility scores did not differ significantly between the dominant and non-dominant limbs. In addition, no significant side-to-side differences were found to exist on any measures of targeting task performance. These results suggest that the right and left lower limbs may be equally adept at novel manipulation and stability tasks, thus implying that limb dominance may only become apparent when an activity has been practiced more often by one limb compared to the other.

Overall, the main findings of this study suggest that gluteus medius strength and endurance do not substantially influence stability, targeting and agility performance as was originally hypothesized. Agility score was the only task performance measure found to significantly correlate with gluteus medius characteristics for both the dominant and non-dominant limbs. Perhaps this result can be explained by the fact that the agility task was the most difficult performance test, thus placing the greatest demands on gluteus medius. During the less challenging performance tasks, participants with decreased gluteus medius strength may have been able to compensate for muscle weakness with increased gluteus medius activation (Homan et al., 2012; Popovich and Kulig, 2012), thus resulting in the observed lack of relationship between strength and performance. However, it seems most likely that strong correlations were not found between gluteus medius characteristics and functional performance measures because, as suggested by DiMattia et al. (2005), the strength of one muscle group such as the hip abductors cannot solely determine the success of a compound, multi-joint lower extremity movement. When coefficients of determination are calculated from the four significant correlations found in the current study between gluteus medius strength and endurance characteristics and functional task performance measures, the results indicate that only 6.4% of stability performance can be explained by gluteus medius endurance while a maximum of 5.24% of targeting speed and 11.22% of agility score can be explained by gluteus medius strength. Thus, the remaining 89-95% of performance on these tasks must be explained by factors other than gluteus medius characteristics.

The large range of scores demonstrated by both the male and female groups for all stability, targeting and agility measures illustrates that clear performance differences were found to exist between study participants. If gluteus medius characteristics are not the main cause of these observed performance differences, then it is evident that there must be other variables involved. Motor control learning is one of the unmeasured variables in this study that likely had a very large impact on functional performance. In support of this theory, Mizner et al. (2008) have previously shown that motor control learning is more important than strength of the hip abductors or other muscle groups in predicting the functional biomechanics of landing during a drop jump task. Although the tests used in the current study were relatively novel and all participants received the same amount of instruction and practice time, it is likely that the task performances of each participant were greatly influenced by the sensorimotor control skills that had been developed through a lifetime of participation in other activities prior to study enrolment.

It is possible that profound gluteus medius weakness may affect performance despite the influence of other factors, but this study of uninjured, healthy participants indicates that there may be a minimum threshold of gluteus medius strength and endurance above which further strength and endurance conditioning do not substantially improve functional performance and motor control training is more beneficial.

Limitations

This study has a number of limitations that need to be considered. Although several methods of determining limb dominance were originally considered, the study results were only evaluated using the manipulation preference method described. It is possible that assessing limb dominance differently prior to analysis may have altered the final statistical results of the study. Determining dominance by calculating which limb actually performed better on the tasks may have been more accurate than relying on subjective predictions of performance via questionnaire. However, the manipulation preference method was selected for ease of comparison to other literature, and examining different processes for determining limb dominance was not one of the goals of this study.

The cross-sectional study design can also be considered a limitation as it is impossible to determine whether or not causal relationships exist between the variables without using a controlled interventional study. Even though it appears that gluteus medius characteristics did not substantially influence stability, targeting and agility performance in the current study, implementation of a gluteus medius strengthening regime followed by re-testing of the same participants would have provided much more robust information regarding the effects of gluteus medius strength and endurance on performance.

Another limitation to consider is the probability that gluteus medius was somewhat active bilaterally during all tasks performed in this study. Gluteus medius was likely involved in stabilizing the non-test leg during both dynamic and isometric strength and endurance assessments and during the stability, targeting and agility tasks. In fact, some participants reported experiencing fatigue in the non-test leg after isometric gluteus medius endurance testing and after dynamic gluteus medius strength and endurance testing. In an attempt to control for any order effects secondary to bilateral gluteus medius involvement during the tasks, half of the participants started all tasks with the right leg while the other half of participants started all tasks with the left leg, and standardized rest times were enforced between trials.

This study also appears to have been underpowered to detect the significance of weaker correlations between the variables. The smallest correlation found to be statistically significant in this study was $r=-0.229$, but several correlations just below that value nearly approached significance. A larger sample size would likely have identified several other significant relationships between gluteus medius characteristics and functional task performance.

