Additional roller massage applied at ten-minute intervals can prolong hip and knee flexion range of motion improvements up to 30-minutes post warmup without impairing neuromuscular performance

by

©Daniel Hodgson

A thesis submitted to the

School of Graduate Studies

In partial fulfillment of the requirements for the degree of

Master of Science in Kinesiology

School of Human Kinetics and Recreation

Memorial University of Newfoundland

February 28, 2017

Newfoundland and Labrador

ABSTRACT

Roller massage (RM) has been shown to increase range of motion (ROM) without incurring subsequent performance deficits; contrarily, prolonged static stretching (SS) can induce performance impairments. It is not known if adding RM to a SS routine would augment stretch-induced ROM improvements. Furthermore, it is not known whether performing RM at intervals after stretching would prolong ROM increases. Hence, the objective of this study was to examine the effects of combining SS and RM with and without subsequent RM at 10-minute intervals on ROM and neuromuscular performance measures, and to monitor changes over 30-minutes. Whereas sessions involving a post-intervention rest period saw a diminishing effect to most ROM measurements over time, sessions including RM at 10 and 20-minutes post-intervention demonstrated maintained or greater active and passive hip and knee flexion ROM after 30-minutes. SS only and SS+RM provided similar ROM improvements, while most neuromuscular performance measures were not adversely affected.

ACKNOWLEDGEMENTS

When I packed up and left my small town comfort zone in rural Ontario and headed east to the city lights of St. John's to pursue my Master's degree, it was hard to imagine how the ensuing journey would play out. Reflecting back now just over two years later, it would seem I have come a lot further than the 3,017 Km from Orono to St. John's. The strides I have taken academically, and as a person, would not have been possible without the support and guidance of my supervisor, professors, colleagues, family, and friends.

I would first like to thank my supervisor, Dr. David Behm, for providing me the opportunity. As a world-class researcher in our field, it was immediately obvious why Dave has garnered a global respect professionally and personally. He has served as an invaluable role model, teacher, and friend, and brought the best out of me from the start. Dave's work ethic is admirable and sets a standard for true professionalism. Thank you for demonstrating this same relentless effort in helping me succeed academically, and for providing me numerous opportunities to collaborate and network with other leaders in our field world-wide. Conferences including CSEP 2016 in Vancouver and ECSS 2017 in Bochum, as well as research trips to the Universities of Potsdam and Kassel in Germany, and Lausanne and Fribourg in Switzerland have contributed immensely to my academic and personal growth while allowing me to explore the realms of our field of study and meet countless colleagues and friends.

I would also like to acknowledge my professors who taught me during my Master's. Drs. Kevin Power, Duane Button, Angela Loucks-Atkinson, Jeanette Byrne, and Fabien Basset have each played a large part in guiding my success by sharing their passion and knowledge towards their areas of expertise. Additionally, I would like to recognize Dr. Thamir (Tim) Alkanani, whose effort in coordinating the labs often slides under the radar. Tim is the engine that makes all research in our labs possible, and has been a great friend and colleague.

I learned quickly that earning a Master's degree is more than just an academic endeavor. It also requires great friends and adventures away from the lab. When I was new in town, the other students did not hesitate to include me and accept me as one of their own, and the friendships we forged will last a lifetime. Thanks to Jon, Pat, Joe, James, Lynsey, and Carla for the unforgettable Europe trips, to Ryan, Chris, Evan, Natasha, Alyssa, Kate, Michael, Devin, Rob, Thomas, and everyone else in the HKR department, to my German exchange friends Alex, Lena, and Karolin, and to my good friend Tyler. The great times we have shared in and out of school have made the hard times seem easy.

Finally, I would like to extend thanks to my family and all my friends back home. My mother Pam, father David, Brother Jeremy, sister Jennilee, Gramma and Papa Hodgson, and the rest of my family have offered endless support and encouragement not only during my time in Newfoundland, but in all of life's adventures and misadventures since day one. I would not be who I am today without you guys. We, are the Hodgson, FAMILY!

Daniel Hodgson

TABLE OF CONTENTS

ABSTRACT i
ACKNOWLEDGEMENTS ii
TABLE OF CONTENTS iv
LIST OF ABREVIATIONS vi

CHAPTER 1: REVIEW OF THE LITERATURE 1-1
1.1 – Introduction 1-1
1.2 – Effects of static stretching on flexibility 1-7
1.3 – Mechanisms for increased flexibility with static stretching 1-9
1.4 – Effects of static stretching on performance 1-11
1.5 – Mechanisms for impaired performance with static stretching 1-17
1.6 – Effects of foam rolling/roller massage on flexibility 1-21
1.7 – Mechanisms for increased flexibility with foam rolling/roller massage 1-23
1.8 – Effects of foam rolling/roller massage on performance 1-28
1.9 – Practical applications and future considerations 1-30
1.10 – Conclusion 1-33
1.11 – References 1-37

CHAPTER 2: CO-AUTHORSHIP STATEMENT 2-1

CHAPTER 3: MANUSCRIPT 3-1
"Additional roller massage applied at ten-minute intervals can prolong hip and knee flexion range of motion improvements up to 30-minutes post warmup without impairing neuromuscular performance."
3.1 – Abstract 3-2
3.2 – Introduction 3-4
3.3 – Methodology 3-8
Subjects: 3-8
Experimental design: 3-9

Interventions (Independent variables): 3-9
Measurements (Dependent variables): 3-12
Statistical analysis: 3-15
3.4 – Results 3-17
Range of Motion: 3-17
Jump Measures: 3-19
Knee Extension and Flexion MVIC Force Measures: 3-20
Reliability Coefficients: 3-20
3.5 – Discussion 3-21
3.6 – References 3-28
3.7 – Table legends 3-35
3.8 – Figure legends 3-36
3.9 – Tables 3-37
3.10 – Figures 3-39

LIST OF ABREVIATIONS

aROM	Active Range of Motion
BPM	Beats per Minute
CMJ	Countermovement Jump
EMD	Electromechanical Delay
EMG	Electromyography
ES	Effect Size
F100	Force generated in the first 100-ms
FR	Foam Rolling
FR/RM	Foam rolling and Roller Massage
GTO	Golgi Tendon Organ
ICC	Interclass Correlation Coefficient
ITT	Interpolated Twitch Technique
MFR	Myofascial Release
Mmax	Maximal muscle compound action potential
MTU	Musculotendinous Unit
MVIC	Maximal Voluntary Isometric Contraction
PF	Peak Force
PNF	Proprioceptive Neuromuscular Facilitation
POD	Point of Discomfort
pROM	Passive Range of Motion
RFD	Rate of Force Development
RM	Roller massage
ROM	Range of Motion
SD	Standard Deviation

SEC	Series-Elastic Component
SMFR	Self-Myofascial Release
SS	Static Stretching
SS_rest	Static stretching only, followed by 30-minutes rest
SS_RM	Static stretching only, followed by roller massage after 10 & 20-minutes
SS+RM_rest	Static stretching plus roller massage, followed by 30-minutes rest
SS+RM_RM	Static stretching plus roller massage, followed by roller massage after 10 & 20-minutes
VAS-10	Visual Analogue Scale

CHAPTER 1: REVIEW OF THE LITERATURE

Acute effects of static stretching and foam rolling on range of motion and neuromuscular performance: a review of the literature

1.1 – Introduction

Injuries to the lower extremity muscles and fascia are some of the most common setbacks in most sports (Mendiguchia et al., 2015). Hamstring strains have been reported to be the most prevalent injuries in the Australian Football League (Orchard & Seward, 2002), account for up to 17% of all injuries in professional European soccer, and 13% of all injuries in America's National Football League (Liu et al., 2012). Quadriceps injuries are also of high occurrence among professional athletes (Vigotsky et al., 2015), in particular the rectus femoris (Cross et al., 2004). One review identified shortened optimal muscle length and poor muscle flexibility as leading modifiable risk factors for these injuries (Liu et al., 2012); and although some research has found inconclusive evidence, this notion has typically received support from subsequent investigations (Van Beijsterveldt et al., 2013). Greater range of motion (ROM) is typically associated with a decreased risk of musculotendinous strains and sprains with high velocity sprints and change of direction (Behm et al. 2016, Mohr et al., 2014), and increased athletic performance (Kokkonen et al., 2007). These findings highlight the prospective benefits of acutely increasing ROM prior to exercise participation.

Static stretching (SS) has traditionally been the method of choice for increasing ROM and thereby reducing injury risk for athletes, healthy individuals, and in rehabilitation and clinical settings. SS involves achieving and sustaining a stretch sensation by passively lengthening a muscle until the point of discomfort (POD) is reached or approached (Behm et al., 2016). Indeed, the beneficial effects of SS on acute flexibility are well documented and have gained tremendous support from the scientific community (Behm & Chaouachi, 2011; Simic et al., 2012; Kay & Blazevich, 2012; Kallerud & Gleeson, 2013; Behm et al., 2016). These improvements are likely due to improved stretch tolerance brought about by neural adaptations (Magnusson et al., 1995; Mizuno et al., 2013) or from acute reductions in muscle and tendon stiffness (Morse et al., 2008). More recently however, SS has been under scrutiny based on reports of its association to subsequent performance deficits. Ample research has emerged claiming that sustained bouts of SS can lead to acute impairments in maximal neuromuscular tasks (Behm & Chaouchi, 2011; Kay & Blazevich, 2012), although there is some belief in a dose-response relationship in which SS only leads to impairments when sustained for >60-seconds (Behm et al., 2016). While some controversy exists, a recent review identified changes in tendon stiffness and the force-length relationship, stretch-induced contractile fatigue or damage, diminished electromechanical coupling, and reduced central drive as mechanisms hypothesized to underpin stretch-induced performance deficits (Behm et al., 2016). Therefore, performance deficits associated with SS may result from changes to the central nervous system, the muscles and fascia, or a combination of both.

The term fascia is inconsistently defined because fascial research is still rather juvenile and because the meaning has evolved with our understanding over time (Beardsley & Skarabot, 2015). What is understood is that fascia is a soft connective tissue system surrounding and linking all body organs and structures including muscles and nerve fibers, forming a whole body matrix of structural support (Findley, 2009). Shleip et al. (2012) added that fascia is also part of a body-wide force transmission system, while others have drawn attention to its important proprioceptive function and the substantial amount of sensory nerve fibers it possesses (Schleip, 2003a; Kumka & Bonar, 2012). Fascial restrictions caused by disease, disuse, tightness, injury, or inflammation can limit flexibility and cause localized pain, along with numerous other physiological impairments (Sullivan et al., 2013). Using manual therapy techniques to relieve symptoms of fascial restrictions has become a common practice.

Manual therapy techniques are well established in healthy, clinical, and athletic populations, during which pressure is applied to muscle and fascia to elicit an array of physiological benefits. Such modalities are referred to as myofascial release (MFR) techniques (Beardsley & Škarabot, 2015). MFR techniques, such as massage, are oriented towards relieving fascial restrictions through the modalities of a therapist; while recent scientific advancement has produced an alternative manual therapy performed by the patient (MacDonald et al., 2013), termed self-myofascial release

(SMFR). There are two primary tools most often associated with the performance of SMFR both in practice and in the literature. Foam rolling (FR) involves the patient using their body weight to apply pressure to specific areas of soft tissue and manipulating the roller by varying their body position (Healey et al., 2014). Alternatively, roller massage (RM) involves a hand-held device requiring the patient's upper body strength to exert pressure while rolling the device along the surface of the target tissues (Sullivan et al., 2013). With each application, a common intended physiological response is typically an increase in flexibility (Beardsley & Škarabot, 2015) resultant of a greater ROM.

Despite their growing popularity, no consensus has been reached regarding the exact mechanisms by which SMFR techniques exert their effects. Principles associated with MFR and SMFR are typically categorized into either mechanical or neurophysiological mechanisms (Schleip, 2003a; Shleip, 2003b; Weppler & Magnusson, 2010; Simmonds et al., 2012; Beardsley & Skarabot, 2015). Mechanical mechanisms include thixotropy, piezoelectricity, facial adhesions, fluid flow, fascial inflammation, and myofascial trigger points, while neurophysiological mechanisms involve mechanoreceptors including Golgi tendon organs (GTOs) and Ruffini and Pacini corpuscles. Given the uncertainty surrounding the cause of its effects and a lack of evidence connecting FR and RM to changes in fascia itself, perhaps a more appropriate term is tool-assisted self-manual therapy. Due to their unproven association to fascial release, foam rolling and roller massage will from here forward be referred to as FR/RM rather than SMFR.

Despite some confusion regarding definitions, FR/RM have been proposed as a method capable of replacing or supplementing SS as a means for acutely improving flexibility. Thus, an immature but strong base of literature has emerged since the turn of the century investigating the acute effects of FR/RM. Indeed, it has garnered the support of many researchers (e.g. Jay et al., 2014; Mohr et al., 2014; Peacock et al., 2014; Cho et al., 2015; Behara & Jacobson, 2015) as a capable means of acutely enhancing ROM. Furthermore, there is a growing body of evidence that FR/RM does not impair (e.g. Mikesky et al., 2002; Sullivan et al., 2013; Halperin et al., 2014; Healey et al., 2014; Bahara & Jacobson, 2015), and may enhance (Peacock et al., 2014) subsequent neuromuscular performance. Thus, it appears that FR/RM may provide an alternative or supplementary method of acutely increasing ROM, eliciting physiological advantages while dodging the potential performance impairments linked to prolonged SS.

As our understanding of SS, FR/RM, and their effects on ROM and neuromuscular performance evolves, consequential questions are also emerging. Limited research has explored the time-course of the effects elicited by these modalities. While acute effects measured immediately following an intervention have garnered substantial attention in the literature, few studies have reported on changes in ROM or performance over an extended time. Furthermore, whether FR/RM used in combination with SS can nullify performance deficits while also improving flexibility remains to be seen. Finally, no researchers to date have investigated the effects of using periodic bouts of FR/RM to sustain ROM improvements elicited during an athletic warmup. The existing literature regarding SS, FR/RM, and their acute effects requires clarification and direction for future examination. Thus, the purpose of this review is to organize the existing literature regarding the effects of SS and FR/RM on ROM and neuromuscular performance, to provide insight on the potential application of these techniques as part of an athletic warm-up, and to determine avenues necessitating future investigation of SMFR techniques.

1.2 – Effects of static stretching on flexibility

Professional and recreational athletes strive to maximize flexibility prior to resistance training or sport participation in order to ensure the required ROM for optimal performance can be achieved, as well as to reduce the risk of injury. SS is well established in the literature as an effective modality for increasing joint ROM (e.g. DePino et al., 2000; Miyahara et al., 2013), and as a result, has become an extremely common practice in flexibility training. Strength and conditioning coaches of major North American professional sports leagues were surveyed, revealing that 100% of National Basketball Association teams (Simenz et al., 2005), 91% of National Hockey League teams (Ebben et al., 2004), and 100% of Major League Baseball teams (Ebben et al., 2005) perform SS as part of their flexibility program (based on 68.9, 76.6, and 70% response rate, respectively). Despite a plethora of support backing the effects of SS on acute flexibility improvements, there is uncertainty regarding the recommended parameters to maximize its benefit. One review examined the effects of SS of the hamstrings on ROM of the hip and knee joints (Decoster et al., 2005). The authors revealed that all twenty-eight articles meeting their inclusion criteria demonstrated significant increases in hamstring flexibility (mean 5.2-33.6 degrees) following stretching; however they were unable to appoint a preferred type (e.g. static, proprioceptive neuromuscular facilitation {PNF}), position (e.g. seated, standing, or supine), or duration of stretch for maximizing ROM improvements. Based on the relevant pool of literature it is accepted that SS is an effective means for acutely improving flexibility by increasing joint ROM.

1.3 – Mechanisms for increased flexibility with static stretching

Improvements in ROM elicited by SS are likely due to increased stretch tolerance brought about by neural adaptations or from acute reductions in muscle and tendon stiffness. One study demonstrated a progressive reduction in stretch resistance with each of five subsequent passive stretches of 90-seconds (Magnusson et al., 1995). A significantly reduced viscoelastic response remained during a sixth passive stretch performed 60-minutes later, illustrating the lasting effects of acute SS (Magnusson et al., 1995). A more recent study reciprocated these effects, reporting a similar decline in viscoelasticity of the medial gastrocnemius following five repeated bouts of 60-seconds SS (Mizuno et al., 2013); however a normal response was restored after only 15-minutes. This discrepancy in effect duration may be due to differences in muscle groups or total stretching volume. Changes to muscle mechanical properties have also been commonly reported (Behm et al. 2016). One study used ultrasonography to demonstrate movement of the distal myotendinous junction of the medial gastrocnemius elicited by SS (Morse et al., 2008). The authors suggested that this migration during a passive stretch, coupled with a 47% reduction in passive stiffness of the muscle-tendon unit, had acutely altered the properties of the connective tissue (Morse et al., 2008). Two additional studies have used ultrasonic shear wave elastography to compute a measure of muscle hardness based on shear elastic modulus (Akagi & Takahashi, 2013; Nakamura et al., 2014). An association appears to exist between reductions in shear elastic modulus and muscle stiffness following acute SS (Nakamura et al., 2014), supporting claims of altered muscle mechanical properties. The effects of stretch tolerance and muscle stiffness on ROM following SS are supported by the literature, although substantial variances in methodology limit our ability to fully determine their importance.

