The Effects of Foam Rolling on Muscular Co-Activation Around the Knee Joint

by

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ABSTRACT

The major objectives of this thesis were to determine if foam rolling had any effect on antagonist muscle activation and whether those changes would alter muscular co-activation patterns. The results from this thesis along with current literature will help clinicians to develop adequate exercise prescription for rehabilitative and pre-activity purposes. The existing literature has shown that foam rolling or roller massagers can increase range of motion (ROM), improve performance, and alter pain perception, however little research exists regarding changes in muscle activation following foam rolling. This study developed a reliable method for measuring muscle activation around the knee joint and using that method found that foam rolling the quadriceps can impair hamstrings muscle activation likely due to greater levels of perceived pain when rolling the quadriceps.

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LIST OF ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Spine
BF	Biceps Femoris
BPM	Beats Per Minute
CV	Coefficient of Variation
DOMS	Delayed Onset Muscle Soreness
EMG	Electromyography
FMS	Functional Movement Screen
GTO	Golgi Tendon Organ
ICC	Interclass Correlation Coefficient
KP	Kilopascal
LG	Lateral Gastrocnemius
MVC	Maximal Voluntary Contraction
N	Newtons
PAR-Q	Physical Activity Readiness Questionnaire
PNF	Proprioceptive Neuromuscular Facilitation
RF	Rectus Femoris
RMS	Root Mean Squared
ROM	Range of Motion
SD	Standard Deviation
SEM	Standard Error of Measurement
SMFR	Self Myofascial Release
TFL	Tensor Fasciae Latae
VL	Vastus Lateralis
VM	Vastus Medialis
Vmax	Maximal Vertical Jump Height

CHAPTER 1: INTRODUCTION

Chapter 1.1 Introduction

There has been an abundance of **r**esearch on foam rollers and roller-massagers in the last several years [1-3,5,10,12,13,15-18,20,21,25]. Thus far roller application has been shown to influence range of motion (ROM) [1,2,10,15,17,18,25], performance [2,12,20,21], and pain perception [1,13,16,21]. Few studies have examined how muscle activation is influenced by rolling [2,15], particularly in the antagonist musculature. With the use of these tools growing rapidly it seems appropriate to examine how they may impact muscle activation and joint mechanics.

Electromyography is a common method for examining muscular activation. Co-activation ratios can be generated from electromyographic data to tell researchers how the muscles around the joint work together to influence joint mechanics [6,9,11,14,19,22]. Co-activation ratios are of interest, particularly around the oft-injured knee joint [11,14,19] as they can provide useful information regarding injury susceptibility, particularly during dynamic movements [11]. The literature regarding muscular co-activation during movement is extensive, however there is inconsistency between testing methods [4,7,23,24]. Many current tests fail to individualize task difficulty and therefore the reliability of these tests should be questioned [4,7,23,24]. A consistently reliable testing method is needed in order to properly examine muscle activation during dynamic movements (IE: is the task the same relative difficulty for each individual).

Once a reliable method for measuring muscle activation has been established it can be utilized to determine what - if any - effect foam rolling has on muscle activation by examining pre-post test differences in activation. The present literature offers little to no guidelines for exercise prescription in regards to foam rolling or roller-massager use. Without knowing the full effects foam rolling may have on muscle activation surrounding a joint it is impossible to know whether or not it may be beneficial or detrimental to an individual. Thus, it is logical to examine whether foam rolling has any effect on local or non-local muscle activation and and co-activation patterns. More specifically, examining the effects of foam rolling on muscle activation around the knee joint may help future clinicians to develop guidelines for proper use and exercise prescription. The purpose of this work is to determine how foam rolling can affect both local and non-local muscle activation and how changes in activation may affect joint function.

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CHAPTER 2: REVIEW OF LITERATURE

Chapter 2.1 Introduction

The connective tissue that connects and surrounds the muscle is known as myofascia. It has been shown to contribute to tissue mobility and elasticity [51]. Myofascial release has been used for the treatment of spasm, tightness, pain and muscle imbalances [52]. Similar to massage, myofascial release involves applying pressure to muscular tissue. A relatively new form of myofascial release is self-myofascial release (SMFR). SMFR research has increased significantly over the last several years [7, 22, 55]. There are many different modalities for applying SMFR. Foam rollers and roller massagers come in different shapes, sizes densities and textures, each of which may produce varying results following their application. SMFR is practical because individuals can utilize the technique without the help of a clinician. Therefore, the use of SMFR may be beneficial in saving both time and money while giving similar performance/rehabilitative results as other myofascial release modalities.

The majority of the SMRF research focuses on a young, healthy and trained population. Benefits appear to include an increase in range of motion [22, 55], a reduction of delayed onset muscle soreness [47], and increased cardiovascular function [42]. Difficulties interpreting the research arise since a variety of SMR techniques have been utilized. Furthermore, there is great variation in application time and pressure exerted, [7, 22, 55]. Curran et al. [17] examined two different types of rollers utilized for SMFR. Subjects used either a multi-ridged roller or a basic foam roller. They discovered that the multi-ridged roller exerted a higher mean pressure and greater mean pressure per contact area. The elevation in pressure could be attributed to different product density. Researchers did not collect physiological data. It is plausible that different pressures could elicit different physiological results. Furthermore, it is possible that a roller with constant pressure and a roller with intermittent pressure could affect different mechanoreceptors and hence produce different results. For example, in accordance with Schleip [51] Pacini receptors would likely be affected by intermittent pressures whereas Ruffini receptors would be more likely to be stimulated by sustained pressure.

Researchers have primarily examined the effects of SMFR when applied to all muscles surrounding a joint. Research of that style produces effects such as an increase in range of motion, improved neuromuscular efficiency and improved arterial function [7, 36, 42, 55] . To date, researchers have not examined the effects of SMFR on agonist-antagonist muscle activation relationships.

It is possible that there are several non-local effects of SMFR given the interconnectivity between agonist-antagonist musculature via the stretch reflex and reciprocal inhibition [11]. If reciprocal inhibition is affected, firing rates during rhythmic movement may be altered. Conversely if co-activation is affected than the muscular response to high

velocity displacement and loaded movements may undergo a change [54]. Furthermore, it is known that antagonist co-activation provides greater joint stabilization [3, 54] and that fatigue, neuromuscular training [28] and gender [24] can alter an individuals ability to co-activate. Therefore since SMFR has been shown to alter neural firing efficiency [7], it must be determined if SMFR has an effect on muscular co-activation and whether differing applications of SMFR result in a variation of co-activation. It is hypothesized that SMFR of a muscle will produce a significant change in activation of the immediate antagonist muscle. Additionally it is expected that changes in muscle activation will produce changes in subsequent co-activation ratios.

Chapter 2.2 Fascial tissue and Self Myofascial Release

Fascia is a tight connective tissue that envelops muscle, cardiovascular and many other tissues throughout the human body. It is said that applying pressure to fascia can help break up adhesions in the fascial tissue and thus increase range of motion [31]. Myofascial trigger points are painful taut bands within fascial tissue that are typically caused by excess acetylcholine release at the neuromuscular junction [57]. Trigger Points are known to cause both local and referred pain [57]. Muscles with myofascial trigger points typically result in local tightness and subsequent vasoconstriction [57]. Since Okamoto et al. [42] showed that the application of SMFR can facilitate vasodilation it may be useful in the treatment of myofascial trigger points. The pressure applied to the muscle using SMFR techniques has been suggested to alter the activity of mechanoreceptors embedded within muscle and fascial tissues. Thus the neural pathways associated with these mechanoreceptors subsequently act to alter tissue properties [51].

There are four types of mechanoreceptors within fascial tissue. They are Golgi, Pacini (and Paciniform), Ruffini and interstitial receptors. These receptors have also been found within muscle, tendon and ligamentous tissues [51]. Each receptor responds to different external stimuli, which subsequently produce distinct neuromuscular responses including change in muscle tone and proprioception [51]. It is possible that each of these receptors have a role in the physiological effects produced following foam rolling [51].

Golgi receptors typically respond to active muscle contraction in order to decrease muscle tension in the activated muscle. Pacini and Paciniform receptors are innervated by type II fibres and typically respond to vibration and quick changes in pressure. They are known to have effects on kinesthetic sense. Similarly, Ruffini fibres are also innervated by type II nerve fibres but respond to sustained pressure and lateral stretching. Ruffini fibres help to inhibit sympathetic processes by lowering nervous system activity. Lastly interstitial receptors respond to changes in both rapid and sustained pressure. They typically result in changes in autonomic responses such as vasodilation and vasoconstriction [51].

To date research has focused on range of motion and performance following SMFR application. SMFR has been shown to be equally as effective as static stretching for increasing range of motion in some studies [22, 36, 40]. Halperin et al., [22] found that while static stretching produces reductions in force SMFR does not.

The lack of SMFR induced force impairments may be attributed to the stimulation of different mechanoreceptors. It is likely that foam rolling stimulates a combination of Golgi, Pacini, Ruffini and interstitial receptors. This may not have been the case in static stretching trials since Golgi receptors are known to respond to an active contraction and therefore would not be active during a passive static stretch [51]. Due to pressure elicited from the application of SMFR it is possible that muscle tissue is slightly contracting and thus activating Golgi receptors. In the case of inhibition, Ib interneurons receive input from

Golgi and other receptors [11]. These interneurons then inhibit motor neurons belonging to the same muscle [11]. Despite the fact that Golgi receptors have inhibitory properties, it is likely that inhibition does not occur for a long enough time period to impair performance. Golgi receptors have several functions including acting as an anti-gravity receptor. Therefore it is likely that the inhibitory function of Golgi receptors are short term as they need to react to several other stimulations and circumstances [51]. Different types of external stimuli activate different mechanoreceptors and subsequently different neural pathways which each produce different physiological responses.

In one study researchers found that even short (≤ 10 s) acute bouts of SMFR can be enough to increase range of motion [55]. It is unlikely that 5-10s of SMFR would substantially alter fascial and muscle characteristics given the thixotropic model of fascial properties. The thixotropic model suggests that tissue changes are only present temporarily while heat and pressure are applied. Once external stimuli such as heat and pressure are removed tissue quickly returns to its normal state [51]. Therefore it is likely that this intervention performed by Sullivan et al. [55] altered the Pacini and Paciniform mechanoreceptors and created proprioceptive changes [51]. An unpublished study by Miller and Rockey (2006) produced conflicting results, finding no significant differences in hamstrings range of motion . The conflicting results could have been a product of variance within interventions including time and roller style. In addition to these variables, the two studies used different methods for measuring hamstrings range of motion, which may have contributed to the opposing conclusions. Miller and Rockey [38] determined hamstrings range of motion by using an inclinometer and a flexometer® in a 90-90 position to examine active knee extension. Conversely, Sullivan et al. used a sit and reach test to determine flexibility. Furthermore, Sullivan et al. [55] used a roller-massager by Theraband® whereas Miller and Rockey [38] used a standard foam roller. Additionally, Miller and Rockey suggested inconsistency in their methodology [38].