Conclusions

The results of this study show that the gluteus medius strength and endurance of healthy individuals may be weakly related to some measures of stability, targeting and agility performance. However, the lack of strong correlations demonstrated between gluteus medius characteristics and functional task performance measures suggests that other factors such as neuromuscular training likely have a much larger influence on stability, foot targeting and agility than the strength and endurance of the hip abductor muscle group alone.

Clinical Relevance

Despite the popularity of gluteus medius strengthening in athletic training programs and injury prevention regimens, this study indicates that improving gluteus medius strength and endurance in healthy individuals may not be an effective way to improve functional task performance. Clinicians should consider that programs focused on training activation patterns and general neuromuscular control may be much more beneficial for improving functional performance than programs solely designed to increase the strength and endurance of smaller muscles such as gluteus medius.

Future Research

In order to further investigate the role of gluteus medius in lower extremity function, future research should compare the strength and endurance of gluteus medius to performance on more challenging static and dynamic balance tasks as well as different types of targeting and agility tasks. Future studies should also consider using a similar testing protocol in the setting of a randomized controlled trial design where participants are assigned to either a gluteus medius strength and endurance training group, a neuromuscular training group, or a control group. Comparing gluteus medius strength and endurance to task performance before and after such a training period would assist in determining whether gluteus medius strength and endurance or motor control play a larger role in predicting functional performance.

References

Al-Hayani, A. (2009). The functional anatomy of hip abductors. *Folia Morphol (Warsz), 68*(2), 98-103.

Arab, A. M., & Nourbakhsh, M. R. (2010). The relationship between hip abductor muscle strength and iliotibial band tightness in individuals with low back pain. *Chiropr Osteopat, 18,* 1. doi: 10.1186/1746-1340-18-1

Arokoski, M. H., Arokoski, J. P., Haara, M., Kankaanpaa, M., Vesterinen, M., Niemitukia, L. H., & Helminen, H. J. (2002). Hip muscle strength and muscle cross sectional area in men with and without hip osteoarthritis. *J Rheumatol, 29*(10), 2185-2195. doi: 0315162X-29-2185

Baldon, R. d. M., Lobato, D. F. M., Carvalho, L. P., Wun, P. Y. L., Santiago, P. R. P., & Serrão, F. V. (2012). Effect of Functional Stabilization Training on Lower Limb Biomechanics in Women. *Medicine & Science in Sports & Exercise, 44*(1), 135-145. doi: 10.1249/MSS.0b013e31822a51bb

Bolgla, L. A., Malone, T. R., Umberger, B. R., & Uhl, T. L. (2011). Comparison of hip and knee strength and neuromuscular activity in subjects with and without patellofemoral pain syndrome. *Int J Sports Phys Ther, 6*(4), 285-296.

Bolgla, L. A., & Uhl, T. L. (2005). Electromyographic analysis of hip rehabilitation exercises in a group of healthy subjects. *J Orthop Sports Phys Ther, 35*(8), 487-494.

Boren, K., Conrey, C., Le Coguic, J., Paprocki, L., Voight, M., & Robinson, T. K. (2011). Electromyographic analysis of gluteus medius and gluteus maximus during rehabilitation exercises. *Int J Sports Phys Ther, 6*(3), 206-223.

Boudreau, S. N., Dwyer, M. K., Mattacola, C. G., Lattermann, C., Uhl, T. L., & McKeon, J. M. (2009). Hip-muscle activation during the lunge, single-leg squat, and step-up-and-over exercises. *J Sport Rehabil, 18*(1), 91-103.

Brophy, R. H., Chiaia, T. A., Maschi, R., Dodson, C. C., Oh, L. S., Lyman, S., . . . Williams, R. J. (2009). The core and hip in soccer athletes compared by gender. *Int J Sports Med, 30*(9), 663-667. doi: 10.1055/s-0029-1225328

Callaway, S., Glaws, K., Mitchell, M., Scerbo, H., Voight, M., & Sells, P. (2012). An analysis of peak pelvis rotation speed, gluteus maximus and medius strength in high versus low handicap golfers during the golf swing. *Int J Sports Phys Ther, 7*(3), 288-295.

Cohen, J. (1992). A power primer. *Psychol Bull, 112*(1), 155-159.

Cowan, S. M., & Crossley, K. M. (2009). Does gender influence neuromotor control of the knee and hip? *J Electromyogr Kinesiol, 19*(2), 276-282. doi: 10.1016/j.jelekin.2007.07.009

Cowan, S. M., Crossley, K. M., & Bennell, K. L. (2009). Altered hip and trunk muscle function in individuals with patellofemoral pain. *Br J Sports Med, 43*(8), 584-588. doi: 10.1136/bjsm.2008.053553

Cutter, N. C., & Kevorkian, G. (Eds.). (1999). *Handbook of Manual Muscle Testing*. New York: McGraw-Hill, Health Professions Division.