1.4 – Effects of static stretching on performance

Despite receiving immense support from the literature for its acute effects on improving flexibility, substantial concern has arose regarding the detrimental effects of SS on subsequent neuromuscular performance. One article investigated the effects of running, SS of the quadriceps, and practice jumps on explosive force production and jumping performance during two subsequent leaping tasks (Young & Behm, 2003). Warmup protocols including SS consistently resulted in decrements in performance measures associated with proceeding jumps. SS alone produced lower concentric force than both the control session (4%) and a warmup consisting of running and SS (5.8%). SS only also elicited impairments compared to warmups consisting of running only and running plus SS and practice jumps in concentric force (8.7 and 7.5%), concentric jump height (both 6.7 %), concentric rate of force development (22 and 17.2%), drop jump height (7.8 and 8.4%), and drop jump height/time (7.4 and 11.4%). The authors concluded that SS had a negative influence on subsequent power and explosive force. Extensive research has echoed this conclusion using various measures of jumping tasks (e.g. Young & Elliott, 2001; Young et al., 2006; Behm & Kibele, 2007; Fletcher & Monte-Colombo, 2010; Haddad et al., 2014) to demonstrate acute impairments on power and explosive force elicited by SS.

Muscle performance in maximum strength efforts has also been under scrutiny following SS. One study applied SS to the quadriceps of fifty physical education students to examine its effects on isometric and concentric peak torque following 10, 20, 30, and 60-seconds of stretching (Siatras et al., 2008). Decrements in torque production were found after stretching bouts of 30 (isometric: 8.5%; concentric: 5.5%) and 60-seconds (isometric: 16%; concentric: 11.6%). Sekir and colleagues (2010) reinforced these findings by applying SS to the hamstrings and quadriceps of ten elite female athletes. Significant impairments were found following two repetitions of 20-second stretches per muscle group in concentric and eccentric muscle strength at two different isokinetic speeds (60 and 180 degrees/second), as well as a reduction in muscle activation recorded via electromyography (EMG). Similarly, another study compared the effects of SS (5 repetitions of 45 seconds) to PNF stretching (5 repetitions, each totaling 61 seconds) of the hamstrings (Miyahara et al., 2013). The authors reported significant reductions in maximum voluntary isometric contraction (MVIC) force following static (6.9%) and PNF (7.1%) stretching. The evidence presented is supported by additional research (e.g. Avela et al., 1999; Fowles et al., 2000; Nelson et al., 2001; Power et al., 2004; Knudson & Guillermo, 2005; Weir et al., 2005; Herda et al., 2008; Bacurau et al., 2009; Trajano et al., 2013) and suggests that SS is responsible for impairments in maximal strength related tasks. A review by Behm and colleagues (2016) insinuated that neuromuscular strength-related performance tasks are altered by a mean of -2.8% following <60-seconds, and -5.1% following ≥60-seconds of SS.

Maximum speed related tasks such as sprinting may also be affected by prior SS. One study examined the effects four sets of 30 second stretching bouts of the hamstrings, quadriceps, and plantar flexors on 20-metre sprint times of elite collegiate track athletes (Nelson et al., 2005). Significant reductions in speed were reported when stretching had been applied to both legs (1.3%), the front starting leg (1.3%), and the rear starting leg (1.6%). A similar subsequent study investigated the effects of three sets of SS applied to the hamstrings, quadriceps, and plantar flexors of elite collegiate track athletes on 40-metre sprint times (Winchester et al., 2008). Contrary to the previous study no differences were reported during the initial 20-metres, however a time increase of 1.3% was seen in the final 20-metre segment for the stretching group. The findings of these studies are supported by additional research (e.g. Fletcher & Monte-Colombo, 2010; Gelen, 2010; Kistler et al., 2010; Haddad et al., 2014), and indicate that SS may have an adverse effect on speed related performance tasks. According to a recent review, neuromuscular power and speed-related performance is altered by a mean of -0.2% following <60-seconds, and -2.6% following ≥60-seconds of SS (Behm et al., 2016).

The effects of SS have also been identified for other measures of performance. Rhythmic gymnasts who performed SS prior to competition experienced increased ground contact time (8.7%), reduced flight time during various leaps (6.4-7.2%), and overall lower scores from the judges (20-36%) compared to those who instead performed a typical warmup (Di Cagno et al., 2011). A warmup consisting of SS only was shown to increase sprint time (8.5%) and slalom dribbling time (4.1%), while decreasing penalty kick velocity (2.1%) in a group of 26 professional soccer players (Gelen, 2010).

Effects of SS on balance are controversial; it has been reported to induce a slight negative effect (Behm et al. 2004) or no significant effect (Handrakis et al, 2010; Murphy et al., 2010; Halperin et al., 2014).

While substantial evidence exists regarding the prospect of performance impairment resulting from acute bouts of SS, there is also a wide base of literature making contradictory claims. Indeed, there is indication that SS as part of a warmup may have no effect (Power et al., 2004; Chaouachi et al., 2009; Dalrymple et al., 2010; Handrakis et al., 2010; Van Gelder & Barts, 2011; Stafilidis & Tilp, 2015) or enhancement (O'Connor et al., 2006; Murphey et al., 2010) of subsequent explosive power, no effect on subsequent strength (Kubo et al., 2001; Behm et al., 2004; Young et al., 2006; Akagi & Takahashi, 2013; Halperin et al., 2014; Stafilidis & Tilp, 2015), and no effect (Young et al., 2004) or enhancement (Little & Williams, 2006) of subsequent speed-related performance tasks.

Recent review articles have emerged, attempting to summarize and add some clarity to the myriad of research pertaining to SS and performance (Behm & Chaouachi, 2011; Kay & Blazevich, 2012; Simic et al., 2012; Kallerud & Gleeson, 2013; Behm et al., 2016). Inconsistencies reported repeatedly amongst the literature may be due in part to inconsistent methodological approaches (Kay & Blazevich, 2012). Behm & Chaouachi (2011) pointed out that stretches of short duration (<90-seconds total), and stretches of intensities less than the point of discomfort may not elicit performance impairments. Kay & Blazevich (2012) added that shorter durations of stretching are likely more typically employed in athletic, pre-exercise, clinical, and healthy populations anyway, and that stretches of ≤60-seconds may be performed in a pre-exercise routine without compromising maximal muscle performance. Furthermore, although the recommended volume of SS required to increase flexibility may induce negative acute effects on some aspects of performance, the effect sizes of these impairments are often small, indicating that acute performance decrements may be limited in practice (Kallerud & Gleeson, 2013). Behm and colleagues (2016) thoroughly analyzed 125 relevant studies pertaining to SS and performance with 2,226 total subjects and 270 findings. The authors noted a dose-response relationship illustrating that greater performance impairments were elicited with stretching durations of ≥60-seconds (-4.6%) than with <60-seconds (-1.1%) per muscle group (Behm et al., 2016). It was also revealed that no effects on performance were experienced when post-stretching dynamic activities were performed prior to the performance task (Behm et al., 2016). The aforementioned review articles yield similar findings, suggesting that shorter duration SS may have little or no negative consequence (Behm & Chaouachi, 2011; Kay & Blazevich, 2012; Simic et al., 2012; Kallerud & Gleeson, 2013; Behm et al., 2016). This approach has been taken by strength and conditioning coaches of major professional North American sports. Players in the National Basketball Association (Simenz et al., 2005), National Hockey League (Ebben et al., 2004), and Major League Baseball (Ebben et al., 2005) hold their SS for an average of 14.5-seconds, 17.35-seconds, and 12.02-seconds, respectively. The ideal pre-exercise warmup routine is encouraged to consist of submaximal intensity aerobic activity and short duration (≤60-seconds per muscle group) SS, followed by bouts of dynamic stretching and completed with sport-specific dynamic practice activities (Behm & Chaouachi, 2011; Behm et al., 2016).

1.5 – Mechanisms for impaired performance with static stretching

In order to successfully implement SS into a regimen intended to increase flexibility and prevent injury while also circumventing reductions in performance, an understanding of the mechanisms of these impairments is required. A recent review by Behm and colleagues (2016) revealed that changes in tendon stiffness and the force-length relationship, stretch-induced contractile fatigue or damage, diminished electromechanical coupling, and reduced central drive are mechanisms hypothesized to underpin stretch-induced performance deficits.

Despite some evidence that a greater strength deficit exists at shorter vs. longer muscle lengths (Nelson et al., 2001; Herda et al., 2008), it is not confirmed that reduced tendon stiffness and an altered force-length relationship contributes to the impairment. Evidence to the contrary was provided when Kay and Blazevich (2009) demonstrated that in spite of a reduction in peak force production following acute muscle stretching, the gastrocnemius works at the same length, indicating that muscle length did not influence the loss of force. Furthermore, an elongated muscle with less than optimal length for force production when returned to the same joint angle following the stretch may potentially affect isometric force, however will have less impact on patterns of dynamic force production with a range of joint angles and muscle lengths (Kallerud & Gleeson., 2013). Our current understanding denotes that SS-induced force impairments are unlikely to develop principally from changes in muscle length.

Some research supports that stretch-induced contractile fatigue or damage may reduce contractile force capacity by damaging the muscle itself. Brooks and colleagues (2005) demonstrated such evidence in mice, and later reports have noted reduced electrically stimulated force following acute SS (Power et al., 2004; Trajano et al., 2013, 2014). The notion that the decline in elicited force resulted from muscle damage is refuted when it is reported that no correlation exists with reductions in voluntary force or recovery of force following the stretch (Trajano et al., 2014). Considering that meaningful muscle damage has not been reported in humans following SS (Behm et al., 2016), its prominence as a mechanism of force impairment remains inconclusive.

Diminished electromechanical coupling may result from SS and participate in eliciting subsequent force impairments through inhibition of action potential transmission in the sarcolemma (Behm et al., 2016). Despite reports of reduced EMG signal frequency during prolonged submaximal muscle contractions following acute stretching (Eguchi et al., 2014), the origin of this effect may be due to either altered sarcolemmal transmission or change in motor unit recruitment towards lower threshold motor units (Behm et al., 2016).

Changes in electromechanical delay (EMD) may be attributed to decreased musculotendinous unit (MTU) stiffness associated with SS. EMD is affected by the amount of slack in the series-elastic component (SEC) that must first be absorbed prior to force transmission (Kallerud & Gleeson, 2013), and influences rate of force development (RFD). Costa and colleagues (2010) demonstrated how acute SS (9 repetitions of 135 seconds to the plantar flexors separated by 5-10 seconds rest) can prolong EMD and RFD. These findings are contradictory to those of Young and colleagues (2006) who observed no change in RFD succeeding more applicable stretching durations of two and four minutes. Furthermore, increasing tendon stiffness by 30% via exercise training did not influence RFD in children (Waugh et al., 2014), and Behm and colleagues (2016) suggested that similar stretch induced decreases in tendon stiffness are also unlikely to be significantly influential. Conflicting reports regarding changes in electromechanical coupling inhibit our ability to draw conclusions of its importance in provoking SS-induced impairments.

Reduced central drive through efferent pathways is considered to be the focal contributor of SS-induced muscle deficits. Conflicting reports have emerged regarding correlations between EMG amplitude and MVIC force reductions, with some reporting in favor of a significant association (Fowles et al., 2000; Kay & Blazevich, 2009; Sekir et al., 2010) while others observed no EMG deficits (Herda et al., 2008; Murphy et al., 2010; Halperin et al., 2014). In order to better quantify changes to central drive, techniques besides EMG can be used, including EMG normalized to the maximal muscle compound action potential amplitude (EMG/Mmax), using the interpolated twitch technique (ITT) to estimate percent voluntary activation, and measuring V-wave amplitudes during MVICs (Trajano et al., 2013). Trajano and colleagues (2013, 2014) observed a decline in each of these measures following SS, and their recovery during fifteen minutes following the intervention was correlated with changes in maximal force production. Based on these mechanisms, altered central drive, likely explained by changes to motor unit firing frequency and recruitment patterns, has a strong association with changes in muscular force production after SS (Behm et al., 2016). With our developing understanding of the acute effects of SS, interest has emerged in its comparison to FR/RM in terms of effects of each technique on ROM and neuromuscular performance, and whether they operate under similar mechanisms.

1.6 – Effects of foam rolling/roller massage on flexibility

In light of recent reports of SS-induced performance impairments, athletes and coaches have begun to implement alternative modalities for acutely improving ROM. FR/RM has been proposed as a suitable method to replace or supplement SS during an athletic warmup, prompting researchers to explore its acute effects on ROM.

Fifteen articles reported on the effects FR/RM application on ROM. One study measured ROM in the quadriceps of eleven physically active males before, 2-minutes, and 10-minutes after they performed two, 60-second trials of FR (MacDonald et al., 2013). The authors reported a 12.7% and 10.3% increase in ROM after 2- and 10-minutes, respectively. Another investigation reported on the effects of RM application to the quadriceps for five sets of 20-, and 60-seconds (Bradbury-Squires et al., 2015). Their results indicated that ROM was increased by 10% following five sets of 20-seconds, and 16% following five sets of 60-seconds, compared to a control session. These findings have gained support from recent literature (Bushell et al., 2015; Marcovic, 2015) and indicate that FR/RM are capable of acutely increasing flexibility in the quadriceps.

Additional research has focused on the fascia and muscles of the hamstrings. One such study investigated the effects of short duration RM of the hamstrings (Sullivan et al., 2013). Participants were subjected to four sessions consisting of either one or two trials, each lasting either 5- or 10-seconds of RM with a constant cadence and pressure. Significant increases in ROM were observed after each intervention, including a 4.3%

improvement following 5-seconds, and 6.6% following 10-seconds of RM. Additional reports have supported these claims (Jay et al., 2014; Mohr et al., 2014; Peacock et al., 2014; Behara & Jacobson, 2015) and further established FR/RM as a capable modality for acutely improving flexibility in the hamstrings. Given a 4.3% improvement after 5-seconds (Sullivan et al., 2013), 9% and 12.7% after 2-minutes (Marcovic, 2015 and MacDonald et al., 2013, respectively), and 16% after 8-minutes of FR/RM (Bahara & Jacobson, 2015), evidence of a dose-response relationship may be emerging; however such conclusions cannot yet be drawn.

Acute ROM enhancements have also been documented in the ankle plantar flexors (Halperin et al., 2014; Skarabot et al., 2015). Despite evidence in favor of acute enhancements of flexibility with FR/RM, some reports revealed conflicting findings indicating null effects on hamstrings ROM (Mikesky et al., 2002; Howe et al., 2013; Roylance et al., 2013). These findings may be due to differences in experimental design, such as type of device used or duration and intensity of rolling. Given our current understanding (12 reports of increased ROM vs. 3 reporting no change), FR/RM appears to increase flexibility acutely, although the existence of a dose-response relationship is yet to be established.

1.7 – Mechanisms for increased flexibility with foam rolling/roller massage

Our understanding of the mechanisms underpinning ROM improvements elicited by FR/RM is rather immature, however several theories have been proposed in the literature. Typically, these theories encompass mechanisms of MFR including SMFR and FR/RM, therefore they will be discussed accordingly here. Principles associated with MFR and SMFR are generally categorized into either mechanical or neurophysiological mechanisms (Schleip, 2003a; Shleip, 2003b; Weppler & Magnusson, 2010; Simmonds et al., 2012; Beardsley & Skarabot, 2015). Mechanical mechanisms include thixotropy, piezoelectricity, facial adhesions, fluid flow, fascial inflammation, and myofascial trigger points.