One group of researchers examined chronic effects of SMFR and found that the only significant increase in hip angle was within one single session [9]. This research suggested that if tissue is affected due to SMFR the effect is not long term. This is consistent with the work by Schleip [51] which suggested a theory was needed to describe short and long term changes in fascial tissue. It was postulated that there are mechanisms in place to prevent daily actions – such as sitting in a chair – from causing extensive changes in fascial tissue properties [51].

Other researchers have focused on the effects of SMFR on delayed onset muscle soreness (DOMS). Pearcey et al. [47] found foam rolling reduced DOMS following a fatigue intervention. Those who utilized SMFR following exercise reported less muscle tenderness compared to those who did not apply SMFR to the affected muscle. Pearcey et al. [47] reported that performance may be limited due to sarcomere damage, fatigue, range of motion impairments, inflammation and fear of movement due to pain. It is possible that SMFR stimulated mechanoreceptors in order to facilitate a neuroendocrine response and subsequently result in serotonin release [51]. Secondly, MacDonald et al. [37] and Pearcey et

al, [47] discovered that in addition to reducing delayed onset muscle soreness, SMFR can also aid in performance following a fatigue inducing intervention. It was found that dynamic movements such as the vertical jump benefited from the application of SMFR. Crane et al. [16] showed that massage may reduce pain and inflammation in muscle tissue, likely due to increased blood flow. Therefore, it is plausible that SMFR, like massage, could also reduce pain and inflammation and thus result in a reduction of performance decrements. Peacock et al. [46] found that strength, power, agility and speed were increased when foam rolling was combined with dynamic stretching in comparison with dynamic stretching alone. Subjects performed significantly better in vertical jump, standing long jump, 18.3M pro agility test, indirect 1-RM bench press and 37 metre sprint tests. It is possible that the application of foam rolling increased atrial dilation and thus improved local bloodflow [42].

Healey et al. [26] found those who utilized foam rolling had a significantly lower level of fatigue perception following foam rolling when compared to subjects who held a standard plank for the same amount of time. The reduced effort may be a result of a serotogenic release due to neuroendocrine changes following the application of SMFR [51]. In addition Healey et al. [26] found no significant changes in performance between groups. This is consistent with the results of Fama and Bueti [19] who suggested SMFR is not beneficial prior to exercise. Conversely Pearcey et al. [47] found performance improvements when recovering from DOMS. Performance improvements as a result of SMFR found by Macdonald et al. [37] and Peacock et al. [46] may also be attributed to a fatigue reduction as a result of increased serotogenic release.

Foam rolling has also been reported to increase neuromuscular efficiency during a lunge by decreasing the amount of muscle activity required to produce the same movement. This could be due to reflex arcs such as the myotactic stretch reflex, reciprocal inhibition and recurrent inhibition associated with muscle activation [11]. These results could also be attributed to an alteration in muscle contractile properties. Greater contractile efficiency leads to less motor unit activation. This may be the product of increased muscle spindle length and subsequent reductions in muscle stiffness. Furthermore, there could be suppressed afferent excitation following the application of SMFR [7]. Anterior cruciate ligament (ACL) injuries often occur when the knee is put into a valgus position, typically from poor medial preparatory activation [44]. Therefore, if SMFR can increase neuromuscular efficiency and activation patterns of specific musculature it may be beneficial in the prevention of serious injury.

Research has also indicated that applying pressure – such is the case in SMFR – could also have cardiovascular benefits. Arroyo-Morales et al., [2] reported that myofascial release can reduce blood pressure following high intensity exercise. In addition, Okamoto et al. [42] examined the effect of SMFR on arterial function by measuring pulse wave velocity (PWV) and blood plasma nitric oxide content. Following the application of SMFR researchers saw a decrease in

PWV and an increase in nitric oxide content. This research is consistent with a concept proposed by Schleip [51], which suggested that stimulation of type III receptors can decrease blood pressure. It is possible that the intervention conducted by Okamato et al. activated type III interstitial mechanoreceptors. As reported earlier, these receptors are said to have autonomic effects, which can alter blood pressure. It is likely that these mechanoreceptors and their subsequent reflexes altered local arterial properties via vasodilation. This in turn could have caused a reduction in PWV [42, 51].

It should be noted that myofascial release has been used to create non-local changes in tissue properties. For example, if SMFR is applied in one part of the body, changes may occur locally and non-locally. One group of researchers applied myofascial release to the suboccipital region and noticed changes in the range of motion of the hamstrings. Hence fascial tissue may communicate throughout the body and the effects may not be primarily localized [13]. Additionally, it has been found that massage in one limb can reduce soreness in the contralateral limb [30]. Furthermore there is literature demonstrating unilateral limb fatigue can affect contralateral limb performance [23]. Physiologically, it is possible that changes as a result of SMFR are not only localized [23]. Thus it is plausible that when a mechanoreceptor is stimulated whether it be Golgi, Pacini, Rufini or interstitial, the effects are both local and non-local. Afferent feedback may crossover at the spinal cord to contralateral areas and may also be transmitted via long reflex loops to the supraspinal region.

In summary it is plausible that changes in tissue elasticity following SMFR are due to the stimulation of mechanoreceptors within muscle, tendon, fascial and ligamentous tissue. It is plausible that changes due to SMFR can be attributed to the stimulation of Pacini, Paciniform, Ruffini, Golgi, and interstitial mechanoreceptors. When different receptors are stimulated different neural networks are activated and hence different results occur.

There are a number of unfounded claims that SMFR may aid in correcting musculature imbalances and thus prevent injury. To date, there has been little research examining the effects of SMFR on muscle imbalances and thus it remains an unfounded claim. In order to examine imbalances, it is important to first consider the relationship between agonist and antagonist muscle groups.

Chapter 2.3 Agonist-Antagonist Relationships

Research examining co-activation relationships between agonist and antagonist musculature is plentiful [1, 3, 4]. The two are connected in that the antagonist passively lengthens when the agonist shortens. . Physiologically, they are also connected via a series of reflexes. These reflexes help to initiate and inhibit movement within muscles via sensory and motor neurons. It is well known that reflex arcs affect agonist-antagonist relationships. When a muscle is stretched an afferent signal relays to motor neurons of that same pool to fire. This is known as the myotactic stretch reflex [11]. Simultaneously reciprocal inhibition occurs when the same signal excites Ia inhibitory neurons, which subsequently cause inhibition in the antagonist muscle [11]. These Ia inhibitory neurons can also be activated via supraspinal centres when the brain activates the agonist [5]. Agonist and antagonist motor neurons usually fire sequentially during locomotor human movement [56]. Future research is required to determine how foam rolling a muscle affects activation in its antagonist.

Given the high levels of interconnectivity it is impossible to apply an intervention to an agonist muscle without considering the effects that may occur to the immediate antagonist. Few researchers have examined the effect an intervention that targets the mechanoceptors and elastic properties of the agonist may have on the antagonist when examining joint mechanics. Those who have examined this relationship have primarily investigated this idea during stretching.

Two studies have examined how the antagonist is affected following static stretching while the third examined proprioceptive neuromuscular facilitation (PNF) stretching. Sandberg et al. [50] explored the effect of antagonist static stretching on a number of performance measures and found an increase in knee extension peak torque at 300˚/s and an increase in vertical jump height and power. Miranda et al. [39] performed static antagonist stretching between repetitions of seated row exercises and found an increase in agonist muscle activity during exercise. In addition, subjects were able to perform more repetitions following the stretch. Authors postulated that by stretching the antagonist musculature the Golgi tendon organ and subsequent 1b afferent nerve fibres may not be as sensitive to changes in tension. Miranda et al. [39] noticed that agonist (non-stretched) muscle activity increased while completing a seated row exercise. In contrast, researchers noted no significant change in pectoral muscle activity following the pectoral stretch. Based on decreased antagonist muscle activity, these results indicate that alpha-gamma co-activation may not be a factor. This is consistent with previous research, which has suggested that passive stretching may not stimulate the Golgi tendon organ [29]. By applying PNF stretching between sets of a seated row exercise, Paz et al. [45] discovered that subjects receiving stretching performed better in subsequent sets compared to those subjects who did not over the same time period. Like SMFR, PNF stretching has been shown to increase neuromuscular efficiency, range of motion, and performance [7, 25, 46].

There are four potential physiological mechanisms involved with potential changes in muscle length and activation following PNF stretching. They are autogenic inhibition, reciprocal inhibition, the gate control theory and the stress relaxation theory [25]. Autogenic inhibition suggests that Golgi tendon organs (GTOs) from a muscle relay signals to the spinal cord to inhibitory interneurons, which in turn inhibit the firing of the motor units from that same muscle. The duration of the inhibitory period is unknown, although the duration of changes in range of motion and performance appear to be too prolonged for the GTO mechanism to predominate [25]. Similarly, reciprocal inhibition occurs when a GTO is stimulated as a result of a stretch, however instead of inhibitory signals being relayed to the same muscle, they are relayed to the immediate antagonist to reduce neural drive. Given that ROM and performance changes tend to be present for significant amounts of time, it is likely not the cause of fast acting reflexes.

When placed under a constant stress, viscoelastic properties of musculotendinous units allow muscle to resist change when stress is applied and then return to their resting state once the pressure is removed. Frequent stretching would reduce the musculotendinous unit's ability to resist change and thus over time, increase the overall muscle length [25]. Gate control occurs when two receptors are activated at the same time. Since spinal interneurons receive and transmit shared signals traveling on myelinated pathways, the myelinated signals will reach the spinal cord first, thus impending signals from unmyelinated fibres [25]. It is possible that neural drive in the antagonist is reduced following a stretch or SMFR. Conversely, it is plausible that these reflexes occur much too rapidly and that the subsequent effects of antagonistic stretching are a result of another, likely mechanical, mechanism such as an increase in muscle length or the stress relaxation theory which suggests a temporary lengthening following the application of stress to a musculotendinous unit [25].