Dell, R. B., Holleran, S., & Ramakrishnan, R. (2002). Sample Size Determination. *Institute for Laboratory Animal Research, 43*(4), 207-213.

Dierks, T. A., Manal, K. T., Hamill, J., & Davis, I. S. (2008). Proximal and distal influences on hip and knee kinematics in runners with patellofemoral pain during a prolonged run. *J Orthop Sports Phys Ther, 38*(8), 448-456. doi: 10.2519/jospt.2008.2490

DiMattia, M. A., Livengood, A. L., Uhl, T. L., Mattacola, C. G., & Malone, T. R. (2005). What Are the Validity of the Single-Leg-Squat Test and Its Relationship to Hip-Abduction Strength? *Journal of Sport Rehabilitation, 14*, 108-123.

Distefano, L. J., Blackburn, J. T., Marshall, S. W., & Padua, D. A. (2009). Gluteal muscle activation during common therapeutic exercises. *J Orthop Sports Phys Ther, 39*(7), 532-540. doi: 10.2519/jospt.2009.2796

Dwyer, M. K., Boudreau, S. N., Mattacola, C. G., Uhl, T. L., & Lattermann, C. (2010). Comparison of lower extremity kinematics and hip muscle activation during rehabilitation tasks between sexes. *J Athl Train, 45*(2), 181-190. doi: 10.4085/1062-6050-45.2.181

Earl, J. E., & Hoch, A. Z. (2010). A Proximal Strengthening Program Improves Pain, Function, and Biomechanics in Women With Patellofemoral Pain Syndrome. *The American Journal of Sports Medicine, 39*(1), 154-163. doi: 10.1177/0363546510379967

Elias, L. J., Bryden, M. P., & Bulman-Fleming, M. B. (1998). Footedness is a better predictor than is handedness of emotional lateralization. *Neuropsychologia, 36*(1), 37-43.

Ferber, R., Kendall, K. D., & Farr, L. (2011). Changes in knee biomechanics after a hip-abductor strengthening protocol for runners with patellofemoral pain syndrome. *J Athl Train, 46*(2), 142-149. doi: 10.4085/1062-6050-46.2.142

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *J Exp Psychol, 47*(6), 381-391.

Flack, N. A., Nicholson, H. D., & Woodley, S. J. (2012). A review of the anatomy of the hip abductor muscles, gluteus medius, gluteus minimus, and tensor fascia lata. *Clin Anat, 25*(6), 697-708. doi: 10.1002/ca.22004

Fredericson, M., Cookingham, C. L., Chaudhari, A. M., Dowdell, B. C., Oestreicher, N., & Sahrmann, S. A. (2000). Hip abductor weakness in distance runners with iliotibial band syndrome. *Clin J Sport Med, 10*(3), 169-175.

Fredericson, M., & Moore, T. (2005). Muscular balance, core stability, and injury prevention for middle- and long-distance runners. *Phys Med Rehabil Clin N Am, 16*(3), 669-689. doi: 10.1016/j.pmr.2005.03.001

Friel, K., McLean, N., Myers, C., & Caceres, M. (2006). Ipsilateral Hip Abductor Weakness After Inversion Ankle Sprain. *Journal of Athletic Training, 41*(1), 74-78.

Geiser, C. F., O'Connor, K. M., & Earl, J. E. (2010). Effects of Isolated Hip Abductor Fatigue on Frontal Plane Knee Mechanics. *Medicine & Science in Sports & Exercise, 42*(3), 535-545. doi: 10.1249/MSS.0b013e3181b7b227

Gottschalk, F., Kourosh, S., & Leveau, B. (1989). The functional anatomy of tensor fasciae latae and gluteus medius and minimus. *J Anat, 166*, 179-189.

Grau, S., Krauss, I., Maiwald, C., Best, R., & Horstmann, T. (2008). Hip abductor weakness is not the cause for iliotibial band syndrome. *Int J Sports Med, 29*(7), 579-583. doi: 10.1055/s-2007-989323

Gray, H., Standring, S., Ellis, H., Collins, P., Wigley, C. B., & Berkovitz, B. K. B. (2005). *Gray's Anatomy: The Anatomical Basis of Clinical Practice*. Edinburgh: Elsevier Churchill Livingstone.