Many mechanical mechanisms have been criticized based on the notion that most human tissues would require exceptional pressures to be exerted outside of normal physiological ranges in order to cause tissue deformation (Chaudhry et al., 2008). Thixotropy refers to the shift in consistency from a viscous to a fluid state that is undertaken by a material when subjected to the application of heat or kinetic energy (Barnes, 1997). However, it is argued that this cannot explain many effects reported by researchers because thixotropy is a transient and reversible effect (Beardsley &Skarabot, 2015); the effects would dissipate very rapidly following treatment (Shleip, 2003a). Piezoelectricity refers to the production of an electric charge in response to mechanical loading, and Barnes (1997) noted that such properties have been demonstrated in human fascia. O'Connell (2003) hypothesized that fibroblasts and fibroclasts act upon collagen in response to the electric charges, facilitating lengthening; however it has been argued that this fails to explain the relatively quick effects observed with MFR (Shleip, 2003). Fascial adhesions are thought to occur when altered layers of fascia that normally would slide relative to one another reach a sticking point preventing natural movement (Hedley, 2010). These adhesions can be pathological in nature. Martinez Rodriguez and Galandel Rio (2013) suggested that the natural repair process following strenuous exercise or muscle strain may deposit scars in the connective tissue, and the accumulation of fibrotic elements may form fascial adhesions, adversely affecting joint extensibility. The application of pressure using manual therapy techniques is considered a means of encouraging the release of these adhesions to restore natural ROM with appropriate application of pressure (Hedley, 2010). Fluid flow is another potential mechanism explaining ROM increases with FR/RM. Water content can affect the stiffness of fascia and, considering that fascia extrudes water when under compression, the pliability of these tissues may be increased through acute alterations in tissue hydration (Schleip & Muller, 2013). A review by Schleip & Muller (2013) indicates that FR may be particularly appropriate for this purpose. Inflammation resulting from exercise or injury may occur in the fascia or muscle tissue, causing it to tighten (Findley et al., 2012). Findley and colleagues (2012) reviewed the relevant literature and deduced that FR/RM may relieve this inflammation by increasing local blood flow. Indeed, there is some indication that FR may effect blood flow by increasing nitric oxide production

(Okamoto et al., 2014), although the relation to inflammation dispersion remains vague. Finally, myofascial trigger points are considered tender areas in discreet, taught bands of hardened muscle producing local and referred pain (Bron & Dommerholt, 2012). They are thought to develop upon excessive acetylcholine release, resulting in shortened sarcomeres, disrupted cell membranes, damaged sarcoplasmic reticulum, and inflammation in a localized area (Bron & Dommerholt, 2012). There is some suggestion that they could be consequence of muscle overuse involving sustained contractions to muscle failure, resulting in localized ischemia and the release of inflammatory mediators due to a drop in pH (Bron & Dommerholt, 2012). Nonetheless, whether myofascial trigger points even exist has been under scrutiny based on the reliability of their clinical identification (Myburgh et al., 2008).

Neurophysiological models, although not as extensively studied as the more traditional mechanical models, are becoming more widely accepted. Mechanorecptors including GTOs and Ruffini and Pacini corpuscles are potential neurophysiological mechanisms for increased ROM experienced with FR/RM. While Golgi receptors are found in all connective tissues (Beardsley & Skarabot, 2015), they are referred as GTOs strictly at the muscle-tendon junction. When GTOs detect stretch within the tissue, afferent feedback is sent to the spinal cord and motor unit firing rate is reduced, subsequently decreasing tension in the muscle (Tozzi, 2012). It is speculated that pressures exerted during FR/RM stimulate the GTOs allowing greater ROM in the relaxed tissue (Roylance et al., 2013). Despite some support for this theory, GTOs appear to be more sensitive to stretch in an active muscle rather than one being passively stretched (Schleip, 2003a). This is thought to result from the GTOs being aligned in series with the muscle fibers, therefore passive lengthening is primarily absorbed by the muscle itself and greater GTO stimulation occurs during active lengthening when a greater tendon stretch occurs (Schleip, 2003a). Ruffini and Pacini corpuscles are mechanoreceptors found in all types of connective tissue, including muscle fascia, tendons, ligaments, and joint capsules, and respond to rapid changes in pressure and vibrations (Schleip, 2003a). Stimulation of these mechanoreceptors through myofascial manipulation alters proprioceptive feedback, ultimately leading to reduced motor neuron firing rate and tonus relief in the muscle (Schleip, 2003a), similarly to how GTOs respond to stretch. Some support for this mechanism emerged with reports of reduced muscle activity during a lunge exercise subsequent to acute FR/RM (Bradbury-Squires et al., 2015). While submaximal EMG was measured during these studies, others have reported no changes in EMG during a MVIC following FR/RM (MacDonald et al., 2013; Sullivan et al., 2013; Halperin et al., 2014). Schleip (2003a) provided further support for the argument of mechanoreceptor involvement in ROM increases following manual therapy, noting that a typical muscle nerve contains nearly three times more sensory than motor fibers, and that only 20% of these sensory fibers belong to type I and II nerves (which include GTOs and Pacini and Ruffini corpuscles). The remaining 80% belong to type III and IV sensory nerves (interstitial muscle receptors), which are linked to the autonomic nervous system, and while some have characterized them as mainly pain receptors, Schleip (2003a) recalls that research has demonstrated that the majority actually function as mechanoreceptors that respond to tension and/or pressure. A deeper understanding of interstitial muscle receptors may provide clues as to how neuromuscular pathways may alter motor output following FR/RM.

1.8 – Effects of foam rolling/roller massage on performance

Recent research has highlighted FR/RM as an alternative or supplementary method for acutely increasing flexibility, however its inclusion into a warmup protocol hinges on its effects on subsequent neuromuscular performance.

Six studies have reported on the effects of FR/RM on power and force production. Healey and colleagues (2014) compared the effects of FR to the effects of light planking exercises of the same duration, stating that this simulates the isometric body weight hold that foam rolling entails. Subjects performed FR on lower extremity tissues including those of the hamstrings and quadriceps. The authors reported no differences in vertical jump height, vertical jump power, isometric squat force, or agility drill speed between experimental groups, and concluded that FR had no acute effects on subsequent power and force development. These findings garnered support from Jones and colleagues (2015), who compared the effects of 30-second bouts of FR on lower extremity muscles including the hamstrings and quadriceps with effects of mimicking the same movements upon a skateboard during a separate session. No differences were observed between conditions for jump height, impulse, ground reaction force, and take-off velocity during vertical jumps performed prior to and following each intervention. Furthermore, Janot and colleagues (2013) assessed peak power output during the 30-second Wingate cycling test and found no differences following three sets of FR of seven muscle groups. These conclusions are reinforced by additional research (Mikesky et al., 2002; Behara & Jacobson, 2015); in fact Peacock and colleagues (2014) observed increases in vertical jump height (7.8%) and standing long jump (4%) following 30-seconds of FR over six muscle groups. Thus, it appears that acute FR/RM does not impair, and may enhance subsequent power and force production.

The impact of FR/RM on strength measurements has been explored in seven articles. MacDonald et al., (2013) reported no change in quadriceps MVIC peak force or EMG following two 60-second foam rolling sets. Similarly, Sullivan et al. (2013) elicited hip flexion ROM improvements using RM on the hamstrings for short durations (1 or 2 sets of 5- or 10-seconds), and reported no change in MVIC peak force or hamstrings muscle activity using surface EMG. Further evidence maintains these findings (Mikesky et al., 2002; Halperin et al., 2014; Healey et al., 2014; Bahara & Jacobson, 2015), while some evidence suggests that FR may enhance acute strength. Indeed, Peacock and colleagues (2014) reported a 3.8% rise in 1-repetition maximum bench press following 30-seconds of FR per muscle group. Based on current evidence, FR/RM have no negative consequence, and may be beneficial for performance in maximal strength efforts.

Limited research has examined how FR/RM affect maximal speed performance, however Mikesky et al. (2002) found no difference in 20-yard sprint speed in thirty male and female college athletes following 2-minutes of RM to the hamstrings. On the other hand, Peacock et al. (2014) observed 3.1% faster times for a 37m sprint in 11 elite male athletes. Despite the conflicting reports, research has yet to demonstrate deficits in maximal speed following FR or RM.

1.9 – Practical applications and future considerations

Given our developing understanding of the consequences arising from SS or FR/RM on both ROM and neuromuscular performance, curiosity has emerged regarding the interplay that may occur when the two methods are combined. While no studies to date have reported on the effects of a warmup involving both SS and FR/RM on performance, there is evidence that such a warmup may elicit greater ROM improvements than either on its own (Mohr et al., 2014). Indeed, ROM gains were observed following FR only (3 sets of 60-s, 6.9%), SS only (2 sets of 60-s, 12.3%), and combination of FR and SS protocols (23.6%) in forty subjects with less than 90-degrees baseline hip flexion. Moreover, Peacock and colleagues (2014) compared a dynamic warmup routine to the same warmup in conjunction with 30-seconds of FR to six muscle groups. Despite improvements in hamstring flexibility elicited by both warmups, the addition of FR provided no extra enhancement compared to the dynamic warmup on its own; however performance gains were observed for power, strength, and speed tasks following the combined warmup (Peacock et al., 2014). Future research should examine how a warmup combining SS and FR/RM impacts subsequent neuromuscular performance.

Another issue when considering a warmup including SS is the duration of effects. While acute effects measured immediately following an intervention have garnered substantial interest in the literature, few studies have reported changes in ROM or performance over time following the intervention. Inconsistent findings were reported by those who have examined a time course of ROM enhancement with SS, with effects having persisted for ≤3 (DePino et al., 2000), ≤5 (Whatman et al., 2006), ≤10 (Behm et al., 2011; Skarabot & Beardsley, 2015), ≤30 (Fowles et al., 2000; Murphy et al., 2010; Mizuno et al., 2013), ≤90 (Knudson, 1999), and ≤120 minutes (Power et al., 2004). Similarly, research is limited as to the lasting effects of FR/RM on ROM. Two studies have reported at multiple time points post-intervention, concluding that ROM enhancements had returned to baseline (Halperin et al., 2014) or still remained to a smaller extent (MacDonald et al., 2013) after 10-minutes. Variances in findings for both SS and FR/RM are likely due to differences in protocols including duration and intensity of the intervention or differences in muscle groups examined. The immature pool of research on this topic exposes a need to further probe into the time-course of effects brought about by acute SS and FR/RM. This information would be of particular interest to athletes who endure prolonged rest between warmup and intense exercise.

Whether performing additional bouts of FR/RM at various time intervals following an intervention may prolong the effects on ROM also requires investigation. For example, will bouts of FR/RM performed at 5-minute intervals prolong or enhance the increases in ROM elicited by an athletic warm-up? This scenario may have a practical application for athletes who sit dormant on the bench after coming out of the game, or following a pre-game warm-up before entering from the bench. Acknowledging the prevalence of hamstring and quadriceps muscle injuries among athletic populations suggests that sustaining an increased ROM on the bench may be beneficial in reducing the risk of these injuries upon return to activity.

1.10 – Conclusion

The primary focus of this review was to first evaluate our understanding of the short term effects of SS on ROM and neuromuscular performance. SS has traditionally been a staple in athletic warmup routines for athletes based on its perceived benefits, a notion which the scientific community has supported with convincing evidence of ROM enhancement (Decoster et al., 2005) and injury prevention (Hadala & Barrios, 2009; Mohr et al., 2014). Perception has changed over the last fifteen years regarding pre-exercise SS based on debate of its detrimental effects on subsequent neuromuscular performance. Indeed, the literature has demonstrated how impairments of power and force development (e.g. Behm & Kibele, 2007; Fletcher & Monte-Colombo, 2010; Haddad et al., 2014), maximal strength (e.g. Power et al., 2004; Knudson & Guillermo, 2005; Weir et al., 2005; Herda et al., 2008; Bacurau et al., 2009; Trajano et al., 2013), and speed (e.g. Fletcher & Monte-Colombo, 2010; Gelen, 2010; Kistler et al., 2010; Haddad et al., 2014) have followed acute bouts of SS. Recent reviews have provided some clarity (Kay & Blazevich, 2012; Kallerud & Gleeson, 2013; Behm et al., 2016), revealing what appears to be a dose-response relationship for which harmful effects of SS are limited to longer durations (>60-seconds) per muscle group, while bouts of shorter durations (≤60-seconds) do no compromise maximal performance efforts. Improved stretch tolerance (Mizuno et al., 2013) resultant of neural adaptations or acute reductions in muscle and tendon stiffness (Morse et al., 2008) are thought to underpin acute ROM changes with SS, while it appears that altered central drive is the primary mechanism inducing performance deficits following SS (Fowles et al., 2000; Kay & Blazevich, 2009; Sekir et al., 2010; Trajano et al., 2013, 2014; Behm et al., 2016).

Second, the effectiveness of FR/RM, a proposed alternative or supplementary technique to pre-exercise SS, was assessed. Reports of increased flexibility have emerged following 5-seconds (Sullivan et al., 2013), 90-100-seconds (Bradbury-Squires et al., 2014; Halperin et al., 2014; Skarabot et al., 2015), 2-minutes (MacDonald et al., 2013; Marcovic, 2015), 3-minutes (Bushell et al., 2015), 5-minutes (Bradbury-Squires et al., 2014), 8-minutes (Behara & Jacobson, 2015), and 10-minutes (Jay et al., 2014) of FR/RM. A dose-response relationship may exist between FR/RM duration and extent of ROM improvements, however a greater body of literature is required to support this notion and to establish optimal volume. The exact mechanisms of these changes is under speculation, however mechanical mechanisms such as thixotropy, piezoelectricity, facial adhesions, fluid flow, fascial inflammation, and myofascial trigger points, along with neurophysiological models involving GTOs and Ruffini and Pacini corpuscles are typically associated with MFR and SMFR techniques (Schleip, 2003a,; Shleip, 2003b; Weppler & Magnusson, 2010; Simmonds et al., 2012; Beardsley & Skarabot, 2015). Aside from its effects on ROM, it has also been demonstrated that acute FR/RM does not provoke impairments in subsequent neuromuscular performance. All studies examined except one, which demonstrated physiological improvements following FR/RM (Peacock et al., 2014), reported no change in power and force development (Mikesky et al., 2002; Janot et al., 2013; Healey et al., 2014; Behara & Jacobson, 2015), maximal strength efforts (e.g. MacDonald et al., 2013; Sullivan et al., 2013; Halperin et al., 2014; Bahara & Jacobson, 2015), or speed related tasks (Mikesky et al., 2002). Additional research is necessary to strengthen the presented evidence that FR/RM may increase ROM without provoking performance impairments that have been reported with SS. Peacock et al., (2014) reported conflicting results with no change in ROM, and improvements in physiological performance measures during subsequent vertical jumping tasks. In this investigation, subjects performed SMFR following a dynamic full-body athletic warm-up. It is possible that this type of warm-up is capable of eliciting similar or greater increases in ROM than FR, and that performance was enhanced when foam rolling was added to the protocol due to a longer overall warm-up.

The final goal for this review was to address questions emerging from our understanding of SS and FR/RM and their place in an athletic warmup, thus identifying directions for future research. Acute effects measured immediately following an intervention have dominated the scope of research – few studies have reported changes in ROM or performance over time. This is necessary information when considering an athletic warmup. Also, whether FR/RM used in combination with SS can nullify potential performance deficits while also improving flexibility remains to be seen; a combination of FR/RM and SS of ≤60-seconds appears to show promise. Furthermore, we are unsure of the consequences when these methods are used in conjunction with a dynamic athletic warmup. Finally, no researchers to date have investigated the effects of using periodic bouts of FR/RM to sustain ROM improvements elicited during an athletic warmup. It may be plausible to prolong the benefits of such a warmup by performing FR/RM in periodic bouts on the sidelines.

A limited, yet promising body of literature has demonstrated that FR/RM techniques may produce similar ROM improvements to SS while avoiding any impairments in subsequent neuromuscular performance. As more research emerges on the practical benefits of FR/RM, its strategic application can be developed to provide optimal benefits to athletes, healthy individuals, and in rehabilitation or therapeutic settings.

1.11 – References

1. Akagi, R. & Takahashi, H. (2013). Acute effects of static stretching on hardness of the gastrocnemius muscle. Medicine & Science in Sports & Exercise, 45(7), 1348-1354.
2. Avela, J., La Inen, H.K., & Komi, P.V. (1999). Altered reflex sensitivity after repeated and prolonged passive muscle stretching. Journal of Applied Physiology, 86(4), 1283-1291.
3. Bacurau, R.F.P., Monteiro, G.A., Ugrinowitsch, C., Tricoli, V., Cabral, L.F., & Aoki, M.S. (2009). Acute Effect of a Ballistic and a Static Stretching Exercise Bout on Flexibility and Maximal Strength. Journal of Strength and Conditioning Research, 23(1), 304-308.
4. Barnes, M. F. (1997). The basic science of myofascial release. Journal of Bodywork and Movement Therapies, 1(4), 231-238.
5. Beardsley, C. & Škarabot, J. (2015). Effects of Self-Myofascial Release: A Systematic Review. Journal of Bodywork & Movement Therapies, 19(4), 747-758.
6. Behara, B., & Jacobson, B.H. (2015). The acute effects of deep tissue foam rolling and dynamic stretching on muscular strength, power, and flexibility in division I linemen. Journal of Strength and Conditioning Research. [Citation].
7. Behm, D.G. & Chaouachi, A. (2011). A review of the acute effects of static and dynamic stretching on performance. European Journal of Applied Physiology, 111(11), 2633-2651.