Thus far – despite limited research – it appears that altering the antagonist musculature has an effect on the ability of the agonistic musculature to perform. It appears that ROM and fatigue may also be affected by antagonist stretching. To date, research regarding antagonist stretching has not considered joint mechanics. For example, researchers have not examined whether flexion range of motion and/or neuromuscular efficiency increases as a result of altering the extensors. It is possible that altering antagonistic musculature around the knee will make the subject move and co-activate more efficiently. In order to understand how musculature relationships work, we must first consider how muscular co-activation works under normal conditions

Chapter 2.4 Co-Activation Around the Knee Joint

The knee is one of the most complex and oft injured joints in the human body. Furthermore, an injury to the ACL causes significant loss in playing time [10]. There is extensive research on subjects following ACL injury [10, 43, 53]. Additionally numerous studies have been published on predisposing factors that may contribute to the incidence of ACL tears [10, 24, 27, 28, 33, 41]. The majority of ACL injuries occur during non-contact situations such as landing from a jump [27]. The ACL is most vulnerable in a position near full extension with a planted foot and externally rotated tibia, which leads to a valgus collapse of the knee [41]. Gender differences in ACL injury incidence have also been researched. An increase in female injury incidence has been attributed to an increase in joint laxity, the presence of the sex hormone estrogen, a larger Q-angle and neuromuscular balances [27, 41, 44]. Faulty alignment is a significant contributor to knee pathologies because it can reduce neuromuscular efficiency, alter range of motion and result in greater amounts of energy consumption [6]. The hamstrings and quadriceps are the primary muscle groups responsible for knee stabilization, if their ability to stabilize is altered, the knee becomes more susceptible to subsequent injury [6].

In order to understand how the ACL becomes injured, it is important to understand how it functions. One of the primary functions of the ACL is to prevent anterior translation of the femur on the tibia [35]. Additionally the ACL provides stability during valgus and varus forces applied to the knee [35]. The ACL works together with the hamstring musculature in order to provide stabilization of the knee joint. It is without question that alteration to any of the musculature around the knee will change the overall ability of the joint to stabilize itself. In a properly functioning knee joint the antagonist is required to stabilize the joint and to equalize articular pressure on the joint [3]. Thus when altering the hamstrings or quadriceps muscle groups it is important to consider the effect it may have on the mechanics of the knee joint.

Within the ACL are several mechanoreceptors including the previously mentioned Golgi, Pacini, and Ruffini receptors which are also found within muscle, tendinous and fascial tissues [35, 51, 58]. These receptors assist the knee in detecting position, speed, acceleration and direction [35, 51, 58]. In addition, knee proprioceptors may also be affected by external stimuli such as foam rolling or stretching. Ghaffarinejad et al. [21] examined the effects of static stretching on thigh musculature and how it affected joint position sense in the knee. They discovered – by way of a reduced average angular error - that a static stretch of the quadriceps, hamstrings, and adductor musculature can alter an individuals position sense at 45˚ of knee flexion. It is likely that a stretch altered the Pacini mechanoreceptors, subsequently changing the kinesthetic sense [51]. Debate exists regarding the mechanisms responsible for reflex regulation following the stimulation of these mechanoreceptors. Impulses may synapse directly with alpha motor neurons or via muscle spindles and the efferent system [35].

When change is applied to the musculature around a joint, it is logical to consider how that joint is affected. Since muscle groups are known to work together, it makes sense to examine the effects of muscles on their synergistic and antagonistic counterparts. Typically failure of musculature to work together effectively will result in muscular imbalances and subsequently injury. It is highly likely that mechanisms behind muscle imbalances are both mechanical and physiological.

One common method of measuring the relationship between muscle groups is through muscular co-activation. Co-activation is used to both stabilize the joint and improve movement efficiency [24]. Muscular co-activation appears to be influenced by both central and peripheral mechanisms [20, 49] . Co-activation is partially affected by afferent signals from mechanoreceptors within the ACL [43, 49]. Additionally stress to the ACL can result in inhibition of the quadriceps musculature and facilitation of the hamstrings [43]. Centrally it has been shown that during muscular co-activation agonist and antagonist motor pools are treated as one via the common drive mechanism [18, 49]. Other factors that contribute to antagonist co-activation include muscles with bi-articular functions, the effect of secondary stabilizers in addition to primary agonist-antagonist muscles, and levels of local and central fatigue [32].

Knee stability is dependent on the stiffness of muscles and ligaments surrounding the joint [53]. There are reflex and non reflex mediated factors that contribute to joint stiffness. Reflex mediated stiffness is dependent on sensory feedback while non-reflex mediated stiffness is dependent on the number of active cross bridges [53]. Impairments in both reflex and non-reflex mediated stiffness can be partially compensated for by an increase in muscular co-activation [53]. Since the hamstrings work with the ACL to prevent anterior shift of the femur, co-activation appears to be an important mechanism in preventing injury to the ACL. Active hamstrings help to create a posterior shear force thereby reducing the anterior shear force and thus resulting in greater overall joint stability [32]. In a situation with excess quadriceps usage injury risk is said to increase [3]. Alternatively, excessive co-activation may also pose a problem because it may result in more joint stiffening as opposed to dynamic stabilization [12]. Excess co-contraction may result in a reduction in shock absorption and thus increase compression within the knee joint when landing [12]. Increases in compression may lead to other knee pathologies such as osteoarthritis [12]. To date, the optimal level of co-activation for muscles around the knee-joint remains unknown.

Muscular co-activation is important for stabilization of the knee joint, however it is important to recognize co-activation differences between genders. Females are typically at a greater risk for ACL injury, one of the proposed reasons is due to differences in neuromuscular activation [24, 27]. Females typically show greater vastus lateralis activation when compared to medial musculature [44]. Lower levels of medial activation lead to greater knee valgus and subsequently predispose individuals to increased risk of ACL injury [44]. While hormonal factors, such as increased estrogen levels, and

anatomical factors, such as a wider Q-angle, are said to predispose females to knee injury it has been suggested that the effects of neuromuscular training can help to override these factors [27]. Females tend to show greater levels of relative quadriceps activation [27]. Additionally, when landing, males tend to show more activation of the flexor musculature than their female counterparts [27]. Timing of firing may also play a role in the incidence of ACL injury between genders. Females tend to show deficits in neuromuscular control in the muscles around the knee joint [28]. When stress is applied to the ACL females have a slower hamstrings response than males [28]. This is important because the hamstrings act as an antagonist to the ACL and can help reduce stress on it. [28]. Some have proposed that ACL injuries may occur too quickly for reflexes to act as a preventative measure [41]. Even if this is the case, proper neuromuscular training may help an individual development movement patterns that reduce the probability of injury [41].

Another tool used to assess the function of the muscles surrounding the knee is the hamstrings to quadriceps ratio (H:Q Ratio). Clinically, this method is often used as a pre-screening tool to identify risks for future knee injury. Aagaard et al. [1] suggested both a functional and conventional H:Q ratio. Calculation of a conventional H:Q ratio is completed by comparing maximal force values from both muscle groups, regardless of contraction type. A functional H:Q ratio is calculated by comparing eccentric hamstrings activity to concentric quadriceps activity and concentric hamstrings activity to eccentric quadriceps activity. The functional measurement was proposed as it is more representative of lifelike movements in comparison with a conventional H:Q ratio. Coombs and Garbutt [14] recommended a Hcon/Qcon ratio of 0.6 and a Hecc/Qcon ratio of 1.0 as the optimal measures suggesting that these measures would give the eccentric hamstrings contraction full ability to brake a concentric quadriceps contraction.

Further research has since examined how functional and conventional H:Q ratios may be altered following a stretch. Costa et al. [15] examined how both ratios responded following a stretch of the hamstrings, a stretch of the quadriceps and a stretch of both muscles. They discovered that conventional ratios only decreased following a hamstrings stretch, while functional ratios decreased following combined and quadriceps only stretching. Two particular points of interest arise from this research. Primarily, functional and conventional ratios were affected differently based on the stretch applied typically by altering eccentric hamstrings ability. Secondly, a reduction in eccentric hamstrings ability reduces braking ability of that muscle group and could potentially lead to injury [15].

Thus far, researchers have not assessed muscular co-activation around the knee or H:Q ratios following the application of SMFR. Additionally, only one study has examined the effects of only applying SMFR to one muscle in the agonist-antagonist set. Researchers examined neuromuscular efficiency (i.e.: reduction in electromyography [EMG] activity while completing the same task) during a lunge. In this study, researchers only applied an SMFR to the quadriceps muscle, however they collected data from both quadriceps and hamstrings musculature. They found that during rolling of the

quadriceps, biceps femoris activity increased. It is unknown whether the increase in biceps femoris activity was a result of applying SMFR to the quadriceps or a result of pressure placed between the hamstrings and the surface. Additionally, It was found that hamstrings activity during a lunge decreased following 60 seconds of quadriceps SMFR when compared with 20 seconds of SMFR on the quadriceps [7]. They did not examine whether the same phenomenon would happen if the hamstrings were rolled and quadriceps activation was measured. Moreover, they did not examine the effect that this intervention had on the H:Q ratio or muscular co-activation. Given the decreased EMG activity and increased neuromuscular efficiency following the application of SMFR it is likely that a change in muscular co-activation occurred. Additionally, these changes may also induce changes in H:Q strength ratios. Furthermore, performance aspects were not extensively examined. It is possible that force, rate of force development, vertical jump height, vertical power and other performance measures may have changed following the SMFR of a single muscle group. When examining the effects of SMFR on agonist-antagonist relationships it is important to determine if SMFR to one muscle group has an effect on its antagonist muscle group. Moreover, if there is an effect it should be determined whether the effect is unidirectional or multidirectional and whether the magnitude of this effect is the same in both directions.

Chapter 2.5 Summary

In summary, benefits have been shown regarding the use of SMFR. Typically subjects found an increase in range of motion and performance aspects such as torque and jump height. Furthermore, SMFR appeared to be more effective than static stretching when comparing performance measures between the two interventions. These findings likely occurred as a result of the stimulation of different mechanoreceptors within the muscle and fascia.

Although research is limited, stretching the antagonist musculature appears to create a positive effect in the ability of the agonist muscle to perform tasks. It is possible that these findings were a result of reflex arcs and other neurophysiological effects such as gate control or the stress relaxation theory.. This might have occurred as a result of decreased neural drive to the stretched muscle. However, muscle activity did not appear to change in the stretched muscle when compared to pre intervention results. Additionally, researchers have suggested that Golgi receptors would not be stimulated during a passive contraction; such was the case in this body of research.