Greve, J., Alonso, A., Bordini, A. C. P. G., & Camanho, G. L. (2007). Correlation between body mass index and postural balance. *Clinics (Sao Paulo), 62*(6), 717-720. doi: S1807-59322007000600010 [pii]

Greve, J. M. D. A., Cuğ, M., Dülgeroğlu, D., Brech, G. C., & Alonso, A. C. (2013). Relationship between anthropometric factors, gender, and balance under unstable conditions in young adults. *Biomed Res Int, 2013*, 850424. doi: 10.1155/2013/850424

Gribble, P. A., Robinson, R. H., Hertel, J., & Denegar, C. R. (2009). The effects of gender and fatigue on dynamic postural control. *J Sport Rehabil, 18*(2), 240-257.

Grouios, G., Hatzitaki, V., Kollias, N., & Koidou, I. (2009). Investigating the stabilising and mobilising features of footedness. *Laterality: Asymmetries of Body, Brain and Cognition, 14*(4), 362-380. doi: 10.1080/13576500802434965

Hassard, T. H. (1991). *Understanding Biostatistics*. St. Louis: Mosby-Year Book, Inc.

Henriksen, M., Aaboe, J., Simonsen, E. B., Alkjær, T., & Bliddal, H. (2009). Experimentally reduced hip abductor function during walking: Implications for knee joint loads. *Journal of Biomechanics, 42*(9), 1236-1240. doi: 10.1016/j.jbiomech.2009.03.021

Hoffmann, E., & Hui, M. (2010). Movement times of different arm components. *Ergonomics, 53*(8), 979-993. doi: 10.1080/00140139.2010.500403

Hoffmann, E. R. (1991). A comparison of hand and foot movement times. *Ergonomics, 34*(4), 397-406. doi: 10.1080/00140139108967324

Hollman, J. H., Ginos, B. E., Kozuchowski, J., Vaughn, A. S., Krause, D. A., & Youdas, J. W. (2009). Relationships between knee valgus, hip-muscle strength, and hip-muscle recruitment during a single-limb step-down. *J Sport Rehabil, 18*(1), 104-117.

Homan, K. J., Norcross, M. F., Goerger, B. M., Prentice, W. E., & Blackburn, J. T. (2012). The influence of hip strength on gluteal activity and lower extremity kinematics. *Journal of Electromyography and Kinesiology*. doi: 10.1016/j.jelekin.2012.11.009

Inman, V. T. (1947). Functional aspects of the abductor muscles of the hip. *J Bone Joint Surg Am, 29*(3), 607-619.

Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2003). Hip strength in females with and without patellofemoral pain. *J Orthop Sports Phys Ther, 33*(11), 671-676.

Itoh, H., Kurosaka, M., Yoshiya, S., Ichihashi, N., & Mizuno, K. (1998). Evaluation of functional deficits determined by four different hop tests in patients with anterior cruciate ligament deficiency. *Knee Surg Sports Traumatol Arthrosc, 6*(4), 241-245.

Jacobs, C., & Mattacola, C. (2005a). Sex Differences in Eccentric Hip-Abductor Strength and Knee-Joint Kinematics When Landing From a Jump. *Journal of Sport Rehabilitation, 14*(4), 346-355.

Jacobs, C., Uhl, T. L., Seeley, M., Sterling, W., & Goodrich, L. (2005b). Strength and fatigability of the dominant and nondominant hip abductors. *J Athl Train, 40*(3), 203-206.

Jacobs, C. A., Uhl, T. L., Mattacola, C. G., Shapiro, R., & Rayens, W. S. (2007). Hip abductor function and lower extremity landing kinematics: sex differences. *J Athl Train, 42*(1), 76-83.

Janda, V. (1983). On the Concept of Postural Muscles and Posture in Man. *The Australian Journal of Physiotherapy, 29*(3), 2.

Jaric, S., Mirkov, D., & Markovic, G. (2005). Normalizing physical performance tests for body size: a proposal for standardization. *J Strength Cond Res, 19*(2), 467-474.

Jaric, S., Radosavljevic-Jaric, S., & Johansson, H. (2002). Muscle force and muscle torque in humans require different methods when adjusting for differences in body size. *European Journal of Applied Physiology, 87*(3), 304-307. doi: 10.1007/s00421-002-0638-9

Johansson, C. A., Kent, B. E., & Shepard, K. F. (1983). Relationship between verbal command volume and magnitude of muscle contraction. *Phys Ther, 63*(8), 1260-1265.

Kendall, K. D., Schmidt, C., & Ferber, R. (2010). The relationship between hip-abductor strength and the magnitude of pelvic drop in patients with low back pain. *J Sport Rehabil, 19*(4), 422-435.