8. Behm, D.G. & Kibele, A. (2007). Effects of static stretching on jump performance. European Journal of Applied Physiology, 101, 587-594.
9. Behm, D.G., Bambury, A., Cahill, F., & Power, K. (2004). Effect of acute static stretching on force, balance, reaction time, and movement time. Medicine & Science in Sports & Exercise, 36(8), 1397-1402.
10. Behm, D.G., Blazevich, A.D., Kay, A.J., & McHugh, M. (2016). Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. Applied Physiology, Nutrition, and Metabolism, 41, 1-11.
11. Behm, D.G., Plewe, S., Grage, P., Rabbani, A., Taghi Beigi, H., Byrne, J.M., & Button, D.C. (2011). Relative static stretch-induced impairments and dynamic stretch-induced enhancements are similar in young and middle-aged men. Applied Physiology, Nutrition & Metabolism, 36(6), 790-798.
12. Bradbury-Squires, A.J., Notfall, J.C., Sullivan, K.M., Behm, D.G., Power, K.E., & Button, D.C. (2015). Roller-massager application to the quadriceps and knee-joint range of motion and neuromuscular efficiency during a lunge. Journal of Athletic Training, 50(2), 133-140.
13. Bron C. & Dommerholt, J.D (2012). Etiology of myofascial trigger points. Current Pain and Headache Reports, 16, 439-444.

14. Bushell, J.E., Dawson, S.M., & Webster, M.M. (2015). Clinical Relevance of Foam Rolling on Hip Extension Angle in a Functional Lunge Position. Journal of Strength and Conditioning Research, 29(9), 2397-2403.
15. Chaouachi, A.G., Castagna, C.G., Chtara, M.G., Brughelli, M.G., Turki, O.G., Galy, O.G., Chamari, K.G., & Behm, D.G. (2010). Effect of Warm-Ups Involving Static or Dynamic Stretching on Agility, Sprinting, and Jumping Performance in Trained Individuals. Journal of Strength and Conditioning Research, 24(8), 2001-2011.
16. Chaudhry, H., Schleip, R., Ji, Z., Bukiet, B., Maney, M., & Findley, T. (2008). Three-dimensional mathematical model for deformation of human fasciae in manual therapy. The Journal of American Osteopathic Association 108, 379-390.
17. Cho, S, Kim, S, & Park, D. (2015). The comparison of the immediate effects of application of the suboccipital muscle inhibition and self-myofascial release techniques in the suboccipital region on short hamstring. Journal of Physical Therapy Science, 27(1), 195-197.
18. Costa, P., Ryan, E., Herda, T., Walter, A., Hoge, K., & Cramer, J. (2010). Acute effects of passive stretching on the electromechanical delay and evoked twitch properties. European Journal of Applied Physiology, 108(2), 301-310.
19. Cross, T.M., Gibbs, N., Houang, M.T., & Cameron, M. (2004). Acute quadriceps muscle strains: magnetic resonance imaging features and prognosis. American Journal of Sports Medicine, 32(3), 710-719.

20. Dalrymple, K.J., Davis, S.E., Dwyer, G.B., & Moir, G.L. (2010). Effect of Static and Dynamic Stretching on Vertical Jump Performance in Collegiate Women Volleyball Players. Journal of Strength and Conditioing Research, 24(1), 149-155.

21. Decoster, L.C., Cleland, J., Altieri, C., & Russell, P. (2005). The effects of hamstring stretching on range of motion: a systematic literature review. Journal of Orthopedic Sports Physical Therapy, 35, 377-387.

22. DePino, G.M., Webright, W.G., & Arnold, B.L. (2000). Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. Journal of Athletic Training, 35(1), 56-59.

23. Di Cagno, A.C., Baldari, C.C., Battaglia, C.C., Gallotta, M.C., Videira, M,C., Piazza, M.C., Guidetti, L.C. (2010). Preecercise static stretching effect on on leaping performance in elite rhythmic gymnasts. Journal of Strength and Conditioning Research, 24(8), 1995-2000.

24. Ebben, W.P., Carroll, R.M., & Simenz, C.J. (2004). Strength and conditioning practices of National Hockey League strength and conditioning coaches. Journal of Strength and Conditioning Research 18(4), 889-897.

25. Ebben, W.P., Hintz, M.J., & Simenz, C.J. (2005). Strength and conditioning practices of Major League Baseball strength and conditioning coaches. Journal of Strength and Conditioning Research 19(3), 538-546.

26. Eguchi, Y., Jinde, M., Murooka, K., Konno, Y., Ohta, M., & Yamato, H. (2014). Stretching versus transitory icing: which is the more effective treatment for

attenuating muscle fatigue after repeated manual labor? European Journal of Applied Physiology, 114(12), 2617-2623.

27. Findley T., Chaudhry H., Stecco A., & Roman M. (2012). Fascia research–a narrative review. Journal of Bodywork and Movement Therapies, 16, 67-75.
28. Findley, T. W. (2009). Second international fascia research congress. International Journal of Therapeutic Massage & Bodywork, 2(2), 1.
29. Fletcher, I.M. & Monte-Colombo, M.M. (2010). An investigation into the effects of different warm-up modalities on specific motor skills related to soccer performance. Journal of strength and Conditioning research, 24(8), 2096-2101.
30. Fowles, J.R., Sale, D.G., & MacDougall, J.D. (2000). Reduced strength after passive stretch of the human plantarflexors. Journal of Applied Physiology, 89, 1179-1188.
31. Gelen, E. (2010). Acute effects of different warm-up methods on sprint, slalom dribbling, and penalty kick performance in soccer players. Journal of strength and Conditioing Research, 24(4), 950-956.
32. Hadala, M., & Barrios, C. (2009). Different strategies for sports injury prevention in an America's Cup yachting crew. Medicine in Science & Sports & Exercise. 41, 1587–1596.
33. Haddad, M., Dridi, A., Chtara, M., Chaouachi, A., Wong, D.P., Behm, D.G., & Chamari, K. (2014). Static stretching can impair explosive performance for at least 24 hours. Journal of Strength and Conditioning Research, 28(1), 140-146.

34. Halperin, I., Aboodarda, S.J., Button, D.C., Anderson, L.L., & Behm, D.G. (2014). Roller massager improves range of motion of plantar flexor muscles without subsequent decreases in force parameters. International Journal of Sports Physical Therapy, 9(1), 92-102.

35. Handrakis, J.P., Southard, V.N., Abreu, J.M., Aloisa, M.R., Doyen, M.M., Echevarria, L.A., Hwang, H.C., Samuels, C.C., Venegas, S.C., & Douris, P.C. (2010). Static Stretching Does Not Impair Performance in Active Middle-Aged Adults. Journal of Strength and Conditioning research, 24(3), 825-830.

36. Healey, K.C., Hatfield, D.L., Blanpied, P., Dorfman, L.R., & Riebe, D. (2014). The effects of Myofascial release with foam rolling on performance. Journal of Strength and Conditioning Research, 28(1), 61-68.

37. Hedley, G. (2010). Notes on visceral adhesions as fascial pathology. Journal of Bodywork and Movement Therapies 14, 255-261.

38. Herda, T.J., Cramer, J.T., Ryan, E.D., & McHugh, M.P. (2008). Acute effects of static versus dynamic stretching on isometric peak torque, electromyography, and mechanomyography of the biceps femoris muscle. Journal of Strength and Conditioning Research, 22(3), 809-817.

39. Hindle, K., Whitcomb, T., Briggs, W., & Hong, J. (2012). Proprioceptive neuromuscular facilitation (PNF): its mechanisms and effects on range of motion and muscular function. Journal of Human Kinetics, 31, 105-113.

40. Howe, E., Lininger, A., Schlegel, L., Harwell, A., Paulson, S., Braun, W., & Sanders, J. (2013). The Effects of Foam Rolling and Static Stretching on Flexibility and Acute Muscle Soreness. International Journal of Exercise Science, 9(1), 33.

41. Janot, J., Malin, B., Cook, R., Hagenbucher, J., Draeger, A., Jordan, M., & Quinn, E. (2013). Effects of Self Myofascial Release and Static Stretching on Anaerobic Power Output. Journal of Fitness Research, 2(1). [Citation].

42. Jay, K., Sundstrup, E., Sondergaard, S.D., Behm, D.G., Brandt, M, Særvoll, C.A., Jakobsen, M.D., & Anderson, L.L. (2014). Specific and cross over effects of massage for muscle soreness: randomized controlled trial. International Journal of Sports Physical Therapy, 9(1), 82-91.

43. Jones, A., Brown, L.E., Coburn, J.W., & Noffal, G.J. (2015). Effects of foam rolling on vertical jump performance. International Journal of Kinesiology & Sports Science, 3(3).

44. Kallerud, H. & Gleeson, N. (2013). Effects of stretching on performances involving stretch-shortening cycles. Sports Medicine, 43, 733-750.

45. Kay, A.D. & Blazevich, A.J. (2012). Effects of acute static stretch on maximal muscle performance: a systematic review. Medicine & Science in Sport & Exercise, 44(1), 154-164.

46. Kay, A.D. & Blazevish, A.J. (2009). Moderate-duration static stretch reduces active and passive plantar flexor moment but not Achilles tendon stiffness or active muscle length. Journal of Applied Physiology, 106(4), 1249-1256.

47. Kistler, B.M., Walsh, M.S., Horn, T.S., & Cox, R.H. (2010). The acute effects of static stretching on the sprint performance of collegiate men in the 60- and 100-m dash after a dynamic warm-up. Journal of Strength and Conditioning Research, 24(9), 2280-2284.

48. Knudson, D. & Guillermo, N. (2005). Time course of stretch-induced isometric strength deficits. European Journal of Applied Physiology, 94(3), 348-351.

49. Knudson, D. (1999). Stretching during warm-up: do we have enough evidence? Journal of Physical Education, Recreation & Dance, 70(7), 24-27.

50. Kubo, K., Kanehisa, H., Kawakami, Y., & Fukunaga, T. (2001). Influence of static stretching on viscoelastic properties of human tendon structures in vivo. Journal of Applied Physiology, 90(2), 520-527.

51. Kumka, M., & Bonar, J. (2012). Fascia: a morphological description and classification system based on a literature review. The Journal of the Canadian Chiropractic Association, 56(3), 179.

52. Little, T. & Williams, A.G. (2006). Effects of differential stretching protocols during warm-ups on high speed motor capacities in professional soccer players. Journal of Strength and Conditioning Research, 20(1), 203-207.

53. Liu, H., Garrett, W.E., Moorman, C.T., & Yu, B. (2012). Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature. Journal of Sport and Health Science, 1(2), 92-101.

54. MacDonald, G.Z., Penny, M.D.H., Mullaley, M.E., Cuconato, A.L., Drake, C.D.J., Behm, D.G., & Button., D.C. (2013). An acute bout of self-myofascial release increases range of motion without a subsequent decrease in muscle activation or force. Journal of Strength and Conditioning Research, 27(3), 812-821.

55. Magnusson, S.P., Simonsen, E.B., Aagaards, P., gleam, G.W., McHugh, M.P., & Kjaer, M. (1995). Viscoelastic response to repeated static stretching in the human hamstring muscle. Scandinavian Journal of Medicine & Science in Sports, 5, 342-347.

56. Markovic, G. (2015). Acute effects of instrument assisted soft tissue mobilization vs. foam rolling on knee and hip range of motion in soccer players. Journal of Bodywork and Movement Therapies, 19(4), 90-696.

57. Martinez Rodriguez, R. & Galandel Rio, F. (2013). Mechanistic basis of manual therapy in myofascial injuries sonoelastographic evolution control. Journal of Bodywork and Movement Therapies, 17, 221-234.

58. Mendiguchia, J., Alentom-Geli, E., Samuelsson, K., & Karlsson, J. (2015). Sports injuries: Prevention, diagnosis, treatment and rehabilitation (2nd ed.). Berlin: Springer-Verlag.

59. Mikesky, A.E. (2002). Acute effects of The Stick on strength, power, and flexibility. Journal of Strength and Conditioning Research, 16(3), 446-450.

60. Miyahara, Y., Naito, H., Ogura, Y, Katamoto, S, & Aoki, J. (2013). Effects of proprioceptive neuromuscular facilitation stretching and static stretching on

maximal voluntary contraction. Journal of Strength and Conditioning Research, 27(1), 195-201.

61. Mizuno, T., Matsumoto, M., & Umemura, Y. (2013). Viscoelasticity of the muscle-tendon unit is returned more rapidly than range of motion after stretching. Scandinavian Journal of Medicine & Science in Sports, 23(1), 23-30.
62. Mohr, A.R., Long, B.C., & Goad, C.L. (2014). Effect of foam rolling and static stretching on passive hip-flexion range of motion. Journal of Sport Rehabilitation, 23, 296-299.
63. Morse, C.I., Degens, H., Seynnes, O.R., Maganaris, C.N., & Jones, D.A. (2008). The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. The Journal of Physiology, 586(1), 97-106.
64. Murphy, J.R., Di Santo, M.C., Alkanani, T., & Behm, D.G. (2010). Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. Applied Physiology, Nutrition, and Metabolism, 35, 679-690.
65. Myburgh C., Larsen A.H., & Hartvigsen, J. (2008). A systematic, critical review of manual palpation for identifying myofascial trigger points: evidence and clinical significance. Archives of Physical Medicine and Rehabilitation, 89, 1169-1176.
66. Nakamura, M., Ikezoe, T., Kobayashi, T., Umegaki, H., Takeno, Y., Nishishita, S., & Ichihashi, N. (2014). Acute effects of static stretching on muscle hardness of the

medial gastrocnemius muscle belly in humans: an ultrasonic shear-wave elastography study. Ultrasound in Medicine & Biology, 40(9), 1991-1997.

67. Nelson, A.G., Allen, J.D., Cornwell, A., Kokkonen, J. (2001). Inhibition of Maximal Voluntary Isometric Torque Production by Acute Stretching is Joint-Angle Specific. Research Quarterly for Exercise and Sport, 72(1), 68-70.
68. Nelson, A.G., Driscoll, N.M., Landin, D.K., Young, M.A., & Schexnayder, I.C. (2005). Acute effects of passive muscle stretching on sprint performance. Journal of Sports Sciences, 23(5), 449-454.
69. O'Connor, D.M., Crowe, M.J., & Spinks, W.L. (2006). Effects of static stretching on leg power during cycling. Journal of Sports Medicine and Physical Fitness, 46(1), 52-56.
70. O'Connell J.A. (2003). Bioelectric responsiveness of fascia: a model for understanding the effects of manipulation. Techniques in Orthopaedics 18, 67-73.
71. Okamoto, T., Masuhara, M., & Ikuta, K. (2014). Acute effects of self-myofascial release using a foam roller on arterial function. Journal of Strength and Conditioning Research, 28(1), 69-73.
72. Orchard, J. & Seward, H. (2002). Epidemiology of injuries in the Australian Football League, seasons 1997-2000. British Journal of Sports Medicine, 36, 39-44.

73. Peacock, C.A., Krein, D.D., Silver, T.A., Sanders, G.J., & Von Carlowitz, K.A. (2014). An acute out of self-myofascial release in the form of foam rolling improves performance testing. International Journal of Exercise Science, 7(3), 202-211.
74. Power, K., Behm, D., Farrell, C., Carroll, M., & Young, W. (2004). An acute bout of static stretching: effects on force and jumping performance. Medicine & Science in Sports & Exercise, 36(8), 1389-1396.
75. Roylance, D.S., George, J.D., Hammer, A.M., Rencher, N., Fellingham, G.W., Hager, R.L., & Myrer, W.J. (2013). Evaluating acute changes in joint range-of-motion using self-myofascial release, postural alignment exercises, and static stretches. International Journal of Exercise Science 6(4), 310-319.
76. Schleip, R. & Muller, D.G. (2013). Training principals for fascial connective tissues: scientific foundation and suggested practical application. Journal of Bodywork and Movement Therapies, 17, 103-115.
77. Schleip, R. (2003a). Fascial plasticity – a new neurobiological explanation: part 1. Journal of Bodywork and Movement Therapies, 7(1), 11-19.
78. Schleip, R. (2003b). Fascial plasticity – a new neurobiological explanation: part 2. Journal of Bodywork and Movement Therapies, 7(2), 104-116.
79. Schleip, R., Jäger, H., & Klingler, W. (2012). What is 'fascia'? A review of different nomenclatures. Journal of Bodywork and Movement Therapies, 16(4), 496-502.