To date there is very little research regarding this phenomenon following a self-myofascial release intervention. The only study in which this has occurred only examined neuromuscular efficiency and noticed a decrease in activity to perform the same task. Given that this was a lunge technique it is possible that rolling the quadriceps altered Pacini and interstitial mechanoreceptor thus altering proprioceptive and/or cardiovascular properties of the quadriceps muscle. Mechanisms responsible for the decreased activity in the hamstrings muscle group following SMFR of the knee extensors remain unclear.

Given the close relationships between agonist and antagonist muscles it is logical to explore the effects that these muscles have on each other, particularly during and immediately following foam rolling. Joint functionality must also be brought into consideration. By utilizing H:Q and co-activation ratios, researchers can identify how muscle groups compare to each other and hence examine muscular imbalances. To date, research has shown that SMFR appears to be more effective than static stretching for range of motion and performance aspects. Furthermore research has primarily focused on local effects while non-local effects remain largely unknown.

Since it appears a positive effect occurs on the non stretched agonist following antagonistic stretching, it is plausible to believe the same may occur with SMFR, given the results of previous studies comparing the two interventions. However, since it is likely that SMFR stimulates different mechanoreceptors than static stretching, it remains plausible that the mechanisms behind any changes would also differ. It is not plausible to alter the musculature primarily responsible for moving a joint without examining the functionality of that joint. It is plausible that different applications of SMFR will alter the functionality of the knee joint in different ways. If there are implications on knee functionality following different

applications of SMFR, it may indicate whether a SMFR intervention has an effect on musculature imbalances and thus injury risk. Furthermore, by isolating muscle groups we will be able to make muscle specific recommendations for the application of SMFR in order to reduce future knee injury risk. The purpose of this research is to examine the effects of foam rolling on antagonist muscle activation and subsequently how those changes in activation may alter muscular co-activation.

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CHAPTER 3: CO-AUTHORSHIP STATEMENT

The following details my role in the preparation of manuscript 1.

Research Design
Methodology was developed based on previous SMFR research by Dr. Behm in combination with my background in athletic training. Discussions with Dr. Aboodarda and Dr. Behm helped to refine details of the experiment. With assistance from Dr. Behm I was able to obtain approval from the Health Research Ethics Authority (HREA) to conduct this research.

Data Collection
All data was collected by me with assistance from Dr. Aboodarda and Dan Hodgson.

Data Analysis
I performed all data analysis procedures.

Manuscript Preparation
I wrote both manuscripts with assistance from Dr. Behm and Dr. Aboodarda

CHAPTER 4: MANUSCRIPT I

Intra- and Inter-session Reliability of Quadriceps' and Hamstrings' Electromyography During a Standardized Hurdle Jump Test with Single Leg Landing

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Running Title: Hurdle Landing Test Reliability

Chapter 4.1 Abstract

The objective of this study was to develop a standardized test to determine quadriceps and hamstrings muscle activation in a position emulating a non-contact anterior cruciate ligament injury. We assessed the intra- and inter-session reliability of surface electromyography (EMG) of the dominant leg following single-leg landing from a standardized hurdle jump. Eighteen subjects (10 male, 8 female) participated in four repeated sessions. During each session, individuals performed three successful jumps over a hurdle set to 75% of their maximal countermovement jump height and landed on their dominant leg. A jump was only considered successful if the individual could maintain the landing position for longer than two seconds following initial ground contact. In one of the four sessions subjects were tested again following a four-minute rest. The activation of the vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF), were examined by quantifying the root mean squared (RMS) EMG for two seconds immediately following the initial contact. Data from all three successful jumps was used to generate intraclass correlation coefficients (ICC), which were then used to determine intra and inter-session reliability of surface EMG for each muscle. Intra-session reliability was excellent with ICC values of 0.96, 0.94, and 0.93 for the VL, VM and BF, respectively. Additionally inter-session ICCs were 0.92 (VL), 0.95 (VM) and 0.94 (BF). The standardized hurdle jump with single leg landing appeared to be a reliable technique for measuring muscle activation for three muscles that contribute to knee stabilization.

Key Words: Knee, muscle activation, stability, ACL, injury

Chapter 4.2 Introduction

Muscular co-activation is an important measure because of its relation to knee stability [1, 17]. Muscular co-activation of the hamstrings reduces the strain on the anterior cruciate ligament (ACL) and thus may play a role in injury reduction [1]. Since muscular co-activation is purported to assist in preventing knee injury, it is logical to examine co-activation in a position where the ACL would be vulnerable to injury. Non-contact ACL injuries often occur when the foot is planted with external tibial rotation and valgus collapse of the knee [20]. Since this type of ACL injury often occurs when landing from a jump [21] it is important to develop a test that may emulate that position.

There are a number of tests used to measure electromyographic (EMG) activity and muscular co-activation around the knee [8, 25]. A common issue with a number of tests for thigh muscle co-activation is that researchers are unable to normalize the task relative to specific individual abilities [14, 25]. For example, many current tests have individuals drop from a predetermined or standard height [6, 24, 25]. Therefore, while the height of the drop remains consistent between trials, it is not relative to the capabilities of the individual. This type of test may have varying outcomes dependent upon individual differences in strength, power, body mass or other physiological and anatomical characteristics. Although Stalbom et al. (2007) showed that a drop jump with single leg landing was reliable with less than a 10% change within measures; the test was not standardized to each individual. Thus the validity of the test can be questioned. Since the workload in these tests is not standardized, fatiguability would not be the same for each individual [2]. Differences in proprioceptive and mechanoreceptive feedback may result in changes in motor control, motor unit recruitment and muscle wisdom and therefore result in changes in EMG output [3].

There are several tests available for objectively measuring knee joint dysfunction, many of which specifically focus on single-leg dysfunction. The single leg vertical jump and single leg hop for distance has the individual jump as far and/or high as possible and land on one leg [14]. These tests outlined by Keskula et al., [14], do not account for any momentum that may be generated via leg swing. If an individual performs a “single-leg hop for distance” or “single-leg vertical jump” it is difficult to control the amount of swing in the contralateral limb. Therefore we do not know if significant changes in muscle activation would occur because of a significant physiological interaction or due to a flaw in the test such as a variation in momentum.

There is limited research examining the reliability of surface EMG during dynamic movements. One study [8] reported hamstrings and quadriceps surface EMG to be reliable during a drop landing from a normalized height. It can be argued however that the method of normalization used (vertical jump) is not representative of a drop landing given differences in the muscular task. It is unreasonable to normalize a drop task to a jump task. In a jump task lower extremity musculature must undergo a propulsion mechanism prior to landing. This is not the case in a drop task. A jump task may

put more stress on the stretch-shortening system and be more representative of sport specific movement. Thus while testing muscle activation any potential for within test variation should be eliminated by ensuring the test is relative to the individual's capabilities and additionally by creating a sport specific task representative of the standardization method.

One factor affecting test reliability may be gender-based differences. Gender based differences with ACL injury risk are well documented. There are a number of factors attributed to this higher risk including a larger Q-angle, hormonal differences, and neuromuscular control [13, 20, 23]. Russell et al., [24] found that immediately following initial contact during a single-leg landing, women landed with more knee valgus while men landed with more varus. A change in knee position would subsequently alter the length-tension relationship and possibly result in changes in muscle activation [16].

The rationale for this study was based on prior research from our laboratory [5], which examined quadriceps EMG following a drop landing from a pre-determined height. The drop-landing task may result in different levels of relative difficulty for each individual. Our proposed test involves a single-leg landing. This was chosen over a bilateral landing as it can help identify activation differences between limbs. Although not completed in our study, testing of a single limb allows for comparison to the contralateral limb. Single-leg tasks can show the presence of asymmetry between limbs [18] thus allowing for a comparison between injured and uninjured limbs. Furthermore single leg landings are more representative of sport specific tasks as athletes rarely land in a bipedal stance. The objective of this study was to test the reliability of surface EMG during the standardized hurdle jump with a single-leg landing task. This task was developed with the goal of developing a test with individualized relative difficulty for measuring surface EMG

Chapter 4.3 Methodology

Subjects:

Eighteen subjects including ten males (25 ± 4.6 years, 180.1 ± 4.4 cm, 86.5 ± 15.7 kg) and eight females (21.75 ± 3.2 years, 166.4 ± 8.8 cm, 58.9 ± 7.9 kg) were recruited to participate in this study. No previous lower extremity injuries were reported. All subjects reported being at least recreationally active. Participants were asked to refrain from alcohol use 24 hours prior to participation. Each participant completed the Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology 2011) to rule out any potential health issues. Subjects were asked to wear the same footwear for each session. Additionally following a debriefing of the study, subjects signed a consent form approved by the Health Research Ethics Authority at Memorial University of Newfoundland (file # 15.133).

Experimental Protocol:

Each participant was required to come to the laboratory on four separate occasions. On the first occasion, subjects practiced the single leglanding task to familiarize themselves with the protocol and reduce variability due to learning effects. At the beginning of each session, subjects were prepared for electrode placement by shaving all hair with reusable razors and removing dead epithelial cells with abrasive sandpaper. The area was then cleaned with an isopropyl alcohol swab. A pair of disc-shaped surface EMG electrodes 10mm in diameter (Meditrace Pellet Ag/AgCl electrodes; Graphic Controls Ltd, Buffalo, NY) were placed 2 cm apart on the muscle bellies of the vastus medialis (VM) 1/3 of the distance between the medial knee joint and the anterior superior iliac spine (ASIS), the vastus lateralis (VL) between the superior patella and ASIS, and biceps femoris (BF) between the popliteal space and gluteal fold on the subjects' dominant limb. A ground electrode was also placed on the fibular head. Tape was then applied to keep electrodes in place. Markings were applied on the skin to ensure inter-session consistency in placement.

Following skin preparation and EMG application subjects were required to warm up with five minutes of lower body cycling (Monark Anerobic Cycle 894e) at a cadence of 70 RPM and a resistance of 1 kilopound. Subjects were then asked to perform three vertical jumps. The highest of the three vertical jump heights was recorded (Vertec, Sports Imports, Hilliard, OH) and later used as a normalization method for determining the height of the hurdle. Then participants performed two knee flexion and two knee extension maximal voluntary isometric contractions (MVCs) in a randomized order. Each MVC was performed for five seconds with a two-minute rest between contractions. EMG data was recorded and used for normalization of muscle activation in the hurdle jump tasks.