Khayambashi, K., Mohammadkhani, Z., Ghaznavi, K., Lyle, M. A., & Powers, C. M. (2011). The Effects of Isolated Hip Abductor and External Rotator Muscle Strengthening on Pain, Health Status, and Hip Strength in Females With Patellofemoral Pain. *Journal of Orthopaedic and Sports Physical Therapy*. doi: 10.2519/jospt.2012.3704

Krause, D. A., Jacobs, R. S., Pilger, K. E., Sather, B. R., Sibunka, S. P., & Hollman, J. H. (2009). Electromyographic analysis of the gluteus medius in five weight-bearing exercises. *J Strength Cond Res, 23*(9), 2689-2694. doi: 10.1519/JSC.0b013e3181bbe861

Leavey, V. J. (2006). *The Comparative Effects of a Six-Week Balance Training Program, GM Strength Training Program and Combined Program on Dynamic Postural Control.* Master of Science in Athletic Training, West Virginia University, Morgantown, West Virginia.

Leetun, D. T., Ireland, M. L., Willson, J. D., Ballantyne, B. T., & Davis, I. M. (2004). Core Stability Measures as Risk Factors for Lower Extremity Injury in Athletes. *Medicine & Science in Sports & Exercise, 36*(6), 926-934. doi: 10.1249/01.mss.0000128145.75199.c3

Long-Rossi, F., & Salsich, G. B. (2009). Pain and hip lateral rotator muscle strength contribute to functional status in females with patellofemoral pain. *Physiotherapy Research International*, 57-64. doi: 10.1002/pri.449

Magee, D. J. (2002). *Orthopedic Physical Assessment* (4th ed.). Philadelphia: Saunders.

Marshall, P. W. M., Patel, H., & Callaghan, J. P. (2011). Gluteus medius strength, endurance, and co-activation in the development of low back pain during prolonged standing. *Human Movement Science*, *30*(1), 63-73. doi: 10.1016/j.humov.2010.08.017

McMullen, K. L., Cosby, N. L., Hertel, J., Ingersoll, C. D., & Hart, J. M. (2011). Lower extremity neuromuscular control immediately after fatiguing hip-abduction exercise. *J Athl Train, 46*(6), 607-614.

McNair, P. J., Depledge, J., Brettkelly, M., & Stanley, S. N. (1996). Verbal encouragement: effects on maximum effort voluntary muscle action. *Br J Sports Med, 30*(3), 243-245.

Millard, M., Wight, D., McPhee, J., Kubica, E., & Wang, D. (2009). Human Foot Placement and Balance in the Sagittal Plane. *Journal of Biomechanical Engineering, 131*(12), 121001. doi: 10.1115/1.4000193

Mizner, R. L., Kawaguchi, J. K., & Chmielewski, T. L. (2008). Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther, 38*(6), 353-361. doi: 10.2519/jospt.2008.2726

Motulsky, H. (2010). *Intuitive Biostatistics* (2 ed.). New York: Oxford University Press.

Nadler, S. F., Malanga, G. A., DePrince, M., Stitik, T. P., & Feinberg, J. H. (2000). The relationship between lower extremity injury, low back pain, and hip muscle strength in male and female collegiate athletes. *Clin J Sport Med, 10*(2), 89-97.

Nakagawa, T. H., Moriya, É. T. U., Maciel, C. D., & Serrão, F. V. (2012). Frontal Plane Biomechanics in Males and Females with and without Patellofemoral Pain. *Medicine & Science in Sports & Exercise, 44*(9), 1747-1755. doi: 10.1249/MSS.0b013e318256903a

Nguyen, A. D., Shultz, S. J., Schmitz, R. J., Luecht, R. M., & Perrin, D. H. (2011). A preliminary multifactorial approach describing the relationships among lower extremity alignment, hip muscle activation, and lower extremity joint excursion. *J Athl Train, 46*(3), 246-256.

Niemuth, P. E., Johnson, R. J., Myers, M. J., & Thieman, T. J. (2005). Hip muscle weakness and overuse injuries in recreational runners. *Clin J Sport Med, 15*(1), 14-21.