80. Sekir, U., Arabaci, R., Akove, B., & Kadagan, S.M. (2010). Acute effects of static stretching on leg flexor and extensor isokinetic strength in elite women athletes. Scandinavian Journal of Medicine & Science in Sports, 20, 268-281.

81. Siatras, T.A., Mittas, V.P., Mameletzi, D.N., & Vamvakoudis, E.A. (2008). The duration of the inhibitory effects with static stretching on quadriceps peak torque production. Journal of Strength and Cpnditioning Research, 22(1), 40-46.

82. Simenz, C.J., Dugan, C.A., & Ebben, W.P. (2005). Strength and conditioning practices of National Basketball Association strength and conditioning coaches. Journal of Strength and Conditioning Research 19(3), 495-504.

83. Simic, L., Sarabon, N., & Markovic, G. (2012). Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. Scandinavian Journal of Medicine and Science in Sports, 23, 131-148.

84. Simmonds, N., Miller, P., & Gemmell, D.C. (2012). A theoretical framework for the role of fascia in manual therapy. Journal of Bodywork & Movement Therapies, 16(1), 83-93.

85. Skarabot, J., Beardsley, C, & Stirn, I. (2015). Comparing the effects of self-myofascial release with static stretching on ankle range-of-motion in adolescent athletes. International journal of Sports Physical Therapy, 10(2), 203-212.

86. Stafilidis, S. & Tilp, M. (2015). Effects of short duration static stretching on jump performance, maximum voluntary contraction, and various mechanical and

morphological parameters of the muscle–tendon unit of the lower extremities. European Journal of Applied Physiology, 115(3), 607-617.

87. Sullivan, K.M., Silvey, D.B.J., Button, D.C., & Behm, D.G. (2013). Roller massager application to the hamstrings increases sit and reach range of motion within five to ten seconds without performance impairments. The International Journal of Sports Physical Therapy, 8(3), 228-236.
88. Tozzi, P. (2012) Selected fascial aspects of osteopathic practice. Journal of Bodywork and Movement Therapies, 16, 503-519.
89. Trajano, G.S., Seitz, L., Nosaka, K., & Blazevich, A.J. (2013). Contribution of central vs. peripheral factors to the force loss induced by passive stretch of the human plantar flexors. Journal of Appied Physiology, 115(2), 212-218.
90. Trajano, G.S., Seitz, L., Nosaka, K., & Blazevich, A.J. (2014). Can passive stretch inhibit motoneuron facilitation in the human plantar flexors? Journal of Applied Physiology, 117(12), 1486-1492.
91. Van Beijsterveldt, A.M.C., Van de Port, L.G.L., & Backx, F.J.G. (2013). Risk factors for hamstring injuries in male soccer players: A systematic review of prospective studies. Scandinavian Journal of Medicine & Science in Sports, 23(3), 253-262.
92. Van Gelder, L.H. & Bartz, S.D. (2011). The Effect of Acute Stretching on Agility Performance. Journal of Strength and Conditioning Research, 25(11), 3014-3021.

93. Vigotsky, A.D., Lehman, G.J., Contreras, B., Beardsley, C., Chung, B., & Feser, E.H. (2015). Acute effects of anterior thigh foam rolling on hip angle, knee angle, and rectus femoris length in the modified Thomas test. PeerJ, 3, e1281.

94. Waugh, C.M., Korff, T., Fath, F., & Blazevich, A.J. (2014). Effects of resistance training on tendon mechanical properties and rapid force production in prepubertal children. Journal of Applied Physiology, 117(3), 257–266.

95. Weir, D, Tingley, J., & Elder, G. (2005). Acute passive stretching alters the mechanical properties of human plantar flexors and the optimal angle for maximal voluntary contraction. European Journal of Applied Physiology, 93(5), 614-623.

96. Weppler, C.H. & Magnusson, P. (2010). Increasing muscle extensibility: a matter of increasing length or modifying sensation? Journal of the American Physical Therapy Association, 90, 438-449.

97. Whatman, C., Knappstein, A., & Hume, P. (2006). Acute changes in passive stiffness and range of motion post-stretching. Physical Therapy in Sport, 7(4), 195-200.

98. Winchester, J.B., Nelson, A.G., Landin, D.A., Young, M.C., Schexnayder, I.C. (2008). Static stretching impairs sprint performance in collegiate track and field athletes. Journal of Strength and Conditioning Research, 22(1), 13-19.

99. Young, W. & Elliott, S. (2001). Acute effects of static stretching, proprioceptive neuromuscular facilitation stretching, and maximum voluntary contractions on

explosive force production and jumping performance. Research Quarterly for Exercise and Sport, 72(3), 273–279.

100. Young, W., Elias, G., & Power, J. (2006). Effects of static stretching volume and intensity on plantar flexor explosive force production and range of motion. Journal of Sports Medicine and Physical Fitness, 46, 403-411.

101. Young, W.B. & Behm, D.G. (2003). Effects of running, static stretching and practice jumps on explosive force production and jumping performance. The Journal of Sports Medicine and Physical Fitness, 43(1), 21-27.

CHAPTER 2: CO-AUTHORSHIP STATEMENT

The following details the roles played in the preparation of the manuscript.

Design and identification of the research proposal

Research questions were generated from previous FR/RM and SS investigations from Dr. Behm's lab. Methodology was developed by myself and Dr. Behm, and was refined based on pilot testing outcomes and feedback from my thesis proposal presentation. I obtained approval from the Human Research Ethics Board (HREB) with some input from Dr. Behm.

Practical aspects of the research

Data collection required a principal investigator (me) and aid from one or two assistants for each experimental session. I collected all data myself, while Joseph Whitten, Patrick Quigley, and Jonathan Reid served as primary assistants.

Data analysis

I performed all data analysis procedures independently. Statistics were run using SPSS software by Dr. Behm and myself.

Manuscript preparation

I wrote all sections of the manuscript myself, with feedback provided by Dr. Behm.

CHAPTER 3: MANUSCRIPT

Additional roller massage applied at ten-minute intervals can prolong hip and knee flexion range of motion improvements up to 30-minutes post warmup without impairing neuromuscular performance

Authors: Hodgson DD, Quigley P, Whitten JHD, Reid J, Behm DG.

Institution: School of Human Kinetics and Recreation
Memorial University of Newfoundland
St. John's, Newfoundland, Canada, A1M 3L8

Running Title: Roller massage subsequent to static stretching & roller massage warmups

3.1 – Abstract

Roller massage (RM) has been shown to increase range of motion (ROM) without incurring subsequent performance deficits. On the contrary, prolonged static stretching (SS) can induce performance impairments. It is not known if adding RM to a stretching routine would augment stretch-induced ROM improvements. Furthermore, it is not known whether performing RM at intervals after stretching would prolong ROM increases. Hence the objective of this study was to examine the effects of combining SS and RM with and without subsequent RM at 10-minute intervals on ROM and neuromuscular performance measures. Subjects (n=12) participated in 5 sessions that included 1) SS only (SS_rest), 2) SS+RM (SS+RM_rest), 3) SS with subsequent RM at 10, 20-min post-stretch (SS_RM), 4) SS+RM with subsequent RM at 10, 20-min post-stretch (SS+RM_RM) and 5) Control. For the SS conditions, the quadriceps and hamstrings received passive SS for two repetitions of 30s each. For the SS+RM conditions, passive SS was applied to the quadriceps and hamstrings for one set of 30s each, and RM was performed for 1 repetition of 30s per muscle group. SS_RM and SS+RM_RM conditions received an additional set of 30s RM at 10 and 20 minutes post-warmup, while sessions without additional RM rested for the same duration. Testing measures included hip (HF) and knee (KF) flexion active and passive ROM, hurdle jump height and contact time, countermovement jump (CMJ) height, and maximal voluntary isometric contraction (MVIC) force, measured in this order. Within condition x time interactions showed that initial ROM improvements provided by SS_RM (KF active: p=0.001, ES: 0.8, 7.7%; KF passive: p=0.001, ES: 1.2, 16.2%; HF active: p=0.001, ES: 0.2, 3.1%; HF passive: p=0.001, ES: 0.3, 6.5%) and SS+RM_RM (KF active: p=0.003, ES: 0.7, 9.9%; KF passive: p=0.000, ES: 1.2, 20.8%; HF active: p=0.015, ES: 0.1, 2.8%; HF passive: p=0.001, ES: 0.3, 7.9%) were sustained up to 30-minutes post intervention. Furthermore, SS_RM exhibited significantly greater ROM improvements compared to sessions lacking additional RM in active (SS_rest at post-20: p=0.055, ES: 0.1, 2.4%; post-30: p=0.004, ES: 0.2, 3.4%), and passive HF (SS_rest at post-20: p=0.017, ES: 0.15, 3.4%; SS+RM_rest at post-20: p=0.011, ES: 0.1, 2.8%), as well as active (SS_rest at post-20: p=0.003, ES: 1.0, 8.3%; post-30: p=0.035, ES: 0.6, 6.5%; SS+RM_rest at post-20: p=0.002, ES: 1.0, 8.3%; post-30: p=0.034, ES: 0.55, 6.0%) and passive (SS_rest at post-20: p=0.003, ES: 1.2, 16.8%; post-30: p=0.001, ES: 1.2, 15.4%) KF. Similarly, SS+RM_RM elicited greater ROM improvements than SS_rest in active HF (post-30: p=0.034, ES: 0.2, 3.6%) and passive KF (post-20: p=0.002, ES: 0.7, 10.4%; post-30: p=0.000, ES: 0.7, 12.7%). Significant main effects for time revealed trivial impairments in CMJ height, hurdle jump height, and knee extension MVIC, however there were no significant differences between sessions for KF MVIC, or hurdle jump contact time. In conclusion, active and passive KF, and HF ROM improvements were prolonged by additional RM, while neuromuscular performance remained relatively unaffected.

3.2 – Introduction

Injuries to the lower extremity muscles and fascia are some of the most common setbacks in most sports (Mendiguchia et al., 2015). Hamstring strains have been reported to be the most prevalent injuries in the Australian Football League (Orchard & Seward, 2002), and account for up to 17% of all injuries in professional European soccer, and 13% of all injuries in America's National Football League (Liu et al., 2012). Quadriceps injuries are also of high occurrence among professional athletes (Vigotsky et al., 2015), in particular the rectus femoris (Cross et al., 2004). One review identified shortened optimal muscle length and poor muscle flexibility as leading modifiable risk factors for these injuries (Liu et al., 2012); and although some research has found inconclusive evidence, this notion has typically received support from subsequent investigations (Van Beijsterveldt et al., 2013). Greater range of motion (ROM) is typically associated with a decreased risk of musculotendinous strains and sprains with high velocity sprints and change of direction (Behm et al. 2016, Mohr et al., 2014), and increased athletic performance (Kokkonen et al., 2007). These findings highlight the prospective benefits of acutely increasing ROM prior to exercise participation.

Static stretching (SS) has traditionally been the method of choice for increasing ROM and reducing musculotendinous injury risk for athletes, healthy individuals, and in rehabilitation and clinical settings. SS involves achieving and sustaining a stretch sensation by passively lengthening a muscle until the point of discomfort (POD) is reached or approached (Behm et al., 2016). Indeed, the beneficial effects of SS on acute flexibility are well documented and have gained tremendous support from the scientific community (Behm & Chaouachi, 2011; Simic et al., 2012; Kay & Blazevich, 2012; Kallerud & Gleeson, 2013; Behm et al., 2016). These improvements are likely due to changes in stretch tolerance (Magnusson et al., 1995; Mizuno et al., 2013), neurophysiological reflex inhibition (Guissard and Duchateau, 2004; Guissard and Duchateau, 2006; Guissard et al., 1988; Trajano et al., 2017), visco-elasticity (McHugh et al., 1992) or from acute reductions in muscle and tendon stiffness (Guissard and Duchateau, 2004; Weppler and Magnusson, 2010; Morse et al., 2008). More recently however, SS has been under scrutiny based on reports of its association to subsequent performance deficits. Ample research has emerged claiming that sustained bouts of SS lead to acute impairments in neuromuscular tasks (i.e. force, power, balance, sprint speed, running economy and others)(Behm et al. 2016, Behm & Chaouchi, 2011; Kay & Blazevich, 2012), although there is evidence for a dose-response relationship in which SS leads to impairments principally when sustained for >60-seconds (Behm et al., 2016). Hence further research is necessary to identify alternative strategies for improving ROM without inducing performance impairments over a prolonged period.

Foam rolling (FR) and roller massage (RM) are manual therapy techniques, each involving the manipulation of a hard cylinder (often wrapped in dense foam) over the surface of muscles and fascia. Among other purported benefits, FR/RM have been proposed as a method capable of replacing or supplementing SS as a means for acutely improving flexibility. Thus, a recent, but relatively consistent base of literature has emerged, with many researchers (e.g. Bradbury-Squires et al., 2015; Halperin et al., 2014; Macdonald et al., 2014; MacDonald et al., 2013; Sullivan et al., 2013; Jay et al., 2014; Mohr et al., 2014; Peacock et al., 2014; Cho et al., 2015; Behara & Jacobson, 2015) supporting FR/RM as a capable means of acutely enhancing ROM. Furthermore, there is a growing body of evidence that FR/RM does not significantly impair (e.g. Mikesky et al., 2002; Sullivan et al., 2013; Halperin et al., 2014; Healey et al., 2014; Bahara & Jacobson, 2015) or may enhance (Peacock et al., 2014) subsequent neuromuscular performance.

Despite promising reports associating FR/RM with improved flexibility, greater improvements in ROM are typically documented with SS for a similar stimulus volume, a notion supported by studies directly comparing SS to FR/RM (Halperin et al., 2014; Mohr et al., 2014; Škarabot et al., 2015). Limited research has examined whether a combination of FR/RM can elicit similar ROM improvements to SS. Mohr and colleagues (2014) reported greater hip flexion ROM improvements following 3-minutes of both FR and SS (23.6%) than 3-minutes of either on their own (FR: 6.9%; SS: 12.3%). Similar findings were reported by Škarabot et al. (2015), who elicited greater ankle dorsiflexion ROM improvements with 90-seconds of both FR and SS (9.1%) than 90-seconds of either on their own (FR: no change; SS: 6.2%). In both studies the total volume was doubled for the combined intervention, and neither study monitored changes in performance. Thus, it remains unknown how combining FR/RM and SS affects ROM and neuromuscular performance compared to the same volume of either intervention alone.

Further research is required to determine if adding RM to a relatively short duration stretching routine would augment stretch-induced ROM improvements. Furthermore, it is not known whether performing RM at intervals after the stretching routine would prolong the ROM increases. Maintaining improved ROM following a warmup would benefit athletes such as basketball, soccer, and football players who substitute into the game from the bench. Prolonged rest periods may cause the positive effects of their warmup to deteriorate, subjecting these athletes to a greater risk of injury and less than optimal performance. Hence the first objective of this study was to compare similar volumes of a SS only routine to a combined SS and RM protocol. A second objective was to examine the effects of adding additional RM at 10-minute intervals to the aforementioned routines on ROM and neuromuscular performance measures. It was hypothesized that combining SS and RM would provide similar ROM improvements as the same total volume of SS alone, and that these enhancements would remain more evident after 30-minutes when additional RM was incorporated compared to sessions instead involving a rest period. Neuromuscular performance measures were not hypothesized to be affected by SS or by the inclusion of RM.

3.3 – Methodology

Subjects:

A prior statistical power analysis to determine sample size was conducted based on similar studies (Behm et al. 2006; Power et al. 2004; Bacarau et al. 2009) measuring ROM and maximal voluntary isometric contraction (MVIC) force. Based on this analysis, it was determined that between 4-30 participants would be needed to achieve an alpha of 0.05 and a statistical power of 0.8. Thus 12 volunteers, including seven males (26.6 years, 180.6cm, 89.8kg) and five females (25.6 years, 165.3cm, 60.8kg) from the university population were recruited to participate in this study. Participants were between the ages of 18-30 years, reported to be recreationally trained (participate in physical activity ≥3times/week), and had no neurological conditions or history of lower body injury during the past 6-months. Participants signed a consent form approved by the Health Research Ethics Authority at Memorial University of Newfoundland (file #: 20170222), in addition to completing the Physical Activity Readiness Questionnaire (Canadian Society for Exercise Physiology 2011). Prior to any testing session, participants were asked to avoid vigorous physical activity and refrain from alcohol consumption for 24-hours. All testing sessions were completed with consistent temperate conditions within the laboratory (~22°C; 35% relative humidity).