A Functional Movement Screen hurdle (FMS™) was set to 75% of the individuals' maximal vertical jump height. The distance of the hurdle from the force plate (AMTI , 400x600 x83 mm, model BP400600 HF-2000 - Watertown,

MA02472-4800 USA) was equal to 25% of the individuals' vertical jump height. A starting line was placed the same distance before the hurdle (Figure 1). From this marked starting position, from a bipedal stance, participants were asked to jump over the hurdle and land in the middle of the force plate on their dominant leg only. Participants completed jumps until three successful trials were completed. Jumps were only deemed successful for analysis if subjects maintained the landing stance for two seconds as indicated by a metronome. A similar method was used by Russell et al. [24] during a drop-landing test. This protocol was repeated on four separate days. On one randomly designated day, participants were asked to rest for four minutes before completing three additional hurdle jumps. Muscular activation levels were measured from the dominant limb in the two seconds immediately following initial ground contact.

Data analysis:

All EMG data was sampled at 2000 Hz with a Blackman 61-dB bandpass filter (Biopac Systems Inc, Holliston, MA) between 10 and 500 Hz and amplified at a gain of 1000. Data was converted using a 12-bit analog-to- digital converter and stored for further analysis. A software program (AcqKnowledge 4.1; Biopac Systems Inc) was used to analyze the data. A high pass filter of 20hz was applied to remove movement artefacts. EMG was synchronized with force plate data and analyzed for two seconds following initial ground contact with a root mean squared (RMS) moving window of 50ms. EMG data from each successful jump was normalized to the individuals' EMG during an MVC. RMS EMG was also used to calculate co-activation ratios as follows; Anterior:Posterior [(VL+VM)/BF], VL:VM [VL/VM], VL:BF[VL/BF] and VM:BF[VM/BF].

Statistical Analysis:

Data was statistically analyzed using SPSS 20.0 (Chicago, IL, USA). Both intra and inter-session EMG reliability were assessed with Cronbach's alpha interclass correlation coefficient (ICC) measurements. Additionally a coefficient of variation (CV) was calculated (SD/Mean) for each session and muscle. Standard error of measurement (SEM) was calculated with the formula SEM = SD * $\sqrt{}$(1-ICC). The ICC, CV, and SEM were calculated for males, females, and for the total sample. The previous measures were also calculated for the Anterior:Posterior components (Average [VL + VM]/BF EMG), as well as specific VL:BF and VM:BF EMG ratios. A separate two-way repeated measures analysis of variance (ANOVA) for 3 (trials) x 2(time points) was used for each of the three muscles to assess whether there were any significant intra-session differences. A one-way (4 sessions) repeated measures ANOVA was also used to assess the consistency of each subjects' maximal vertical jump height. A three way ANOVA 2 (gender) x 3 (trial) x 4 (days) was used to determine

any gender-based differences in activation and ratios. Greenhouse-Geisser corrections were applied where applicable.

Chapter 4.4 Results

A summary of intra and inter-session descriptive and reliability measures are available in tables 1 and 2 respectively. ICCs for RMS EMG were very reliable for the VL (0.96 intra-session, 0.92 inter-session), the VM (0.94 intra-session, 0.95 inter-session) and the BF (0.93 intra-session, 0.94 inter-session). Coefficients of variation ranged from 31.8-58.4% across all muscles and conditions (Table 1; Table 2). Gender –based results showed high reliability with males for VL (0.95 intra-session, 0.85 intersession), VM (0.93 intra-session, 0.93 inter-session), and BF (0.92 intra-session, 0.91 inter-session) with CVs ranging from 28.5-66.1% in all cases (Table 1; Table 2). Females' muscle activation was also highly reliable for the VL (0.98 intra-session, 0.90 inter-session), VM (0.94 intra-session, 0.96 inter-session) and BF (0.93 intra-session, 0.94 inter-session) with CVs ranging from 34.1-49.9% (Table 1; Table 2).

Additionally there were no significant differences in intra-session muscle activation for VL EMG ($F_{(2,32)} = 0.438$, $p = 0.649$), VM EMG ($F_{(2,32)} = 0.389$, $p = 0.681$) or BF EMG ($F_{(2,34)} = 0.820$, $p = .449$). Furthermore no significant day-trial in inter-session VL EMG ($F_{(6,90)} = 1.008$, $p = 0.425$) VM EMG ($F_{(6,90)} = 0.091$, $p = 0.971$) or BF EMG ($F_{(6,96)} = 0.338$, $p = 0.915$). Anterior:Posterior, VL:BF, and VM:BF EMG co-contraction ratios also were reliable with intra-session ICCs of 0.96, 0.94, and 0.93 and inter-session ICCs of 0.92, 0.95, and 0.94 respectively. There was no significant gender based effects for VL EMG ($F_{(6, 30)} = 1.268$, $p = 0.323$), VM EMG ($F_{(6,30)} = 0.459$, $p = 0.833$) or BF EMG ($F_{(6,36)} = 1.881$, $p = 0.647$). Furthermore Anterior:Posterior ($F_{(6,36)} = 1.231$, $p = 0.328$), VL:BF ($F_{(6,30)} = 1.132$, $p = 0.952$) and VM:BF EMG ratios ($F_{(6,36)} = 0.706$, $p = 0.647$) showed no significant gender based interactions. No significant within subjects differences were found for maximum vertical jump heights for males ($F_{(3,21)} = 1.99$, $p = 0.146$) or females ($F_{(3,15)} = .235$, $p = 0.87$). This suggests that the standardization (normalization) method used was relatively consistent between days.

Chapter 4.5 Discussion

This is the first study examining the reliability of surface EMG during a standardized jump task with a dominant single-leg landing. This study showed high intra- and inter-session reliability for the VL, VM and BF EMG in both male and female subjects. Intra-session ICCs ranging from 0.93-0.96 are comparable to results found by Fauth et al. [8] following post-foot contact of a normalized bipedal landing test. Moreover, inter-session CVs ranging from 37.7-53.6% are much lower than those reported by Fauth et al. (2010). In addition to having high intra-session reliability when compared to similar research, this study also illustrated high inter-session reliability with ICCs of 0.92, 0.95, and 0.94, for the VL, VM, and BF EMG respectively. Intersession CVs ranged from 31.8-58.4% across all muscle groups.

Goodwin et al., [11] reported a low ICC (0.24) for BF EMG during a vertical jump task. These results contradict our high BF EMG ICC ranging from 0.76 to 0.94 across all genders, sessions, and trials. In the study by Goodwin et al., [11] BF EMG was measured during the propulsion phase. During a vertical jump, the hamstrings at the end range of motion are required to decelerate the jumping motion whereas in the task of the present study, the individual moved into hip and knee flexion to stabilize themselves during the landing. Our data is in agreement with that of Fauth et al., [8] where the hamstrings muscle group acted more as a stabilizer.

Previous research by Cappa and Behm [4] showed differences in muscle activation and stiffness between drop and hurdle jumps. Furthermore, a drop landing and a jump test may differ in the response of stretch receptors and subsequent excitation of the motor neurons due to differences in contraction speed and stored elasticity [7, 15]. Therefore individualizing a drop task to a jump task is not optimal. The hurdle jump test may be more applicable because the vertical jump provided a standardization method based on an individual's abilities. A drop landing and a jump landing may require different methods of stabilization.

There are a number of factors that may affect intra- and inter-session EMG reliability. Despite careful and precise placement of electrodes, EMG activity differences may still be present between days. Differences in skin preparation may result in resistance and impedance differences each day thus altering the EMG outcomes. Given the difficulty and unfamiliarity in landing on a single leg, it is possible that differences in motor control and motor unit recruitment can occur [8]. Additional alterations to EMG activity can occur with multiple repetitions if fatigue is a consideration [3]. According to Behm [3], fatigued, untrained individuals may experience greater decreases in EMG activity and motor unit synchronization. Trained individuals may be more efficient at sustaining submaximal contractions while additionally showing increases in EMG and reflex potentiation [3]. This may result in variability within a population of subjects with differences in training status. However neuromuscular fatigue is less likely to be a confounding factor in the current data

because rest periods were given between trials.

Further variability may be attributed to biomechanical factors. It is unreasonable to expect subjects to land exactly the same each time. Previously, drop-vertical jump and step-down kinematics have been compared and have shown both gender and task based differences in knee and hip joint angles [6]. Given their attachment sites, the VL, VM, and BF muscles are susceptible to changes in length following changes to hip or knee angle. Subsequent differences in muscle length can result in EMG activity changes [19]. Changes in muscle tension can be attributed to changes in motor unit recruitment and firing frequency [26] thus differences in EMG would be expected. Synergist muscle recruitment may also differ between both individual jumps and between sessions [27].

Muscular co-contraction is a necessary mechanism for knee stabilization. Levels of muscular co-contraction vary, immediately following single leg landing. Yang and Winter [27] suggested differences in antagonist co-contraction between trials and days would be varied hence differences could have occurred with the co-activation of quadriceps and hamstrings EMG measurements. Data for three different co-contraction ratios around the knee joint were highly reliable in this study. The CV measures appeared to be high during gender specific measures however this is likely attributed to a small sample size. Significant research regarding gender based differences in muscular co-activation and recruitment during weight bearing [9, 10] and during functional activities [12, 13, 20, 24] also exists. Hewett et al., [13] reported gender based differences in antagonist and synergist muscle activation patterns in a position that mimics ACL injury risk. Furthermore results from Harput et al., [12] demonstrated greater medial to lateral activation ratios in male subjects in a number of lunge and squat exercises. Female subjects have also demonstrated greater valgus knee angles upon initial contact when performing drop landing tests [24]. Additionally females have demonstrated higher rectus femoris (RF), lateral gastrocnemius (LG) and tensor fascia latae (TFL) during fixed isometric tasks [10]. Our data presented no significant gender based differences in EMG or co-activation ratios. Despite previous gender based differences in muscle activation our study showed high reliability both overall and within specific genders. It is possible that evidence of gender based differences in muscle activation with some other studies may be related to a lack of task individualization and variation in relative difficulty.

Chapter 4.6 Conclusion

The standardized hurdle jump test with dominant leg landing proved to be reliable for three muscles that significantly contribute to knee joint stability. It is unknown whether measurement of additional muscles would prove to be equally reliable. Given the strong ICCs, moderate CVs compared to previous research, and small SEM, our test demonstrated high inter- and intra-session reliability. It is recommended that subjects thoroughly practice the hurdle jump prior to testing as a single-leg landing is unfamiliar to most individuals. This may help to reduce variability due to learning effects. Future research is needed to determine the test-retest reliability of this task at varying levels of difficulty.

Chapter 4.7 References

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Chapter 4.8 Table Legends

Table 4.1: Intra-session Mean, SD(standard deviation), ICC(intraclass correlation coefficient), CV(coefficient of variation), and SEM(standard error of measurement) values for the VL(Vastus Lateralus), VM(Vastus Medialis) and BF(Biceps Femoris) muscles.