O'Sullivan, K., Smith, S. M., & Sainsbury, D. (2010). Electromyographic analysis of the three subdivisions of gluteus medius during weight-bearing exercises. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology, 2*(1), 17. doi: 10.1186/1758-2555-2-17

O'Sullivan, M., Blake, C., Cunningham, C., Boyle, G., & Finucane, C. (2008). Correlation of accelerometry with clinical balance tests in older fallers and non-fallers. *Age and Ageing, 38*(3), 308-313. doi: 10.1093/ageing/afp009

Ortiz, A., Olson, S., Trudelle-Jackson, E., Rosario, M., & Venegas, H. L. (2011). Landing Mechanics During Side Hopping and Crossover Hopping Maneuvers in Noninjured Women and Women With Anterior Cruciate Ligament Reconstruction. *Pm&R, 3*(1), 13-20. doi: 10.1016/j.pmrj.2010.10.018

Palastanga, N., Field, D., & Soames, R. (2002). Chapter 4: The Lower Limb. *Anatomy and Human Movement: Structure and Function* (pp. 246-263). Edinburgh: Butterworth Heinemann. (Reprinted from: Fourth Edition).

Patrek, M. F., Kernozek, T. W., Willson, J. D., Wright, G. A., & Doberstein, S. T. (2011). Hip-abductor fatigue and single-leg landing mechanics in women athletes. *J Athl Train, 46*(1), 31-42. doi: 10.4085/1062-6050-46.1.31

Peters, M. (1988). Footedness: asymmetries in foot preference and skill and neuropsychological assessment of foot movement. *Psychol Bull, 103*(2), 179-192.

Piva, S. R., Teixeira, P. E., Almeida, G. J., Gil, A. B., DiGioia, A. M., 3rd, Levison, T. J., & Fitzgerald, G. K. (2011). Contribution of hip abductor strength to physical function in patients with total knee arthroplasty. *Phys Ther, 91*(2), 225-233.

Popovich, J. M., & Kulig, K. (2012). Lumbopelvic Landing Kinematics and EMG in Women with Contrasting Hip Strength. *Medicine & Science in Sports & Exercise, 44*(1), 146-153. doi: 10.1249/MSS.0b013e3182267435

Powers, C. M. (2010). The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther, 40*(2), 42-51. doi: 10.2519/jospt.2010.3337

Presswood, L., Cronin, J., Keogh, J. W. L., & Whatman, C. (2008). Gluteus Medius: Applied Anatomy, Dysfunction, Assessment, and Progressive Strengthening. *Strength and Conditioning Journal, 30*(5), 41-53.

Prins, M. R., & van der Wurff, P. (2009). Females with patellofemoral pain syndrome have weak hip muscles: a systematic review. *Australian Journal of Physiotherapy, 55*(1), 9-15. doi: 10.1016/s0004-9514(09)70055-8

Reiman, M. P., Bolgla, L. A., & Loudon, J. K. (2011). A literature review of studies evaluating gluteus maximus and gluteus medius activation during rehabilitation exercises. *Physiotherapy Theory and Practice*, 1-12. doi: 10.3109/09593985.2011.604981

Robinson, R. L., & Nee, R. J. (2007). Analysis of hip strength in females seeking physical therapy treatment for unilateral patellofemoral pain syndrome. *J Orthop Sports Phys Ther, 37*(5), 232-238.

Rohr, L. E. (2006). Upper and lower limb reciprocal tapping: evidence for gender biases. *J Mot Behav, 38*(1), 15-17. doi: 10.3200/JMBR.38.1.15-17

Salavati, M., Moghadam, M., Ebrahimi, I., & Arab, A. M. (2007). Changes in postural stability with fatigue of lower extremity frontal and sagittal plane movers. *Gait & Posture, 26*(2), 214-218. doi: 10.1016/j.gaitpost.2006.09.001

Snyder, K. R., Earl, J. E., O'Connor, K. M., & Ebersole, K. T. (2009). Resistance training is accompanied by increases in hip strength and changes in lower extremity biomechanics during running. *Clinical Biomechanics, 24*(1), 26-34. doi: 10.1016/j.clinbiomech.2008.09.009

Souza, R. B., & Powers, C. M. (2009). Differences in hip kinematics, muscle strength, and muscle activation between subjects with and without patellofemoral pain. *J Orthop Sports Phys Ther, 39*(1), 12-19. doi: 10.2519/jospt.2009.2885

Sparrow, W. A., van der Kamp, J., Savelsbergh, G. J. P., & Tirosh, O. (2003). Foot-targeting in reaching and grasping. *Gait & Posture, 18*(1), 60-68. doi: 10.1016/s0966-6362(02)00162-5

Thijs, Y., Pattyn, E., Van Tiggelen, D., Rombaut, L., & Witvrouw, E. (2011). Is hip muscle weakness a predisposing factor for patellofemoral pain in female novice runners? A prospective study. *Am J Sports Med, 39*(9), 1877-1882. doi: 10.1177/0363546511407617

Trendelenburg, F. (1998). Trendelenburg's test: 1895. *Clin Orthop Relat Res*(355), 3-7.

Tyler, T. F., Nicholas, S. J., Mullaney, M. J., & McHugh, M. P. (2006). The role of hip muscle function in the treatment of patellofemoral pain syndrome. *Am J Sports Med, 34*(4), 630-636. doi: 10.1177/0363546505281808

Wang, Z., & Newell, K. M. (2013). Footedness exploited as a function of postural task asymmetry. *Laterality: Asymmetries of Body, Brain and Cognition, 18*(3), 303-318. doi: 10.1080/1357650x.2012.672423

Whitney, S. L., Roche, J. L., Marchetti, G. F., Lin, C. C., Steed, D. P., Furman, G. R., . . . Redfern, M. S. (2011). A comparison of accelerometry and center of pressure measures during computerized dynamic posturography: A measure of balance. *Gait & Posture, 33*(4), 594-599. doi: 10.1016/j.gaitpost.2011.01.015

Willson, J. D., & Davis, I. S. (2009). Lower extremity strength and mechanics during jumping in women with patellofemoral pain. *J Sport Rehabil, 18*(1), 76-90.

Willy, R. W., & Davis, I. S. (2011). The Effect of a Hip-Strengthening Program on Mechanics During Running and During a Single-Leg Squat. *Journal of Orthopaedic and Sports Physical Therapy*. doi: 10.2519/jospt.2011.3470

Appendix A

RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM

The Relationship of Gluteus Medius Strength and Endurance to Lower Limb Stability, Targeting and Agility

Principal Investigator: Lori Graumann
University of Manitoba
R106 - 771 McDermot Avenue, Winnipeg, MB R3T 2N2
[redacted]

Co-Investigators: Dr. Dean Kriellaars
University of Manitoba
R106 - 771 McDermot Avenue, Winnipeg, MB R3T 2N2
[redacted]

Dr. Barbara Shay
University of Manitoba
R106 - 771 McDermot Avenue, Winnipeg, MB R3T 2N2
[redacted]

You are being asked to participate in a research study. Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this study and you may discuss it with your friends or family before you make your decision. This consent form may contain words that you do not understand. Please ask the study staff to explain any words or information that you do not clearly understand**.**

Purpose of Study

This research study is being conducted to study the role of hip muscles (gluteus medius and other hip abductors) in the functional ability of the lower limbs in healthy individuals.

A total of 50 participants will participate in this study.

Study procedures

If you take part in this study and sign this informed consent form, you will participate in the following procedures:

- You will complete a questionnaire about which foot you use for different tasks.

- Your height, weight and leg lengths will be measured.

- Hip strength of your right and left legs will be measured. You will be asked to generate a maximal effort contraction in standing for less than 4 seconds and repeat this a few times. You will then be asked to perform the same procedure but to hold the contraction for approximately 40 seconds to see how much you fatigue. You will also be required to lie on your side and lift your leg as many times as possible. Rest will be given between all the tests.

- You will then be asked to perform a standing broad jump. Instruction will be provided if you do not know how to perform this test.

- Your balance will be tested while you stand on one foot. This test will be repeated for both legs.

- Your ability to move your foot from one place to a target location will be assessed. This test will be repeated for both legs.

- Your ability to hop from one position to another (between two lines on the floor a few inches apart) will be assessed. This test will be repeated for both legs.

Your feet will be videotaped during some of the above tasks to assist with analysis. No imagery of your face or other identifying features will be included on the videotapes.

Participation in the study will be completed within two hours. This is the only session you will be asked to attend.

The researcher may decide to take you off this study if you are having significant difficulty performing the tasks as required due to physical limitations not previously identified.

You can stop participating at any time. However, if you decide to stop participating in the study, we encourage you to talk to the study staff first.

Participants who are interested in the final results of this study may contact the principal investigator by phone or e-mail after September 2012 and a copy of the overall results and conclusions will be provided. No individual information will be included in this report.

Risks and Discomforts

There is a very low risk of acquiring a lower body injury such as a muscle strain or ligament sprain while participating in the physical tasks of this study. The risk of injury while participating in these tasks is no more than the risk of acquiring injury while participating in a regular exercise program. The investigators will explain all tasks in detail and allow supervised practice with more difficult tasks prior to testing in order to minimize the risk of injury due to improper technique. You will be encouraged to express your concerns and withdraw from the study if you feel that you are presented with a task that you cannot safely perform.

You may also experience very minor muscle soreness in the lower limbs in the hours following this study for up to 72 hours. This is a normal response to exercise and is not harmful to you in any way.

During the balance test, a small device that measures your movement (approximately the size of a match box) will be attached to your breastbone with adhesive tape. Removal of the tape may cause very minor discomfort and slight redness may remain on the skin for a short period of time following completion of the study. People who have allergies to adhesives may experience a mild skin rash or local inflammation after tape removal that lasts for several hours or days. You will be asked to advise the investigator if you have a known allergy to adhesive tape.

Benefits

There may or may not be direct benefit to you from participating in this study. We hope the information learned from this study will provide useful information regarding the role of hip muscles in performing functional tasks. This information can help guide physiotherapists and other fitness professionals in the development of appropriate rehabilitation programs or injury prevention programs.

Costs

All the procedures, which will be performed as part of this study, are provided at no cost to you.

Payment for participation

You will receive no payment or reimbursement for any expenses related to taking part in this study.

Confidentiality

Information gathered in this research study may be published or presented in public forums, however your name and other identifying information will not be used or revealed. After you have completed the testing procedure only a study ID is kept with your data, and no personal identifying information is retained. All videotapes made during the study will be destroyed immediately after analysis.

Despite efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

The consent form will be the only document that retains your name and this form will be kept in a locked filing cabinet.

The University of Manitoba Health Research Ethics Board may review records related to the study for quality assurance purposes.

All records will be kept in a locked secure area and only those persons identified will have access to these records. If any of your research records need to be copied to any of the above, your name and all identifying information will be removed. No information revealing any personal information such as your name, address or telephone number will leave the University of Manitoba.

Voluntary Participation/Withdrawal from the Study

Your decision to take part in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time. If the study staff feels that it is in your best interest to withdraw you from the study, they will remove you without your consent.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study.

If you are a student or an employee of one of the investigators, your decision to participate will not influence your performance evaluation.

Medical Care for Injury Related to the Study

You are not waiving any of your legal rights by signing this consent form nor releasing the investigator(s) or the sponsor(s) from their legal and professional responsibilities. Any injury arising from this study will be managed within the health care system.

Questions

You are free to ask any questions that you may have about this study and your rights as a research participant. If any questions come up during or after the study or if you have a research-related injury, contact the study staff: Lori Graumann at [redacted] or Dr. Dean Kriellaars at [redacted] [redacted].

For questions about your rights as a research participant, you may contact The University of Manitoba, Bannatyne Campus Research Ethics Board Office at (204) 789-3389

Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

Statement of Consent

I have read this consent form. I have had the opportunity to discuss this research study with Lori Graumann, Dean Kriellaars or Barb Shay and or his/her study staff. I have had my questions answered by them in language I understand. The risks and benefits have been explained to me. I believe that I have not been unduly influenced by any study team member to participate in the research study by any statements or implied statements. Any relationship (such as employer, supervisor or family member) I may have with the study team has not affected my decision to participate. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this study is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed. I authorize the inspection of any of my records that relate to this study by The University of Manitoba Research Ethics Board for quality assurance purposes.

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

I agree to be contacted for future follow-up in relation to this study: Yes _ No _

Participant signature__________________________ Date ______________
(day/month/year)

Participant printed name: ____________________________

Relationship (if any) to study team members:_________________________

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Printed Name: _______________________________ Date ________________
(day/month/year)

Signature: ____________________________

Role in the study: ____________________________

Appendix B

Participant Questionnaire

(Powered by Google Docs)

Participant Number

Age

Birth Month : Write down the month NUMBER (Example: For April you would write down "4")

Birth Day

Birth Year: Write down the full year (Example: "1982")

Height (cm)

Weight (kg)

RIGHT Leg Length 1(cm)

LEFT Leg Length 1 (cm)

RIGHT Leg Length 2 (cm)

LEFT Leg Length 2 (cm)

How would you rate the amount of physical activity required by your current occupation (school, work, etc.)?

1 - Minimal Physical Activity	2	3 - Moderate Physical Activity	4	5 - Intense Physical Activity
○	○	○	○	○

How would you rate your current level of participation in exercise and sport?

Exercise AND/OR play sports less than 1x/week	Exercise moderately AND/OR play recreational sports 2-3x/week	Exercise moderately AND/OR play recreational sports more than 3x/week	Exercise intensely AND/OR play competitive sports almost daily	ELITE competitive athlete
○	○	○	○	○

What is the highest level of participation in exercise and sport that you have achieved in the past 5 years?

Exercise AND/OR play sports less than 1x/week	Exercise moderately AND/OR play recreational sports 2-3x/week	Exercise moderately AND/OR play recreational sports more than 3x/week	Exercise intensely AND/OR play competitive sports almost daily	ELITE competitive athlete
○	○	○	○	○