Experimental design:

This research used a within subject, repeated measures design during which participants completed five testing conditions on separate days, in a randomized order. Experimental conditions included 1) SS only (SS_rest), 2) SS and RM (SS+RM_rest), 3) SS with additional RM after 10 and 20-minutes (SS_RM), 4) SS and RM with additional RM after 10 and-20 minutes (SS+RM_RM), and 5) control. Testing measures were performed prior to, as well as immediately, 10, 20, and 30-minutes post-intervention (prior to additional RM in the SS_RM and SS+RM_RM conditions), and included hurdle jumps, countermovement jump (CMJ), and active (aROM) and passive (pROM) hip and knee flexion ROM in that order. Knee flexion and extension maximal voluntary isometric contractions (MVIC) were also measured following all other tests prior to, immediately post, and 30-minutes post-intervention. Each round of testing took approximately two and a half minutes when MVICs were not included (post-10 and post-20), or 4.5 minutes when MVICs were included (Pre, post, and post-30). Post-10 and post-20 measurements during sessions with additional RM lasted approximately five-minutes (including the RM). Following post, post-10, and post-20 measurements, the subject then rested in a comfortable seated position for the remainder of each 10-minute segment.

Interventions (Independent variables):

All participants completed a dynamic warmup on a cycle ergometer (Monark; Ergomedic 828E) at 60-70-rpm with a resistance of 1-kp (70 Watts) for 5-minutes. Following pretest measurements, subjects completed one of five additional warmup protocols, selected randomly by rolling a standard six-sided dice until a session number (1-5) was rolled which the subject had not yet completed.

All warm-up interventions other than control included SS of the hamstrings and quadriceps. The SS condition only involved SS with no RM either in conjunction with or subsequent to the stretching. Hamstring stretches were performed with the subject lying supine with both knees fully extended. The researcher then passively raised one limb to increase the ROM until the subject indicated that the point of discomfort (POD) had been reached. The quadriceps stretch was performed with the subject in a lunge position with the front limb fixed at 90° hip, knee, and ankle flexion. The rear hip was extended as far as possible with the knee resting on a foam pad. A metal frame was provided to hang onto for stability. The researcher then flexed the knee joint, raising the rear foot, until the POD was reached. Subjects were asked to provide feedback during all stretches allowing the researcher to adapt to changes in the POD. All stretches were held for two repetitions of 30-seconds in a randomized order for the hamstrings and quadriceps of each limb. This duration is supported by recent reviews suggesting that SS ≤60-seconds per muscle group can be performed prior to activity without compromising neuromuscular performance (Kay & Blazevich, 2012; Behm et al., 2011, 2016).

Two interventions included both SS and RM of the hamstrings and quadriceps during the warm-up (SS+RM_rest and SS+RM_RM). The previously described SS protocol preceded the RM protocol except with only one, rather than two 30-second SS bouts per muscle group. RM was then performed passively by the researcher using the Roller Massager by Theraband®, a portable rolling device wrapped with dense ridged foam. With one set of SS and RM each in the combined conditions (SS+RM_rest and SS+RM_RM), the intervention volume durations were equal (60-s) in all experimental conditions. Subjects were positioned prone (for hamstring RM) or seated on the edge of a chair (for quadriceps RM) with their knees fully extended while RM was applied over the full length of the intended muscles, without crossing any joints. All RM was performed for one repetition of 30-seconds per muscle group (in order to match the total volume of the SS only conditions) in a randomized order to a cadence of 60-beats per minute (BPM). This cadence allowed one full cycle to be completed every 2-seconds (1-second from distal to proximal, 1-second returning from proximal to distal). The researcher applied pressure eliciting a perceived pain of 7/10 on the visual analogue scale (VAS-10) as indicated by the subject.

Two conditions applied additional RM following SS only (SS_RM) and SS and RM (SS+RM_RM) at 10 and 20-minutes post-intervention. This interval was selected to ensure that a sufficient rest period would be provided following each round of testing and additional RM. These supplementary bouts were performed by the researcher as previously described, for 30-seconds per muscle group at 60-BPM, and were always performed following the completion of other tests and measurements.

The control condition consisted of a 5-minute rest period between pre and post-test measurements, and then proceeded with additional measurements at 10, 20, and 30-minutes with no SS or RM at any point.

Measurements (Dependent variables):

Countermovement jump (CMJ)

A Vertec measuring device was used to assess CMJ height (Vertec, Sports Imports, Hilliard, OH). The height of the device was adjusted until the fingertips of the subject's dominant arm, extended overhead, brushed against the bottom vein. Subjects were instructed to leap vertically from a two-foot stance as high as possible, reaching with one arm to slap the Vertec at their peak. Although no steps were permitted prior to the leap, it was acceptable for subjects to squat (countermovement without pausing at the bottom) and swing their arms during the movement, thus making the task as natural as possible. The highest vein displaced (measured in ½" intervals) was counted as their CMJ height.

Hurdle jump

The hurdle jump is a modified version of the test first described by Cavanaugh et al. (2017). The test requires the subject's maximum CMJ height to be established. This was measured immediately following the dynamic warmup at the beginning of each testing session using a Vertec measuring device while subjects performed two CMJs, the better of which was used. A hurdle was then set to 75% of the maximum value and placed 6" away from a force plate (AMTI, Watertown, MA, USA). The hurdle jump required subjects to leap over the hurdle starting with a two foot stance from a distance of 6", land with both feet on the force plate, and immediately launch into a vertical CMJ, landing again on the force plate. Subjects were instructed to perform the task as quickly as possible while leaping as high as possible. Vertical jump height and contact time were assessed using force plate analysis. A sampling rate of 2000-Hz and a gain of 1000 was used for force plate data, which was used to measure contact time and hurdle jump height.

Range of motion (ROM)

Active and passive hip flexor ROM was measured using a large protractor designed on the wall of the laboratory. Subjects were positioned supine on the floor against the wall with their hip joint placed against the centre of the protractor. During the initial measurement, tape was placed on the floor marking the heel position to ensure consistent positioning of the subject during subsequent measurements. All measurements were taken from the dominant limb while the non-dominant hip and knee were held securely on the floor. For aROM the participant was asked to raise their leg as far as possible without bending their knee. For pROM the researcher passively raised the subject's leg, maintaining neutral ankle flexion and a fully extended knee, until the end of the ROM was indicated by the subject. The maximum angle of hip flexion achieved was recorded. Active and passive knee flexion ROM was measured for the dominant limb with the subject placed in a lunge position as described in the SS protocol. Measurements were recorded using a handheld goniometer while the subject (aROM) or the researcher (pROM) raised the rear foot to the end of the ROM (MacDonald et al., 2013; Grabow et al. 2017).

Maximal voluntary isometric contraction (MVIC)

To perform MVICs, subjects were seated on the edge of a table with a backrest and a handle on either side. Their torso and upper legs were strapped securely in place, and the ankle of their dominant leg was inserted into a padded strap attached by a high tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., LCCS 250). The knee joint angle was fixed at 120° for knee flexion and 90° for knee extension MVICs. Subjects were instructed to rapidly flex (knee flexion) or extend (knee extension) their knee joint to achieve maximal force as quickly as possible. Each attempt was held for 3-5-seconds once an appropriate plateau in force was observed by the researcher. The greater of two attempts was accepted during pre-testing, while one attempt was performed at post and 30-minutes post-intervention. Data collected with the strain gauge was sampled at 2000-Hz, amplified (Biopac Systems Inc., DA 100, and analog to digital converter MP100WSW), and analyzed using a commercially designed software program (Acq-Knowledge III, Biopac Systems Inc.). Strain gauge data was used to measure peak force (PF) and the F100 (force generated in the first 100-ms of the contraction).

Statistical analysis:

Statistical analyses were computed using SPSS software (Version 22.0, SPSS, Inc., Chicago, IL). Dependent variables underwent assumption of normality (Shapiro-Wilk test) and sphericity (Mauchley test), and if violated, the corrected value for non-sphericity with Greenhouse-Geisser Epsilon was reported. A two-way repeated measures ANOVA (5x5) was performed to determine the existence of significant differences between warmup conditions (SS_rest, SS+RM_rest, SS_RM, SS+RM_RM, control) and time (pre, post, 10-post, 20-post, and 30-post). An alpha level of P=0.05 was considered statistically significant. If significant main effects were demonstrated, Bonferroni post hoc analysis were conducted. The magnitude of change was calculated and reported as trivial (<0.2), small (0.2-0.49), medium (0.5-0.79) or large (≥0.8) effect sizes (ES) (Cohen, 1988). Reliability was calculated with Cronbach alpha interclass correlation coefficient (ICC). Descriptive statistics include means ± standard deviation (SD).

3.4 – Results

Range of Motion:

Active and passive knee flexion, and hip flexion ROM improvements were prolonged by additional RM. Within condition x time interactions showed that initial improvements provided by SS_RM were sustained up to 30-minutes post intervention (knee flexion active: p=0.001, ES: 0.792, 7.7%; knee flexion passive: p=0.001, ES: 1.184, 16.2%; hip flexion active: p=0.001, ES: 0.176, 3.1%; hip flexion passive: p=0.001, ES: 0.334, 6.5%) following additional RM (Table 1). Similarly, initial improvements elicited by SS+RM_RM remained evident 30-minutes post intervention (knee flexion active: p=0.003, ES: 0.718, 9.9%; knee flexion passive: p<0.0001, ES: 1.269, 20.8%; hip flexion active: p=0.015, ES: 0.136, 2.8%; hip flexion passive: p=0.001, ES: 0.316, 7.9%) following additional RM (Table 1). Meanwhile, smaller ROM improvements remained evident for knee flexion passive (SS_rest: p=0.003, ES: 0.634, 10.8%; SS+RM_rest: p=0.009, ES: 0.477, 8.2%) and hip flexion passive (SS_rest: p=0.008, ES: 0.178, 4.1%; SS+RM_rest: p=0.010, ES: 0.258, 5.9%) ROM after 30-minutes of rest compared to respective pre-test values (Table 1).

Between condition x time interactions revealed significantly greater ROM improvements for SS_RM compared to sessions lacking additional RM in active (SS_rest – post-20: p=0.055, ES: 0.146, 2.4%; post-30: p=0.004, ES: 0.218, 3.4%), and passive hip flexion (SS_rest – post-20: p=0.017, ES: 0.152, 3.4%; SS+RM_rest – post-20: p=0.011, ES:

0.125, 2.8%), as well as active (SS_rest – post-20: p=0.003, ES: 1.036, 8.3%; post-30: p=0.035, ES: 0.596, 6.5%; SS+RM_rest – post-20: p=0.002, ES: 1.000, 8.3%; post-30: p=0.034, ES: 0.554, 6.0%) and passive (SS_rest – post-20: p=0.003, ES: 1.260, 16.8%; post-30: p=0.001, ES: 1.175, 15.4%) knee flexion (Table 1). Similarly, SS+RM_RM elicited greater ROM improvements than SS_rest in active hip flexion (post-30: p=0.034, ES: 0.217, 3.6%) and passive knee flexion (post-20: p=0.002, ES: 0.661, 10.4%; post-30: p<0.0001, ES: 0.758, 12.7%).

With initial warmups pooled into either SS only (SS_rest and SS_RM) or SS+RM (SS+RM_rest and SS+RM_RM), hip flexion active (SS: p=0.045, ES: 0.076, 1.2%; SS+RM: p=0.025, ES: 0.093, 1.6%; CONTROL: p=0.049, ES: 0.095, 1.7%) and passive (SS: p<0.0001, ES: 0.211, 4.8%; SS+RM: p<0.0001, ES: 0.282, 6.5%; CONTROL: p=0.037, ES: 0.074, 1.6%), and knee flexion active (SS: p<0.0001, ES: 0.588, 6.5%; SS+RM: p=0.007, ES: 0.450, 5.9%) and passive (SS: p<0.0001, ES: 1.008, 17.4%; SS+RM: p<0.0001, ES: 0.755, 12.6%) ROM were all improved, while CMJ height (SS: p=0.001, ES: 0.215, -2.3%; SS+RM: p<0.0001, ES: 0.202, -2.4%; CONTROL: p<0.0001, ES: 0.272, -3.3%) was impaired from pre-test to post-test (Figures 1-3). Significant condition x time interactions revealed that sessions with initial warmups including SS only (aROM: p=0.019, ES: 0.624, 8.7%; pROM: p=0.001, ES: 0.853, 16.7%) as well as SS+RM (pROM: p=0.010, ES: 0.697, 12.5%) improved knee flexion ROM compared to control, while no differences emerged between SS and SS+RM (Figures 1-2). Significant main effects for time indicate improved post-test ROM compared to pre-test for hip flexion (aROM: p=0.014, ES: 0.087, 1.5%; pROM: p<0.001, ES: 0.190, 4.3%) and knee flexion (aROM: p=0.001, ES: 0.329, 4.4%; pROM: p<0.001, ES: 0.552, 10.6%), while there were no main effects for condition.

Jump Measures:

A significant main effect for condition demonstrated that CMJ height was compromised in SS_rest (p=0.050, ES: 0.309, 3.9%) compared to control. Significant main effects for time revealed that CMJ height was impaired at post (p=0.005, ES: 0.218, 2.6%), post-10 (p<0.0001, ES: 0.259, 3.1%), post-20 (p<0.0001, ES: 0.288, 3.5%), and post-30 (p=0.006, ES: 0.318, 3.9%) compared to pre-test, with the exception of SS+RM_RM during which no significant differences were found at post-test or post-30 (Table 2). There were significant but small magnitude differences between pre-test measures for SS_rest (p=0.036, ES: 0.260, -3.3%), SS+RM_rest (p=0.025, ES: 0.344, -4.3%), and SS_RM (p=0.023, ES: 0.389, -4.7%) compared to control. With all conditions combined, there were also significant time effects revealing deficits in hurdle jump height at post-test (p=0.009, ES: 0.267, 7.0%) and post-20 (p=0.034, ES: 0.266, 6.6%) only, while there were no significant changes in contact time (Table 2).

Significant condition effects indicate reduced post-test CMJ height compared to control for sessions containing SS only (p=0.012, ES: 0.275, -3.5%) and SS+RM (p=0.017, ES: 0.224, -3.4%) in the initial warmup, however no interactions occurred between SS only and SS+RM (Figure 4). Main time effects demonstrate a reduction in CMJ height from pre-test to post-test ($p<0.001$, ES: 0.231, 2.7%) with no significant condition x time interactions.

Knee Extension and Flexion MVIC Force Measures:

Significant main effects for time indicate a reduction in knee extension peak force at post-test ($p=0.002$, ES: 0.152, 3.8%) and post-30 ($p=0.024$, ES: 0.170, 4.3%) only. There were no significant differences found in knee flexion peak force and f100, or in knee extension f100.

Reliability Coefficients:

ICC reliability coefficients for hamstrings active (0.98) and passive (0.993) ROM, CMJ (0.98), quadriceps MVIC (0.98) and F100 (0.92), hamstrings MVIC (0.97) and F100 (0.91), hurdle jump height (0.96) and contact time (0.91) were all categorized as excellent. Moderate reliability correlations were found for quadriceps active (0.68) and passive (0.74) ROM.

3.5 – Discussion

The most important findings in the present study were that applying RM 10 and 20-minutes following SS (SS_RM) or following a combination of SS+RM (SS+RM_RM) prolonged knee flexion and hip flexion aROM and pROM improvements up to 30 minutes. Whereas there were some ROM improvements provided by SS (SS_rest) and combining SS and RM (SS+RM_rest) that persisted up to 30-minutes without additional RM, all ROM enhancements provided by SS_RM and SS+RM_RM were maintained or augmented with additional RM. Main condition interactions demonstrated that SS_rest was the only condition to impair CMJ height; while conditions involving RM (SS+RM_rest, SS_RM, SS+RM_RM) did not adversely affect subsequent performance measures compared to control. Sessions grouped by initial warmup (SS only or SS+RM) generated similar improvements in pre-test to post-test ROM, while eliciting similar decrements to CMJ height.