Table 4.2: Inter-session Mean, SD(standard deviation), ICC(intraclass correlation coefficient), CV(coefficient of variation), and SEM(standard error of measurement) values for the VL(Vastus Lateralus), VM(Vastus Medialis) and BF(Biceps Femoris) muscles.

Table 4.3: Intra-session mean, SD(standard deviation), ICC(intraclass correlation coefficient), CV(coefficient of variation), and SEM(standard error of measurement) values for the Anterior:Posterior, VL:BF, and VM:BF co-activation ratios.

Table 4.4: Inter-session mean, SD(standard deviation), ICC(intraclass correlation coefficient), CV(coefficient of variation), and SEM(standard error of measurement) values for the Anterior:Posterior, VL:BF, and VM:BF co-activation ratios.

Chapter 4.9 Figure Legends

Figure 4.1: Setup of the standardized hurdle jump test with single leg landing.

Table 4.1:

Intra Session	Mean % Of MVC Active			SD			ICC			CV			SEM (SD*√(1-icc))		
	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total
VL PreTest	42.935	42.366	42.677	15.760	16.823	16.093	0.950	0.955	0.952	0.367	0.397	0.377	3.524	3.569	3.526
VL PostTest	42.458	41.961	42.237	20.647	19.930	20.142	0.924	0.964	0.910	0.486	0.475	0.477	5.692	3.782	6.043
VL Pre+Post Test	42.692	42.164	36.886	18.251	18.246	16.026	0.954	0.975	0.960	0.428	0.433	0.434	3.914	2.885	3.205
VM PreTest	38.968	34.421	36.909	15.019	13.698	14.480	0.957	0.979	0.960	0.385	0.398	0.392	3.114	1.985	2.896
VM PostTest	38.313	35.053	36.864	18.275	16.803	17.548	0.880	0.929	0.854	0.477	0.479	0.476	6.331	4.477	6.705
VM Pre+Post Test	37.093	34.737	36.886	17.564	15.169	16.026	0.931	0.966	0.942	0.473	0.437	0.434	4.614	2.797	3.860
BF PreTest	24.654	20.742	22.883	13.068	9.437	11.628	0.877	0.888	0.867	0.530	0.455	0.508	4.583	3.158	4.241
BF PostTest	25.547	18.540	22.433	13.181	9.259	12.026	0.808	0.757	0.829	0.516	0.499	0.536	5.776	4.564	4.973
BF Pre+Post Test	25.108	19.641	22.655	13.020	9.315	11.777	0.919	0.925	0.926	0.519	0.474	0.520	3.705	2.551	3.204

Table 4.2:

Inter Session	Mean % Of MVC Active			SD			ICC			CV			SEM (SD*√(1-icc))		
	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total
VL 1	42.935	42.366	42.677	15.760	16.823	16.093	0.950	0.955	0.952	0.367	0.397	0.377	3.524	3.569	3.526
VL 2	42.778	39.933	41.513	12.199	14.507	13.221	0.935	0.939	0.936	0.285	0.363	0.318	3.110	3.583	3.345
VL 3	45.837	40.966	43.631	13.825	16.486	15.137	0.933	0.322	0.711	0.302	0.402	0.347	3.579	13.575	8.137
VL 4	44.450	41.592	43.180	20.212	18.179	19.209	0.960	0.972	0.960	0.455	0.437	0.445	4.042	3.042	3.842
TOTAL	**43.993**	**41.214**	**42.747**	**15.648**	**16.312**	**15.972**	**0.852**	**0.897**	**0.918**	**0.356**	**0.396**	**0.374**	**6.020**	**5.235**	**4.574**
VM 1	38.968	34.421	36.909	15.019	13.698	14.480	0.957	0.979	0.960	0.385	0.398	0.392	3.114	1.985	2.896
VM 2	42.487	36.892	40.000	20.487	16.811	18.978	0.975	0.939	0.962	0.482	0.456	0.474	3.239	4.152	3.699
VM 3	41.578	29.654	36.178	14.708	10.114	14.058	0.894	0.936	0.924	0.354	0.341	0.389	4.789	2.559	3.876
VM 4	45.125	34.345	40.334	23.931	14.519	20.834	0.936	0.961	0.943	0.530	0.423	0.517	6.054	2.867	4.974
TOTAL	**42.070**	**33.828**	**38.372**	**18.884**	**14.021**	**17.333**	**0.931**	**0.962**	**0.951**	**0.449**	**0.414**	**0.452**	**4.960**	**2.733**	**3.837**
BF 1	24.654	20.742	22.883	13.068	9.437	11.628	0.877	0.888	0.867	0.530	0.455	0.508	4.583	3.158	4.241
BF 2	24.114	20.609	22.556	11.765	10.135	11.109	0.871	0.931	0.891	0.488	0.492	0.492	4.226	2.662	3.668
BF 3	24.482	20.610	22.728	16.175	8.434	13.272	0.965	0.768	0.930	0.661	0.409	0.584	3.026	4.062	3.511
BF 4	25.277	22.570	24.074	12.492	8.193	10.787	0.793	0.767	0.780	0.494	0.363	0.448	5.683	3.955	5.059
TOTAL	**24.633**	**21.133**	**23.063**	**13.291**	**8.978**	**11.663**	**0.906**	**0.941**	**0.943**	**0.540**	**0.425**	**0.506**	**4.075**	**2.181**	**2.785**

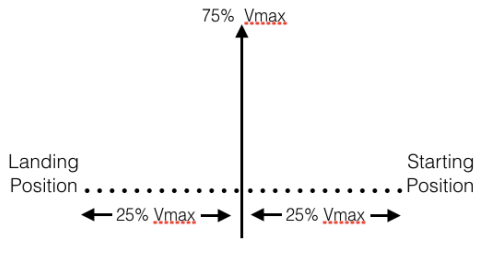
Table 4.3

Intra Session	Mean Ratio			SD			ICC			CV			SEM (SD*√(1-icc))		
	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total
Ant:Post Pre Test	1.912	2.319	2.104	1.316	2.988	1.332	0.926	0.965	0.943	0.688	1.288	0.633	0.358	0.559	0.318
Ant:Post Post Test	1.996	2.687	2.290	1.165	3.201	1.475	0.926	0.958	0.944	0.584	1.191	0.644	0.317	0.656	0.349
Ant:Post Pre + Post Test	1.886	2.488	2.169	1.620	4.384	1.979	0.958	0.980	0.971	1.691	1.762	0.912	0.332	0.620	0.337
VL:BF Pre Test	2.005	2.525	2.250	1.184	2.578	1.230	0.904	0.953	0.931	1.310	1.021	0.547	0.367	0.559	0.323
VL:BF Post Test	2.118	2.871	2.453	1.389	3.608	1.632	0.935	0.963	0.950	1.485	1.257	0.665	0.354	0.694	0.365
VL:BF Pre + Post	1.980	2.698	2.318	1.722	2.229	2.044	0.958	0.979	0.971	1.798	0.826	0.882	0.353	0.323	0.348
VM:BF Pre Test	1.852	2.113	1.958	0.868	3.496	1.462	0.829	0.972	0.950	0.469	1.655	0.747	0.359	0.585	0.327
VM:BF Post Test	1.873	2.442	2.126	1.034	3.200	2.044	0.917	0.952	0.971	0.552	1.310	0.961	0.298	0.701	0.348
VM:BF Pre + Post Test	1.863	2.277	2.020	1.149	4.525	1.385	0.930	0.980	0.939	0.617	1.987	0.686	0.304	0.640	0.342

Table 4.4

Inter Session	Mean Ratio			SD			ICC			CV			SEM (SD*√(1-icc))		
	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total	Male	Female	Total
Ant:Post 1	1.912	2.319	2.104	1.316	2.988	1.332	0.926	0.965	0.943	0.688	1.288	0.633	0.358	0.559	0.318
Ant:Post 2	2.107	2.698	2.339	0.654	2.802	1.195	0.805	0.886	0.865	0.311	1.038	0.511	0.289	0.946	0.439
Ant:Post 3	2.293	2.191	2.274	1.373	1.885	1.146	0.906	0.901	0.916	0.599	0.860	0.504	0.421	0.593	0.332
Ant:Post 4	1.915	2.090	1.993	0.205	2.132	0.705	0.298	0.916	0.841	0.107	1.020	0.354	0.172	0.618	0.281
TOTAL	**2.070**	**2.307**	**2.219**	**0.651**	**3.544**	**1.465**	**0.856**	**0.968**	**0.948**	**0.314**	**1.536**	**0.660**	**0.247**	**0.634**	**0.334**
VL:BF 1	2.005	2.525	2.250	1.184	2.578	1.230	0.904	0.953	0.931	0.591	1.021	0.547	0.367	0.559	0.323
VL:BF 2	2.148	2.756	2.418	0.731	2.950	1.256	0.812	0.893	0.870	0.340	1.070	0.520	0.317	0.965	0.453
VL:BF 3	2.412	2.529	2.417	1.243	1.025	0.708	0.896	0.758	0.802	0.516	0.405	0.293	0.401	0.504	0.315
VL:BF 4	1.898	2.267	1.807	0.188	2.025	0.217	0.302	0.897	0.623	0.099	0.893	0.120	0.157	0.650	0.133
TOTAL	**2.117**	**2.514**	**2.248**	**0.775**	**2.937**	**1.077**	**0.876**	**0.954**	**0.910**	**0.366**	**1.168**	**0.479**	**0.273**	**0.630**	**0.323**
VM:BF 1	1.852	2.113	1.958	0.868	3.496	1.462	0.829	0.972	0.950	0.469	1.655	0.747	0.359	0.585	0.327
VM:BF 2	2.066	2.500	2.259	0.773	2.676	1.171	0.840	0.879	0.862	0.374	1.071	0.518	0.309	0.931	0.435
VM:BF 3	2.282	1.873	2.082	3.493	2.623	1.531	0.973	0.961	0.945	1.531	1.400	0.735	0.574	0.518	0.359
VM:BF 4	1.933	1.912	1.924	0.261	2.259	0.681	0.387	0.932	0.837	0.135	1.181	0.354	0.204	0.589	0.275
TOTAL	**2.081**	**2.100**	**2.087**	**0.624**	**3.982**	**1.381**	**0.829**	**0.974**	**0.946**	**0.300**	**1.896**	**0.662**	**0.258**	**0.642**	**0.321**

Figure 4.1



CHAPTER 5: MANUSCRIPT II

Foam Rolling of Quadriceps Decreases Biceps Femoris Activation

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Running Title: Antagonist Foam Rolling

Chapter 5.1 Abstract

Foam rolling has been shown to increase range of motion without subsequent performance impairments of the rolled muscle, however there are no studies examining rolling effects on antagonist muscles. The objective of this study was to determine whether foam rolling either the hamstrings or quadriceps would affect antagonist muscle activation and co-activation. Additionally co-contraction ratios were examined to determine the magnitude of muscular co-activation following foam roller application. Gender-based differences were also considered. Surface electromyography was analyzed in the dominant vastus lateralis (VL), vastus medialis (VM), and biceps femoris (BF) muscles. BF activation significantly decreased following quadriceps foam rolling ($F_{(1,16)} = 7.45$, $p = 0.015$, *-8.9%*). There were no significant changes in quadriceps activation following hamstrings foam rolling. This might be attributed to the significantly greater levels of perceived pain with quadriceps rolling applications ($F_{(1,17)} = 39.067$, $p < 0.001$, *98.2%*). There were no gender-based changes in activation following foam rolling for VL ($F_{(6,30)} = 1.31$, $p = 0.283$) VM ($F_{(6,30)} = 1.203$, $p = 0.332$) or BF ($F_{(6,36)} = 1.703$, $p = 0.199$). Antagonist muscle activation may be altered following agonist foam rolling however it can be suggested that any changes in activation are likely a result of reciprocal inhibition due to increased agonist pain perception.

Chapter 5.2 Introduction

Foam rollers or roller-massagers are used to treat muscle spasm, tightness, pain, and muscle imbalances [37] and can increase range of motion (ROM) [15, 23, 28, 39]. This technique is often referred to as self-myofascial release (SMFR) and may stimulate mechanoreceptors and induce physiological changes in myofascia. It has been suggested that ROM increases might be attributed to the thixotropic properties of fascia [6]. Changes in fascial properties are only present temporarily while heat and pressure are applied [36]. Once external stimuli such as heat and pressure are removed tissue quickly returns to its normal state [36].

Muscular activation and neuromuscular efficiency have also changed following the application of a roller-massager [5], however claims of SMFR-induced alterations to muscular imbalances remain unproven. On the contrary, Aboodarda et al. [1] found pain pressure threshold was reduced following roller-massager application to both the ipsilateral and contralateral calf musculature suggesting that neural responses may play a more significant role as opposed to changes in fascial properties. Further research is needed to elucidate the extent and variety of neural responses to foam rolling.

Agonist-antagonist pairs are connected via a series of reflexes that help to initiate and inhibit contractions via sensory and motor neurons [8]. Given the interconnectivity between agonist and antagonist muscle groups it is illogical to apply a change to a muscle without considering how the antagonist is affected. Thus far – despite limited research – it appears that altering the length tension relationship of a muscle alters antagonist performance [11, 27, 32, 35]. Little research exists regarding the effect of foam rolling and agonist-antagonist relationships. Only one study has examined the effects of roller massager on the antagonist musculature. It was found that hamstrings activation was higher following 60s of quadriceps roller massage when compared with a 20s application [5]. This finding suggests that rolling the quadriceps may affect hamstrings activation. Given these results, it is logical to further examine changes in antagonist activation following foam rolling.

Muscular co-activation patterns are important for stabilizing the knee joint. Faulty alignment is a significant contributor to knee pathologies because it has been shown to reduce neuromuscular efficiency, alter ROM, and result in greater energy consumption [4]. The hamstrings and quadriceps muscle groups are primarily responsible for knee stabilization. If the stabilization mechanisms are compromised, the knee becomes more susceptible to injury [4]. Foam rolling-induced changes in co-contractions and muscle imbalances could contribute to subsequent injury if agonist-antagonist musculature fail to work together effectively. [2, 38]

The complexity of the knee joint makes it susceptible to injury, particularly to the anterior cruciate ligament (ACL) [7, 10, 17-19, 21, 29, 31, 38]. The majority of ACL injuries occur from non-contact situations such as landing from a jump

[19]. Knee stability may be affected by reflex mediated factors dependent on sensory feedback or non-reflex mediated factors such as the prevalence of active cross-bridges [38], both of which may be altered with foam rolling. Given that foam rolling and roller massagers have shown to change ROM, performance and neuromuscular efficiency it is possible that it may also affect muscular co-activation around a joint [5, 15, 23, 24, 28, 33].

In summary, it is plausible that changes in tissue elasticity following foam roller application may be due to the stimulation of mechanoreceptors within muscle, tendon, fascial and ligamentous tissue, which in turn may cause a change in muscle activation through reflex inhibition. Given recent research findings [1], foam rolling effects may be more predominantly neural responses that could affect both intra- and inter-muscular activation and forces. It was hypothesized that rolling a muscle would affect antagonist activation and co-activation ratios.

Chapter 5.3 Methodology

Subjects:

Eighteen subjects, ten males (25 ± 4.6 years, 180.1 ± 4.4 cm, 86.5 ± 15.7 kg) and eight females (21.75 ± 3.2 years, 166.4 ± 8.8 cm, 58.9 ± 7.9 kg) were recruited to participate in this study. No previous lower extremity injuries were reported. All subjects reported being at least recreationally active (participating in physical activity at least 3x/week). Participants were asked to refrain from alcohol use 24 hours prior to participation. Each participant completed the Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology 2011) to rule out any potential health issues. Subjects were asked to wear the same footwear for each session. Additionally following a debriefing of the study, subjects signed a consent form approved by the Health Research Ethics Authority at Memorial University of Newfoundland (file # 15.133).

Experimental Design:

This study utilized a repeated measures within subjects pre-post test design. Participants performed four randomized experimental conditions separated by 24-48 hours. Conditions included rolling the hamstrings, quadriceps, both muscle groups and a control session.

At the beginning of each session, subjects were prepared for electrode placement by shaving hair with reusable razors and removing dead epithelial cells with abrasive sandpaper. The area was then cleaned with an isopropyl alcohol swab. A pair of disc-shaped surface electromyographic (EMG) electrodes 10mm in diameter (Meditrace Pellet Ag/AgCl electrodes; Graphic Controls Ltd, Buffalo, NY) were placed 2 cm apart on the muscle bellies of the vastus medialis (VM), 1/3 of the distance between the medial knee joint and the anterior superior iliac spine (ASIS), the vastus lateralis (VL) between the superior patella and ASIS, and biceps femoris (BF) between the popliteal space and gluteal fold on the subjects' dominant limb. A ground electrode was also placed on the fibular head. Tape was then applied to keep electrodes in place. Markings were applied on the skin to ensure inter-session consistency in placement.

Following skin preparation and EMG electrode application, subjects were required to warm up with five minutes of lower body cycling (Monark Anerobic Cycle 894e) at a cadence of 70 RPM and a resistance of 1 kilopound. Subjects were then asked to perform three vertical jumps. The highest of the three vertical jump heights was recorded (Vertec, Sports Imports, Hilliard, OH) and later used as a normalization method for the standardized hurdle jump with single leg landing test [9]. Participants performed two knee flexion and two knee extension maximal voluntary isometric contractions (MVCs) in a randomized order. Each MVC was performed for five seconds with a two-minute rest between contractions. EMG data

was recorded and used for normalization of muscle activation in the subsequent hurdle jump task. A Functional Movement Screen hurdle (FMS™) was set to 75% of the individuals' maximal vertical jump height. The distance of the hurdle from the force plate (AMTI , 400x600 x83 mm, model BP400600 HF-2000 - Watertown, MA02472-4800 USA) was equal to 25% of the individuals' vertical jump height. A starting line was placed the same distance before the hurdle (Figure 1). From this marked starting position, with a bipedal stance, participants were asked to jump over the hurdle and land in the middle of the force plate on their dominant leg only [9]. Participants completed jumps until three successful trials were completed. Jumps were only deemed successful for analysis if subjects maintained the landing stance for two seconds as indicated by a metronome. Following the pre-test, consisting of two knee extension and flexion MVCs and three successful hurdle jumps, participants were required to complete one of four interventions. After the completion of the rolling and control interventions individuals completed three more successful hurdle jumps then one flexion and one extension MVC in randomized order for post-test measures. The experimental design is further outlined in figure 2.

Interventions:

Following the pre-test, individuals performed one of four randomized interventions. Each condition - with the exception of the control condition - required the individual to foam roll a muscle group for four sets of 45 seconds with 15 seconds rest between sets. One condition involved rolling only the hamstrings, between the gluteal fold and popliteal fossa. Another condition involved rolling only the quadriceps, between the apex of the patella and the ASIS. Additionally one condition involved rolling both the hamstrings and quadriceps in a randomized order. A control condition had participants sit for four minutes. Participants were asked to roll over medial and lateral aspects of each muscle group with as much pressure as possible. Participants used a closed cell expanded polypropylene pro foam roller; 15.24 cm (6 inches) in diameter and 91.4 cm (36 inches) long (Thera-Band; The Hygenic Corporation, Akron, OH). A new foam roller was used after every six uses to maintain consistent density. All foam rolling was completed at a cadence of 40bpm. Participants were asked to rate their perceived pain (0-10) following foam rolling for each muscle group.

Data analysis:

All EMG data was sampled at 2000 Hz with a Blackman 61-dB bandpass filter (Biopac Systems Inc, Holliston, MA) between 10 and 500 Hz and amplified at a gain of 1000. Data was converted using a 12-bit analog-to- digital converter and stored for further analysis. A software program (AcqKnowledge 4.1; Biopac Systems Inc) was used to analyze the data. A high pass filter of 20hz was applied to remove movement artefacts. Force plate data was sampled at 2000 and amplified at a

gain of 1000. EMG was synchronized with force plate data and analyzed for two seconds following initial ground contact with a root mean squared (RMS) moving window of 50ms. EMG data from each successful jump was normalized to the individuals' EMG during an MVC. Anterior:Posterior (Average VL+VM), VL:VM, VL:BF, VM:BF ratios were generated for each jump. Hamstrings:Quadriceps MVC force ratios were also generated.

Statistical Analysis:

A two way (3 trial x 2 test) analysis of variance (ANOVA) was used to determine the presence of within session interactions for each muscle group and each co-contraction ratio. A three way (3 trial x 2 test x 4 days) was used to examine differences between rolling interventions. A three way ANOVA (2 gender x 2 test x 4 days) was used to calculate any gender-based interactions. A one way ANOVA was used to examine any differences in pain perception between muscle groups. Greenhouse-Geisser corrections were applied where applicable.

Chapter 5.4 Results

Muscle Activation & Co-Contraction Ratios:

There were no significant between session differences in VL, VM, or BF muscle activation. There was a significant pre-post test decrease in BF activation following quadriceps foam rolling ($F_{(1,16)} = 7.45$, $p = 0.015$, *-8.9%*) (Figure 3). No significant differences in VL:VM, VL:BF, VM:BF or Anterior:Posterior co-activation ratios were found within or between sessions.

Pain Perception:

There was a significant interaction between perceived pain and muscle group rolled ($F_{(1,17)} = 39.067$, $p < 0.001$, *98.2%*) . Participants reported that rolling the quadriceps (5.9 ± 0.49) was more painful than rolling the hamstrings (2.9 ± 0.37).

Gender-Based Differences:

No significant gender-based interactions were found in muscle activation, co-contraction ratios or pain perception across all days. Additionally there were no within session gender-based differences in muscular activation or co-contraction.

Chapter 5.5 Discussion

The most important finding in this study was the significant decrease in BF activation following quadriceps foam rolling. This was only evident when the quadriceps were rolled alone and not in combination with the hamstrings. There was no effect on the quadriceps when the hamstrings were rolled. Furthermore, there were no sex-specific related effects.

There are a number of reasons why the aforementioned phenomenon was not reciprocated (i.e.: reductions in quadriceps activity following foam rolling of the hamstrings). The principal reason is related to the subjects' pain-pressure threshold during different foam rolling interventions. There was a significant interaction between the muscle group being rolled and pain perception. Pain was rated at 5.9 ± 0.49 and 2.9 ± 0.37 during quadriceps and hamstrings rolling respectively. Aboodarda et al., [1] discovered that roller massage of plantar flexor muscles with tender spots had diverse effects, acutely increasing pain pressure threshold (decrease pain perception) in the target muscle as well as the contralateral muscle. It is possible that foam rolling a larger volume of muscle such as the quadriceps stimulated a diverse and more extensive array of sensory afferents (i.e. mechanoreceptors, nociceptors) [36] compared to rolling the hamstrings. Greater interstitial receptor stimulation can result in a larger inhibitory effect [36, 22]. Related findings by Kennedy et al. [22] suggested that afferent firing of the elbow extensors resulted in reduced elbow flexor activation.

Given that our subjects reported higher levels of pain when rolling the quadriceps than the hamstrings, it is possible that the amount of pressure on the muscle groups was not equal. Since deeper pressures have been shown to diminish H-reflex amplitude [14] and that different roller application can alter pressure [12] it is reasonable to expect pressure differences between muscle groups when foam rolling. It can be suggested that with deeper pressure, greater afferent stimulation may have occurred. Post analysis, three subjects repeated the rolling intervention on a force plate to determine the amount of pressure on each muscle group. Pressure on the force plate while rolling was 62.9% (± 4.99%) of the individual's body weight for the hamstrings and 63.1% (± 2.26 %) for the quadriceps. Nijs et al., [30] suggested that tonic nociceptive stimuli (thermal, mechanical, or chemical) can result in inhibitory responses from the motor cortex resulting in both ipsilateral and contralateral inhibition. Furthermore, it was suggested that motor cortex inhibition would subside as pain perception stabilized. Falla and colleagues [13] suggested that local nociception has inhibitory effects on a muscle, which is impeded by a rearrangement of motor strategy. Thus, synergist and antagonist activity is altered following noxious stimuli to the agonist [13]. Additionally, it was postulated that changes in antagonist and synergist activity were task specific following painful stimuli to the agonist [13]. Moreover, previous research has shown that neuromuscular response to massage may be muscle specific [40]. They found that triceps surae H-reflex amplitude decreased during massage of the affected muscle but not during massage of the contralateral muscle or the hamstrings muscles. It is possible that changes in

antagonist (hamstrings) motor neuron excitability following quadriceps foam rolling may also follow the same specificity principle.

Finally, reciprocal inhibition effects only occurred when foam rolling was applied to a single muscle group of the agonist-antagonist set. Our data showed no significant changes in the combination rolling condition (i.e.: when both muscle groups were rolled.). Although the combination condition involved the same total volume of rolling (4 sets), the four sets were partitioned between the two muscles whereas the other single muscle rolling conditions experienced four sets of rolling on an individual muscle group. Hence the volume or dosage of rolling per muscle group with the combination condition may have been insufficient to elicit a reciprocal inhibitory response. Previous research has indicated that roller interventions can induce non-local decreases in pain pressure thresholds [1]. Hence, the inclusion of both muscle groups with the combination condition could have decreased pain perception or increased pain tolerance in the antagonist muscle leading to no significant pain-induced effects on either muscle. This sensation of increased pain or discomfort tolerance is consistent with the stretching-induced increased stretch tolerance initially proposed by Magnusson [25, 26] and others [3], which suggest that increases in ROM following stretching are due to a greater ability to withstand discomfort.

This was the first study to examine gender based responses to foam rolling. Our data suggest no significant differences in muscle activation or co-activation ratios between sexes. Our findings are consistent with results by Sullivan et al., [39] who found no gender-based differences in motor neuron excitability following massage. This is beneficial as it can help future researchers with mixed sample pools. The present study may also help validate previous studies, which have examined EMG in single gender populations [5, 23, 24].

Chapter 5.6 Conclusion

Based on the results from this study it appears that foam rolling a muscle group may alter antagonist muscular activity. It is likely that sufficient levels of pain need to be inflicted to elicit an antagonist inhibitory response. This is the first study to examine sex-based effects of foam rolling. Thus far it appears that men and women respond similarly. Given the prevalence of ACL injuries as a result of changes in muscular co-activation further research is needed to examine the effects of foam rolling on co-activation around the knee joint. There may be practical applications to this research as clinicians may be able to develop individualized foam rolling programs based on patient needs. Based on the results of this study, athletes are advised to not roll their quadriceps exclusively. Given that the hamstrings act as an antagonist to the ACL and help reduce anterior shear force on the ligament, lower hamstrings activation in most cases would not be recommended [20]. However, further research is needed to determine the duration of foam rolling induced changes in antagonist muscle activation.

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Chapter 5.8 Figure Legend

Figure 1: Set-up for the hurdle jump test with single-leg landing.

Figure 2: Experimental design.

Figure 3: Pre-post test differences in BF activation following quadriceps foam rolling.

Figure 4: Level of perceived pain while rolling each muscle group.

Figure 1:

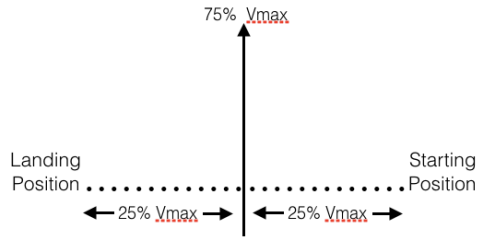


Figure 2:

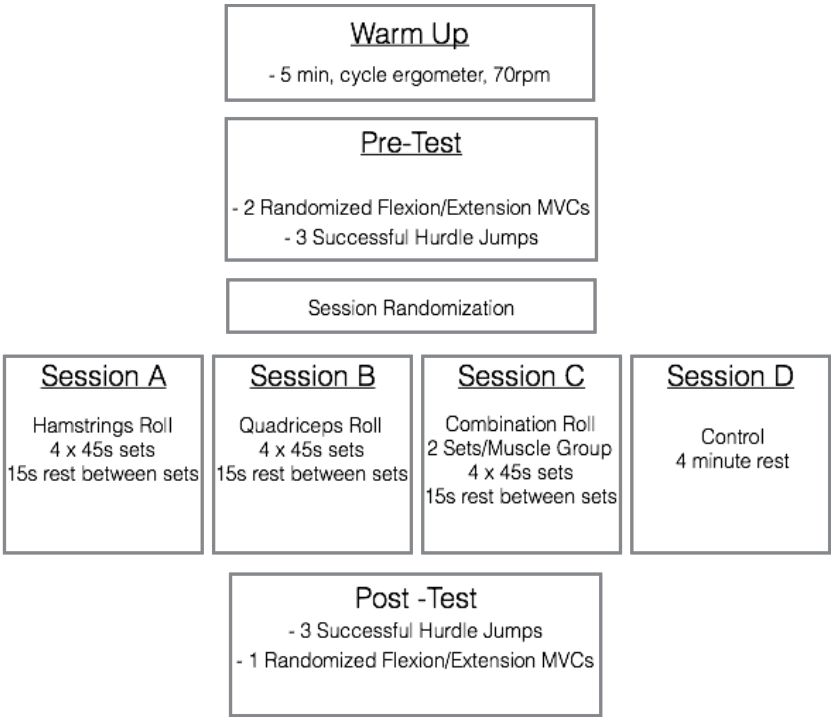


Figure 3:

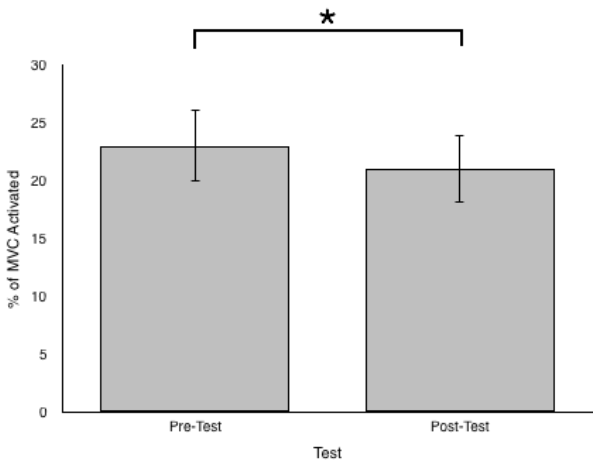
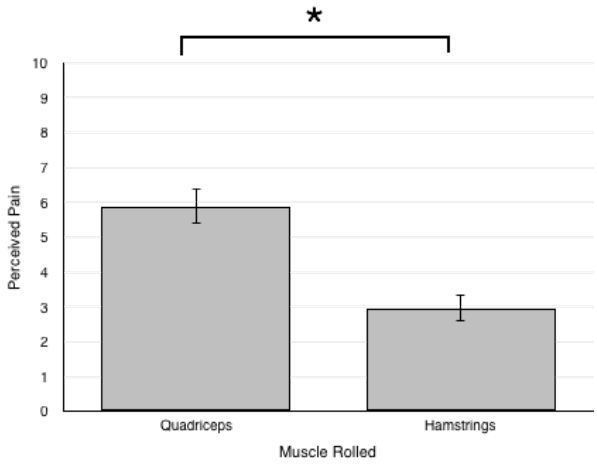


Figure 4:



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