Initial knee (18.3%) and hip flexion (4.1%) pROM improvements brought about by SS_rest remained evident throughout the 30-minute recovery period (10.8% and 4.1% respectively). Initial knee flexion aROM improvements (6.0%) persisted for 10-minutes (3.4%) but returned to baseline prior to 20-minutes. ROM has been demonstrated to persist for ≤3 (DePino et al., 2000), ≤5 (Whatman et al., 2006), ≤10 (Behm et al., 2011; Skarabot & Beardsley, 2015), ≤30 (Fowles et al., 2000; Murphy et al., 2010; Mizuno et al., 2013), ≤90 (Knudson, 1999), and ≤120 minutes (Power et al.,

2004) following acute SS; therefore the present study joins a relatively conflicting pool of literature. These variances are likely due to inconsistent protocols such as stretching duration and intensity or different muscle groups examined.

Similar to SS_rest, initial knee (10.9%) and hip flexion (6.6%) pROM improvements elicited by SS+RM_rest remained significantly improved following 30-minutes of rest (8.2% and 5.9% respectively). This is the first study monitoring the effects of combined SS and RM over time. These findings suggest that SS+RM may exhibit similar lasting effects on ROM to SS alone. The scant pool of research on this topic exposes a need to further probe into the time-course of effects brought about by acute SS+RM. This information would be of particular interest to athletes who endure prolonged rest between warmup and intense exercise.

Considering this uncertainty, a mechanism to sustain acute ROM improvements following a warmup may be beneficial for athletes entering a game from the bench. The present study is the first to report on RM applied subsequent to a SS or SS+RM routine. Whereas sessions involving a post-intervention rest period saw a diminishing effect to most ROM measurements over time, sessions including RM at 10 and 20-minutes post-intervention demonstrated maintained or greater ROM after 30-minutes (Table 1). Initial improvements in knee flexion (aROM: 7.1%, pROM: 16.5%) and hip flexion (aROM: 2.0%, pROM: 5.5%) ROM for SS_RM remained elevated up to 30-minutes (knee flexion aROM: 7.7%, pROM: 16.2%; hip flexion aROM: 3.1%, pROM: 6.5%). Similarly, initial ROM improvements brought about by SS+RM_RM for knee flexion (aROM: 7.7%, pROM:

14.1%) and hip flexion (aROM: 2.0%, pROM: 6.4%) were sustained up to 30-minutes (knee flexion aROM: 9.9%, pROM: 20.8%; hip flexion aROM: 2.8%, pROM: 7.9%). Thus, additional RM appears capable of prolonging, or augmenting ROM improvements elicited during warmups involving SS and SS+RM. RM (or FR) on its own has been reported to elicit enhancements to ROM that return to baseline (Halperin et al., 2014) or remain to a smaller extent (MacDonald et al., 2013) after 10-minutes. These findings are in contrast to the current study which indicates that RM, when combined with SS (SS+RM_rest), or when performed at 10-minute intervals (SS_RM, SS+RM_RM), can exhibit ROM improvements up to 30-minutes. It remains unknown whether RM alone, with or without subsequent RM (e.g. RM_rest and RM_RM) is capable of providing a similar warmup effect to combined SS+RM routines. The optimal frequency of additional RM intervals to maximize ROM whilst minimizing impairments is also unclear. Therefore, future investigations should deploy warmups comparing SS, RM, and SS+RM with subsequent RM performed at varying intervals. Furthermore, it may be beneficial to investigate the effects of additional RM following intense dynamic exercise. This would simulate athletes resting during a game or at intermission, and help determine if ROM can be effectively maintained using RM while they wait to resume activity.

In addition to ROM measurements, neuromuscular performance was also monitored. According to a main condition effect, SS_rest exhibited significantly impaired CMJ height (-3.9%) compared to control. This is the lone intervention (SS_rest) containing no RM at any point, while the remaining 3 conditions were not significantly different than control. Despite indications that performance deficits occur mainly with SS >60-seconds duration (Kay & Blazevich, 2012; Kallerud & Gleeson, 2013; Behm et al., 2016), the 60-seconds of SS performed in this study was enough to elicit minor impairments to CMJ height. It is unclear if the inclusion of RM in all other sessions was responsible for counterbalancing the negative effects of SS. Main time effects demonstrate impaired CMJ height at all times compared to pre-test, however the absence of condition effects or condition x time interactions suggests that impairments to CMJ height were primarily a result of testing effects or fatigue, rather than RM or SS. The SS+RM_RM condition demonstrated no impairments at post-test or post-30 (Table 2). This is the condition with the greatest volume of RM. It is possible that the larger volume of RM in SS+RM_RM was accountable for masking these testing effects, thus minimizing performance deficits for this condition. One previous study (Peacock et al., 2014) reported improved performance (i.e. +7.8% vertical jump height) following 30-seconds FR. Hence, it is not unreasonable to suggest that RM played a role in abating the impairments brought about by the SS routine. It would be beneficial for future investigations to further investigate whether RM can improve performance, or even simply mask the negative effects of prolonged SS.

Trivial deficits in hurdle jump height at post-test and post-20, and knee extension peak force at post-test and post-30 were strictly main effects for time, and the lack of condition effects (Table 2) suggest that these reductions were a result of the testing procedure rather than the intervention. Furthermore, there were no changes in hurdle jump contact time, knee flexion peak force or f100, or knee extension f100. These findings are consistent with previous reports (Mikesky et al., 2002; MacDonald et al. 2013; Sullivan et al. 2013; Halperin et al., 2014; Healey et al., 2014; Bahara & Jacobson, 2015; Jones et al. 2015) illustrating no changes in maximal strength or power tasks following FR or RM, while also aligning with those advocating a dose-response effect for SS with impairments being more prevalent following prolonged stretches of >60s (Kay & Blazevich, 2012; Kallerud & Gleeson, 2013; Behm et al., 2016).

Another research objective was to compare the immediate effects of SS and SS+RM. Sessions involving an initial intervention of SS+RM (30s each), and those consisting of SS only (60s total), each provoked hip and knee flexion active and passive ROM improvements that were not significantly different (Table 4). This is in contrast to Mohr et al. (2014) and Škarabot et al. (2015), who reported greater improvements in knee flexion and ankle dorsiflexion respectively following SS+FR/RM compared to SS alone. This discrepancy is likely due to differences in total intervention volume. Both aforementioned studies combined their FR/RM and SS protocols, thereby doubling the total volume, for the combined condition, whereas in the current study the duration of SS was reduced by half to accommodate an equal volume of RM, and maintain a consistent total volume compared to the SS only conditions. This is the first study to directly compare equal volumes of SS to combined SS+FR/RM. The results suggest that both warmups provide similar ROM improvements, while neither produced adverse performance decrements. Whether longer duration combined warmup routines would counterbalance impairments from prolonged (e.g. >60-s) SS remains unclear. Thus, future research should aim to elicit significant performance impairments with prolonged SS and compare the effects to conditions with equal and double duration combined protocols, and to RM on its own.

The small sample size (n=12) may be a limiting factor for this study; however it was determined that between 4-30 subjects were required to achieve an alpha of 0.05 and a power of 0.8 based on similar prior studies (Power et al. 2004; Behm et al. 2006; Bacarau et al. 2009). Furthermore, although all subjects reported being at least recreationally active, the findings of this study may be of interest to competitive athletes. The relationship of these effects between recreational and highly trained athletes is unclear. Another limitation to the current study is the absence of sessions including RM only (e.g. RM_rest and RM_RM). Inclusion of these conditions would allow direct comparison of RM, SS, and SS+RM; and this concept may be ideal for future investigations.

In summary, the current study suggests that while SS and SS+RM warmup routines can elicit ROM increases lasting up to 30-minutes, the maintenance of these improvements can be maximized or augmented with additional RM applied at 10-minute intervals. Furthermore, SS and combined SS+RM routines of equal total duration can provide similar ROM improvements. Finally, the combination of SS+RM, or the addition of subsequent RM to a SS or SS+RM routine, does not appear to exert adverse effects on neuromuscular performance. This research may be of benefit to athletes who are exposed to prolonged rest before entering (e.g. from the bench) a game following a warmup. Maintaining increased flexibility on the sidelines may help reduce musculotendinous injury risk during ensuing vigorous exercise.

3.6 – References

1. Bacurau, R.F.P., Monteiro, G.A., Ugrinowitsch, C., Tricoli, V., Cabral, L.F., & Aoki, M.S. (2009). Acute Effect of a Ballistic and a Static Stretching Exercise Bout on Flexibility and Maximal Strength. Journal of Strength and Conditioning Research, 23(1), 304-308.

2. Behara, B., & Jacobson, B.H. (2015). The acute effects of deep tissue foam rolling and dynamic stretching on muscular strength, power, and flexibility in division I linemen. Journal of Strength and Conditioning Research. [Citation].

3. Behm, D.G. & Chaouachi, A. (2011). A review of the acute effects of static and dynamic stretching on performance. European Journal of Applied Physiology, 111(11), 2633-2651.

4. Behm, D.G., Blazevich, A.D., Kay, A.J., & McHugh, M. (2016). Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. Applied Physiology, Nutrition, and Metabolism, 41, 1-11.

5. Behm, D.G., Bradbury, E.E., Haynes, A.T., Hodder, J.N., Leonard, A.M. & Paddock, N.R. (2006). Flexibility is not related to stretch-induced deficits in force or power. Journal of Sports Science and Medicine, 5, 33-42.

6. Behm, D.G., Plewe, S., Grage, P., Rabbani, A., Taghi Beigi, H., Byrne, J.M., & Button, D.C. (2011). Relative static stretch-induced impairments and dynamic stretch-

induced enhancements are similar in young and middle-aged men. Applied Physiology, Nutrition & Metabolism, 36(6), 790-798.

7. Bradbury-Squires, A.J., Notfall, J.C., Sullivan, K.M., Behm, D.G., Power, K.E., & Button, D.C. (2015). Roller-massager application to the quadriceps and knee-joint range of motion and neuromuscular efficiency during a lunge. Journal of Athletic Training, 50(2), 133-140.

8. Cavanaugh, M.T., Aboodara, S.J. & Behm, D.G. (2017). Intra-and inter-session reliability of quadriceps' and hamstrings' electromyography during a standardized hurdle jump test with single leg landing. Journal of Strength and Conditioning Research. Advance online publication. doi: 10.1519/JSC.0000000000001631.

9. Cho, S, Kim, S, & Park, D. (2015). The comparison of the immediate effects of application of the suboccipital muscle inhibition and self-myofascial release techniques in the suboccipital region on short hamstring. Journal of Physical Therapy Science, 27(1), 195-197.

10. Cross, T.M., Gibbs, N., Houang, M.T., & Cameron, M. (2004). Acute quadriceps muscle strains: magnetic resonance imaging features and prognosis. American Journal of Sports Medicine, 32(3), 710-719.

11. DePino, G.M., Webright, W.G., & Arnold, B.L. (2000). Duration of maintained hamstring flexibility after cessation of an acute static stretching protocol. Journal of Athletic Training, 35(1), 56-59.

12. Fowles, J.R., Sale, D.G., & MacDougall, J.D. (2000). Reduced strength after passive stretch of the human plantarflexors. Journal of Applied Physiology, 89, 1179-1188.

13. Grabow, L., Young, J.D., Alcock, L.R., Quigley, P.J., Byrne, J.M., Granacher, U., Škarabot, J. & Behm, D.G. (2017). Higher quadriceps roller massage forces do not amplify range-of-motion-increases or impair strength and jump performance. Under review Journal of Strength and Conditioning Research, 2017.

14. Guissard, N. & Duchateau, J. (2004). Effect of static stretch training on neural and mechanical properties of the human plantar-flexor muscles. Muscle and Nerve, 29, 248-255.

15. Guissard, N. & Duchateau, J. (2006). Neural aspects of muscle stretching. Exercise and Sport Sciences Reviews, 34, 154-158.

16. Guissard, N., Duchateau, J., & Hainaut, K. (1988). Muscle stretching and motoneuron excitability. European Journal of Applied Physiology, 58, 47-52.

17. Halperin, I., Aboodarda, S.J., Button, D.C., Anderson, L.L., & Behm, D.G. (2014). Roller massager improves range of motion of plantar flexor muscles without subsequent decreases in force parameters. International Journal of Sports Physical Therapy, 9(1), 92-102.

18. Healey, K.C., Hatfield, D.L., Blanpied, P., Dorfman, L.R., & Riebe, D. (2014). The effects of Myofascial release with foam rolling on performance. Journal of Strength and Conditioning Research, 28(1), 61-68.

19. Jay, K., Sundstrup, E., Sondergaard, S.D., Behm, D.G., Brandt, M, Særvoll, C.A., Jakobsen, M.D., & Anderson, L.L. (2014). Specific and cross over effects of massage for muscle soreness: randomized controlled trial. International Journal of Sports Physical Therapy, 9(1), 82-91.

20. Kallerud, H. & Gleeson, N. (2013). Effects of stretching on performances involving stretch-shortening cycles. Sports Medicine, 43, 733-750.

21. Kay, A.D. & Blazevich, A.J. (2012). Effects of acute static stretch on maximal muscle performance: a systematic review. Medicine & Science in Sport & Exercise, 44(1), 154-164.

22. Knudson, D. (1999). Stretching during warm-up: do we have enough evidence? Journal of Physical Education, Recreation & Dance, 70(7), 24-27.

23. Kokkonen, J., Nelson, A.G., Eldredge, C., & Winchester, J.B. (2007). Chronic static stretching improves exercise performance. Medicine & Science in Sports & Exercise, 39(10), 1825-1831.

24. Liu, H., Garrett, W.E., Moorman, C.T., & Yu, B. (2012). Injury rate, mechanism, and risk factors of hamstring strain injuries in sports: A review of the literature. Journal of Sport and Health Science, 1(2), 92-101.

25. MacDonald. G.Z., Button, D.C., Drinkwater, E.J. & Behm, D.G. (2014). Foam rolling as a recovery tool after an intense bout of physical activity. Medicine & Science in Sports & Exercise, 46, 131-142.

26. MacDonald, G.Z., Penny, M.D.H., Mullaley, M.E., Cuconato, A.L., Drake, C.D.J., Behm, D.G., & Button., D.C. (2013). An acute bout of self-myofascial release increases range of motion without a subsequent decrease in muscle activation or force. Journal of Strength and Conditioning Research, 27(3), 812-821.

27. Magnusson, S.P., Simonsen, E.B., Aagaards, P., gleam, G.W., McHugh, M.P., & Kjaer, M. (1995). Viscoelastic response to repeated static stretching in the human hamstring muscle. Scandinavian Journal of Medicine & Science in Sports, 5, 342-347.

28. McHugh, M., Magnusson, S., Gleim, G., & Nicholas, J. (1992). Viscoelastic stress relaxation in human skeletal muscle. Medicine & Science in Sports & Exersice, 24, 1375-1382.

29. Mendiguchia, J., Alentom-Geli, E., Samuelsson, K., & Karlsson, J. (2015). Sports injuries: Prevention, diagnosis, treatment and rehabilitation (2nd ed.). Berlin: Springer-Verlag.

30. Mikesky, A.E. (2002). Acute effects of The Stick on strength, power, and flexibility. Journal of Strength and Conditioning Research, 16(3), 446-450.

31. Mizuno, T., Matsumoto, M., & Umemura, Y. (2013). Viscoelasticity of the muscle-tendon unit is returned more rapidly than range of motion after stretching. Scandinavian Journal of Medicine & Science in Sports, 23(1), 23-30.

32. Mohr, A.R., Long, B.C., & Goad, C.L. (2014). Effect of foam rolling and static stretching on passive hip-flexion range of motion. Journal of Sport Rehabilitation, 23, 296-299.

33. Morse, C.I., Degens, H., Seynnes, O.R., Maganaris, C.N., & Jones, D.A. (2008). The acute effect of stretching on the passive stiffness of the human gastrocnemius muscle tendon unit. The Journal of Physiology, 586(1), 97-106.

34. Murphy, J.R., Di Santo, M.C., Alkanani, T., & Behm, D.G. (2010). Aerobic activity before and following short-duration static stretching improves range of motion and performance vs. a traditional warm-up. Applied Physiology, Nutrition, and Metabolism, 35, 679-690.

35. Orchard, J. & Seward, H. (2002). Epidemiology of injuries in the Australian Football League, seasons 1997-2000. British Journal of Sports Medicine, 36, 39-44.

36. Peacock, C.A., Krein, D.D., Silver, T.A., Sanders, G.J., & Von Carlowitz, K.A. (2014). An acute out of self-myofascial release in the form of foam rolling improves performance testing. International Journal of Exercise Science, 7(3), 202-211.

37. Power, K., Behm, D., Farrell, C., Carroll, M., & Young, W. (2004). An acute bout of static stretching: effects on force and jumping performance. Medicine & Science in Sports & Exercise, 36(8), 1389-1396.

38. Simic, L., Sarabon, N., & Markovic, G. (2012). Does pre-exercise static stretching inhibit maximal muscular performance? A meta-analytical review. Scandinavian Journal of Medicine and Science in Sports, 23, 131-148.

39. Skarabot, J., Beardsley, C, & Stirn, I. (2015). Comparing the effects of self-myofascial release with static stretching on ankle range-of-motion in adolescent athletes. International journal of Sports Physical Therapy, 10(2), 203-212.

40. Sullivan, K.M., Silvey, D.B.J., Button, D.C., & Behm, D.G. (2013). Roller massager application to the hamstrings increases sit and reach range of motion within five to ten seconds without performance impairments. The International Journal of Sports Physical Therapy, 8(3), 228-236.

41. Trajano, G.S., Nosaka, K., & Blazevich, A.J. (2017). Neurophysiological mechanisms underpinning stretch-induced force loss. Sports Medicine, Jan 24.

42. Van Beijsterveldt, A.M.C., Van de Port, L.G.L., & Backx, F.J.G. (2013). Risk factors for hamstring injuries in male soccer players: A systematic review of prospective studies. Scandinavian Journal of Medicine & Science in Sports, 23(3), 253-262.

43. Vigotsky, A.D., Lehman, G.J., Contreras, B., Beardsley, C., Chung, B., & Feser, E.H. (2015). Acute effects of anterior thigh foam rolling on hip angle, knee angle, and rectus femoris length in the modified Thomas test. PeerJ, 3, e1281.

44. Weppler, C.H. & Magnusson, P. (2010). Increasing muscle extensibility: a matter of increasing length or modifying sensation? Journal of the American Physical Therapy Association, 90, 438-449.

45. Whatman, C., Knappstein, A., & Hume, P. (2006). Acute changes in passive stiffness and range of motion post-stretching. Physical Therapy in Sport, 7(4), 195-200.

<u>3.7 – Table legends</u>

Table 1: **Range of Motion**

ROM reported in degrees for each condition measured at five time points relative to the intervention. Values demonstrating significant relationships between sessions with additional RM vs. sessions with rest are highlighted.

Table 2: **Jump performance**

Jump performance reported at five time points relative to the intervention. CMJ and hurdle jump height reported in inches, hurdle jump contact time reported in seconds.

3.8 – Figure legends

Figure 1: PRE-POST knee flexion aROM with conditions pooled for initial warmups of SS only vs. SS+RM. Smaller numbers reflect ROM increase.

*Indicates value is significantly different from PRE value.

° Indicates value is significantly different from CONTROL value at the same time point.

Figure 2: PRE-POST knee flexion pROM with conditions pooled for initial warmups of SS only vs. SS+RM. Smaller numbers reflect ROM increase.

*Indicates value is significantly different from PRE value.

° Indicates value is significantly different from CONTROL value at the same time point.

Figure 3: PRE-POST hip flexion pROM with conditions pooled for initial warmups of SS only vs. SS+RM. Larger numbers reflect ROM increase.

*Indicates value is significantly different from PRE value.

Figure 4: PRE-POST CMJ height with conditions pooled for initial warmups of SS only (SS_rest and SS_RM) vs. SS+RM (SS+RM_rest and SS+RM_RM).

*Indicates value is significantly different from PRE value.

3.9 – Tables

Table 1: **Range of motion**

	PRE	POST	POST-10	POST-20	POST-30
Hip flexion active ROM (larger numbers reflect ROM increase)					
SS_rest	92.0 ± 15.0	92.4 ± 13.9	92.1 ± 14.4	93.2 ± 14.7	91.1 ± 13.6
SS+RM_rest	92.5 ± 14.6	93.5 ± 12.6	93.7 ± 14.0	92.6 ± 17.2	92.3 ± 16.5
SS_RM	91.5 ± 16.0	93.3 ± 15.8*	94.0 ± 16.5*	95.5 ± 16.7*[1]	94.3 ± 15.8*[1]
SS+RM_RM	92.0 ± 18.9	93.8 ± 17.4*	93.2 ± 16.9	93.5 ± 16.5	94.5 ± 17.8*[1]
CONTROL	92.7 ± 15.6	94.3 ± 17.7	92.1 ± 16.5	92.4 ± 15.6	93.9 ± 17.1
Hip flexion passive ROM (larger numbers reflect ROM increase)					
SS_rest	101.2 ± 22.2	105.4 ± 22.9*°	105.1 ± 24.4*°	104.1 ± 25.5*	105.4 ± 24.9*
SS+RM_rest	99.6 ± 19.9	106.1 ± 22.4*	106.5 ± 24.0*°	104.8 ± 24.9*	105.5 ± 25.9*
SS_RM	101.0 ± 24.3	106.6 ± 25.0*°	106.8 ± 23.9*°	107.8 ± 23.1*°[1,2]	107.6 ± 23.7*°
SS+RM_RM	98.5 ± 24.6	104.8 ± 25.8*	103.3 ± 24.5*	105.5 ± 24.9*	106.3 ± 24.8*°
CONTROL	101.2 ± 22.3	102.8 ± 22.9	102.7 ± 23.6	104.0 ± 23.0	103.5 ± 23.7
Knee flexion active ROM (smaller numbers reflect ROM increase)					
SS_rest	53.2 ± 5.2	50.0 ± 7.9*	51.4 ± 5.0*	52.0 ± 4.8	52.3 ± 6.8
SS+RM_rest	53.8 ± 7.4	51.7 ± 4.4	51.8 ± 6.7	52.0 ± 5.1	52.0 ± 6.6
SS_RM	53.0 ± 5.7	49.2 ± 5.0*°	49.2 ± 4.0*°	47.7 ± 3.5*°[1,2]	48.9 ± 4.6*°[1,2]
SS+RM_RM	57.1 ± 9.6	52.7 ± 7.3*	52.9 ± 6.8*	52.8 ± 7.0*	51.5 ± 6.0*
CONTROL	54.8 ± 8.6	54.3 ± 8.9	54.2 ± 7.9	52.8 ± 7.6	51.7 ± 6.0*
Knee flexion passive ROM (smaller numbers reflect ROM increase)					
SS_rest	41.6 ± 7.9	34.0 ± 6.6*°	36.0 ± 6.6*	37.6 ± 5.9*	37.1 ± 6.3*
SS+RM_rest	37.5 ± 5.9	33.4 ± 5.9*°	34.0 ± 5.8*	33.9 ± 6.0*°	34.4 ± 7.1*
SS_RM	37.5 ± 6.9	31.3 ± 5.5*°	33.0 ± 5.1*	31.3 ± 4.1*°[1]	31.4 ± 3.4*°[1]
SS+RM_RM	40.9 ± 7.3	35.2 ± 6.8*°	37.8 ± 6.9*	33.7 ± 5.9*°[1]	32.4 ± 6.1*°[1]
CONTROL	39.9 ± 11.3	39.2 ± 7.9	37.7 ± 7.7*	37.8 ± 7.3	36.3 ± 6.9*

*Indicates value is significantly different from PRE value

° Indicates value is significantly different from control value at the same time point

[1] Indicates value is significantly different from SS_rest value at the same time point

[2] Indicates value is significantly different from SS+RM_rest value at the same time point

Table 2: **Jump performance**

	PRE	**POST**	**POST-10**	**POST-20**	**POST-30**
CMJ height					
SS_rest	18.125 ± 2.2	17.750 ± 1.9*	17.458 ± 2.0*	17.625 ± 2.0*	17.375 ± 1.8*
SS+RM_rest	17.942 ± 2.1	17.375 ± 2.2*	17.542 ± 2.4*	17.167 ± 2.1*	17.208 ± 2.4*
SS_RM	17.875 ± 1.9	17.417 ± 1.9*	17.250 ± 2.0*	17.250 ± 2.1*	17.333 ± 2.2*
SS+RM_RM	18.208 ± 2.1	17.917 ± 2.3	17.708 ± 2.3*	17.625 ± 2.5*	17.792 ± 2.7
CONTROL	18.750 ± 2.6	18.125 ± 2.1*	18.125 ± 2.3*	18.083 ± 2.3*	17.667 ± 2.3*
Hurdle jump height					
SS_rest	0.244 ± .060	0.220 ± .054	0.235 ± .059	0.224 ± .055	0.223 ± .069
SS+RM_rest	0.233 ± .054	0.220 ± .063	0.219 ± .065	0.217 ± .049	0.231 ± .062
SS_RM	0.245 ± .061	0.227 ± .068	0.231 ± .063	0.228 ± .045	0.222 ± .052
SS+RM_RM	0.246 ± .065	0.233 ± .064	0.229 ± .067	0.224 ± .072	0.232 ± .073
CONTROL	0.246 ± .066	0.231 ± .081	0.233 ± .073	0.243 ± .073	0.231 ± .072
Hurdle jump contact time					
SS_rest	0.236 ± .049	0.229 ± .048	0.249 ± .048	0.226 ± .038	0.230 ± .039
SS+RM_rest	0.224 ± .033	0.236 ± .044	0.228 ± .034	0.228 ± .030	0.235 ± .023
SS_RM	0.221 ± .031	0.231 ± .039	0.232 ± .038	0.231 ± .030	0.224 ± .026
SS+RM_RM	0.226 ± .049	0.249 ± .042	0.244 ± .033	0.233 ± .036	0.246 ± .035
CONTROL	0.240 ± .045	0.231 ± .035	0.243 ± .044	0.239 ± .031	0.238 ± .033

*Indicates value is significantly different from PRE value

3.10 – Figures

Figure 1:

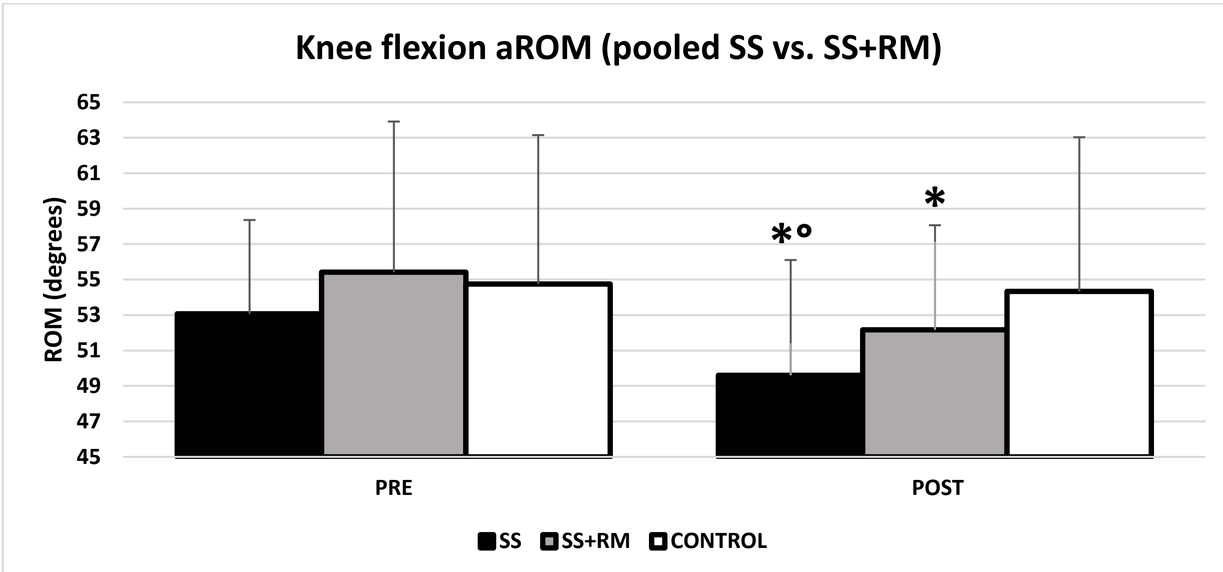

Figure 2:

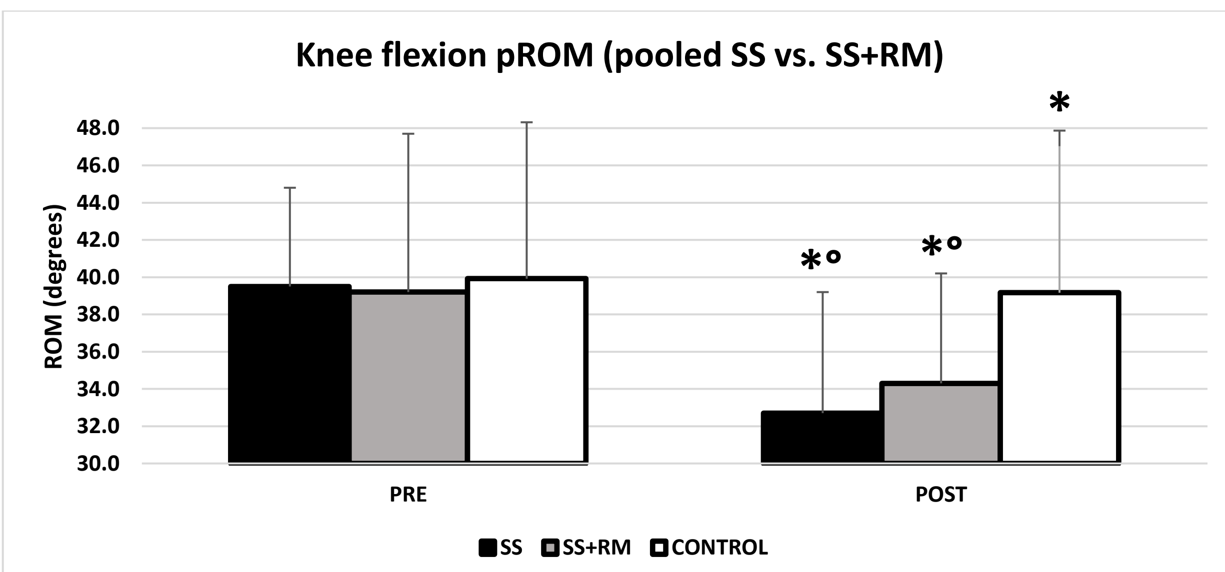

Figure 3:

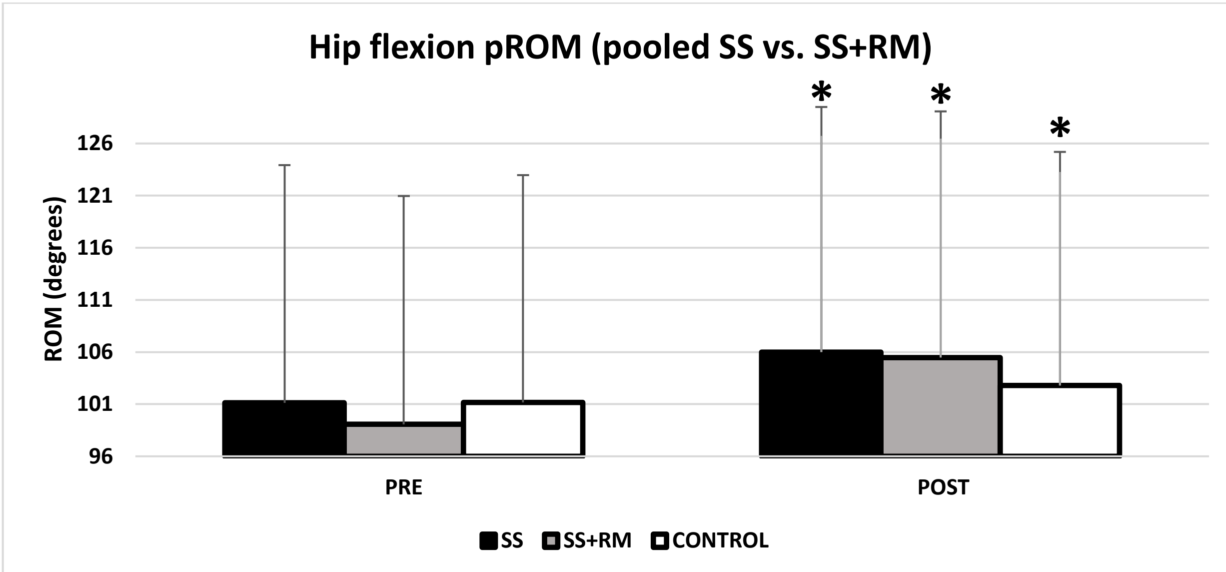

Figure 4: