TITLE: An Acute Bout of Self Myofascial Release Increases Range of Motion Without a Subsequent Decrease in Muscle Activation or Force.

AUTHORS: Graham MacDonald, Michael Penney, Michelle Mullaley, Amanda Cuconato, Corey Drake, David G. Behm and Duane C. Button.

AFFILIATION: School of human Kinetics and Recreation, Memorial University of Newfoundland, St. John’s, NL, Canada A1C 5S7

Address correspondence to Duane Button, School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John’s, NL, A1C 5S7, E-mail - dbutton@mun.ca
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Subsequent Decrease in Muscle Activation or Force.
ABSTRACT
Foam rolling is thought to improve muscular function, performance, overuse and joint range of motion (ROM), however, there is no empirical evidence demonstrating this. Thus, the objective of the study was to determine the effect of self-myofascial release (SMR) via foam roller application on knee extensor force and activation and knee joint range of motion. Eleven healthy male (height 178.9 ± 3.5 cm, mass 86.3 ± 7.4 kg, age 22.3 ± 3.8 years) subjects who were physically active participated. Subjects’ quadriceps maximum voluntary contraction force, evoked force and activation, and knee joint ROM were measured prior to, two minutes, and 10 minutes following two conditions; 1) two, one minute trials of SMR of the quadriceps via a foam roller and 2) no SMR (Control). A two-way ANOVA (condition x time) with repeated measures was performed on all dependent variables recorded in the pre- and post-condition tests. There were no significant differences between conditions for any of the neuromuscular dependent variables. However, following foam rolling, subjects’ ROM significantly (ρ < 0.001) increased by 10 and 8% at 2 and 10 minutes, respectively. There was a significant (ρ < 0.01) negative correlation between subjects’ force and ROM prior to foam rolling, which no longer existed following foam rolling. In conclusion an acute bout of SMR of the quadriceps was an effective treatment to acutely enhance knee joint range of motion without a concomitant deficit in muscle performance.

KEY WORDS: myofascial release, foam rolling, quadriceps, force, range of motion
INTRODUCTION:

Fascial restrictions often occur in response to injury, disease, inactivity, or inflammation, causing fascial tissue to lose elasticity and become dehydrated. When fascia loses its elasticity and becomes dehydrated, fascia can bind around the traumatized areas, causing a fibrous adhesion to form. Fibrous adhesions are known to be painful, prevent normal muscle mechanics (i.e. joint range of motion, muscle length, neuromuscular hypertonicity, and decreased strength, endurance and motor coordination) and decrease soft-tissue extensibility (5, 15, 36).

Myofascial release (MFR) therapy is a manual therapy technique developed by John F. Barnes (5), to help reduce restrictive barriers or fibrous adhesions seen between layers of fascial tissue. A new technique of MFR termed self-induced myofascial release (SMR) has become of increasingly common practice for treating soft-tissue restrictions. SMR works under the same principles as myofascial release. The difference between the two techniques is that instead of a therapist providing manual therapy to the soft-tissue, an individual uses their own body mass on a foam roller to exert pressure on the soft-tissue. The SMR technique involves small undulations back and forth over a dense foam roller, starting at the proximal portion of the muscle, working down to the distal portion of the muscle or vice versa (28). The small undulations place direct and sweeping pressure on the soft-tissue, stretching the tissue and generating friction between the soft-tissue of the body and the foam roller. The friction generated from the undulations causes warming of the fascia, promoting the fascia to take on a more fluid-like form (known as the thixotropic property of the fascia), breaking up fibrous adhesions between the layers of fascia and restoring soft-tissue extensibility (32).

In the past decade, therapists and fitness professionals have implemented SMR via foam rolling as a recovery and maintenance tool to aid in the process of soft-tissue healing. It has been
postulated that fascia can form abnormal crosslinks and have changes in the ground substance viscosity, changing from a gel to a more solid state (4, 34). These changes may cause the fascia to become less pliable, potentially restricting movement patterns and muscular forces due to a lack of movement in response to injury or inactivity (4). Foam rolling can be implemented into a number of different rehabilitation and training programs to promote soft-tissue extensibility, potentially enhancing joint range of motion (ROM) and promoting optimal skeletal muscle function. Furthermore, advocates (5, 15, 36) believe that foam rolling corrects muscular imbalances, alleviates muscle soreness, relieves joint stress, improves neuromuscular efficiency and improves ROM. Unfortunately, the literature on foam rolling is rudimentary, thus there are no peer-reviewed empirical data to support such beliefs. To our knowledge, there was only one non-peer-reviewed research study on foam rolling and ROM (23). Miller and Rockey (23) investigated the chronic effects of an eight week foam rolling program on hamstring flexibility. They found that the foam rolling program was ineffective in increasing ROM of the hamstring muscles. Curran et al. (15) determined that myofascial rollers made of harder material (a hollow polyvinyl chloride pipe surrounded by a thin layer of neoprene) significantly increased soft tissue pressure and better isolated contact area on the soft-tissue in comparison to foam rollers made of softer material (uniform polystyrene foam). Thus, when utilizing SMR, a foam roller made of hard material may be more beneficial to optimize muscle function.

There is little empirical evidence supporting SMR and the literature that does exist mainly reports the chronic, but not the acute effects, of myofascial release on muscle performance. The objectives of the present study were two-fold. The first objective was to determine if an acute bout of SMR via a high-pressure foam roller affects volitional and evoked quadriceps muscle force. The second objective was to determine if foam rolling improves knee
joint ROM. In the current study the term “acute” refers to the period immediately following foam rolling (2 min and 10 min). These time points were chosen to demonstrate how foam rolling could be used as part of a warm-up for a muscular performance event. We hypothesized that there would be an increase in knee joint ROM and a decrease in quadriceps force output. Our hypothesis was based on results from previous massage (by a therapist) research that demonstrated increased ROM following massage (2, 21, 39), and decreased muscle electromyography (3) and spinal motoneuron excitability (17, 24, 35) during massage. A portion of these results have been reported elsewhere in abstract form (29).
METHODS

Experimental Approach to the Problem

A within-subject design was used to examine the acute effects of self-induced myofascial release of the quadriceps muscles on: ROM, maximum voluntary force, muscle activation, tetanic force, twitch force and $\frac{1}{2}$ relaxation time, and rate of force development. Subjects performed the experimental conditions over four sessions, with 24-48 hours rest between each session (see figure 1 for details). Conditions were divided by intervention and measure. Conditions 1 and 2 measured ROM and force, respectively, during the control intervention whereas conditions 3 and 4 measured ROM and force, respectively, during the foam roller intervention. During each experimental condition all dependent variables were measured pre-condition, two minutes and 10 minutes post-condition. Condition 1 (control ROM) was used as a testing and familiarization day. Subjects were tested for ROM prior to two minutes of rest and again 2 and 10 minutes post-rest. Following ROM measurements, subjects were then familiarized with the myofascial foam rolling technique, performed the maximum voluntary contraction (MVC) with the interpolated twitch technique (ITT) and received a 100 Hz tetanic muscle stimulation. A single familiarization session for foam rolling was enough for the participants to learn the proper foam rolling technique. After experimental condition 1 was complete, the order in which subjects completed the remaining three testing conditions was randomized. During condition 2 (control force), subjects performed a MVC and received a tetanus prior to 2 minutes of rest and again 2 and 10 minutes post rest. During Conditions 3 (foam roller ROM) and 4 (foam roller force) subjects were tested for ROM and MVC, twitch force, and tetanus, respectively prior to 2 minutes of foam rolling and again 2 and 10 minutes post foam rolling. Subjects foamed rolled the right quadriceps for 2, 1-minute bouts with 1
minute rest between bouts. This time was chosen based on previous literature which suggests that a constant pressure should be applied to the muscle from 60 to 90 s up to 5 min or until a release is felt (28, 34).

Preceding the start of all experimental sessions subjects performed a warm up on a Monark cycle ergometer for five minutes at an intensity of 1kp and 60 rpm. Dependent variables related to muscle force and muscle contractile properties were measured during different sessions than ROM measures because static stretching, even for short durations, has been shown to cause impairments in force production (8, 30). Subjects were instructed to refrain from heavy exercise 24 hours before testing and followed the Canadian Society for Exercise Physiology (CSEP) preliminary instructions (no eating, drinking caffeine, smoking, or drinking alcohol for 2, 2, 2, or 6 hours respectively) prior to the start of each intervention.

Subjects

Eleven healthy male (height 178.9 ± 3.5 cm, mass 86.3 ± 7.4 kg, age 22.3 ± 3.8 years) subjects from the university population volunteered for the study. All of the subjects were recreational resistance trainers and would be classified by the CSEP as moderate to very physically active. Subjects were verbally informed of all procedures, and if willing to participate, read and signed a written consent form and a Physical Activity Readiness Questionnaire (PAR-Q) prior to participation. The Memorial University of Newfoundland Human Investigation Committee approved this study.

Independent Variables

Foam Roller and Foam Rolling Technique
Subjects foam rolled on a custom made foam roller that was constructed of a hollow polyvinyl chloride (PVC) pipe (10.16 cm outer diameter and 0.5 cm thickness) surrounded by neoprene foam (1 cm thickness). This type of foam roller was used because it places more pressure on the myofascia compared to a Bio-foam roller made from uniform polystyrene foam (15.24 cm diameter) (15). Thus, hereafter all foam rolling in the current study will be considered high pressure. For the myofascial foam rolling technique, the subjects were instructed to begin in a plank position, with the foam roller at the most proximal portion of the quadriceps of the right leg with their left leg crossed over the right (Figure 2). They were told to place as much of their body mass as possible onto the foam roller. They were instructed to roll the foam roller down the quadriceps of the right leg using short kneading like motions until the foam roller was just above the patella. Once the foam roller reached the patella, subjects were told to quickly roll the foam roller back to the initial position in one fluid motion. They repeated this for one minute, rested for 30 seconds, and then repeated the procedure for another minute. Subjects rolled out the quadriceps 3-4 times during each minute of foam rolling.

Dependent Variables

*Knee Extensor Force*

To determine right knee extensor MVC force production, subjects were seated on a knee extension table with the knee and hip flexed at 90°. Restraints were placed around their upper leg and trunk, and an adjustable backrest was used to provide support. The ankle was inserted into a padded strap, attached by a high-tension wire that measured force using a Wheatstone bridge configuration strain gauge (Omega Engineering Inc. LCCA 250, Don Mills, Ontario). The subjects performed a 4.5 second isometric MVC with all forces detected by a strain gauge,
amplified (Biopac Systems Inc. DA 150 and analog to digital (A/D) converter MP100WSW; Hilliston, MA), and displayed on a computer monitor. Data was sampled at 2000 Hz. The subjects were instructed to give maximal effort and to produce force as quickly as possible, allowing maximal rate of force development to be measured. Verbal encouragement was given to all subjects during the MVC to provide motivation.

*Rate of force development (RFD)*

RFD (N·s\(^{-1}\)) was measured as the amount of force (N) that was generated in the first 200 ms of maximum voluntary contraction and then converted to the amount of force generated in one second. The maximal rate of rise in muscle force [rate of force development (RFD)] has important functional consequences in neuromuscular performance as it determines the force that can be generated in the early phase of muscle contraction (0–200 ms) (1).

*Muscle Activation*

Prior to attempting maximal contractions, subjects’ would perform approximately 3-5 submaximal knee extension isometric contractions. During the pre-condition test, subjects performed two MVCs (with 5 minutes rest between each MVC) to determine their maximum isometric force output. In order to ensure a consistent maximal effort, the subjects proceeded with the ITT if there was less than 5% difference between the two MVCs (13). The ITT was utilized as a measure of the CNS ability to fully activate the contracting muscle and has been extensively described previously (7, 11, 12). ITT was performed with four evoked Twitches at two second intervals throughout a nine and a half second data collection trial as suggested by (33) (Figure 3). Prior to performing a MVC, subjects were administered an initial doublet twitch, relaxed, and then told to maximally contract their quadriceps. Doublets rather than single stimuli were used to increase the signal to noise ratio (10). During the MVC, subjects received two
additional doublet twitches and then were instructed to relax. A fourth potentiated twitch was administered 1.5 seconds following the completion of the MVC. An interpolated twitch ratio was calculated comparing the amplitude of the interpolated twitch with the potentiated twitch to estimate the extent of inactivation during a voluntary contraction (interpolated doublet force/potentiated doublet force X 100 = % of muscle inactivation) (10).

Superimposed stimulation was accomplished with bipolar surface stimulating electrodes, 4-5 centimeters (cm) in width. Electrodes were secured over the proximal and distal portion of the quadriceps. Stimulating electrodes were constructed from aluminum foil, coated with conduction gel, (Eco-Gel 200, Eco-Med Pharmaceutical Inc., Mississauga, Ontario), wrapped with paper towel and then immersed in water. The electrode length was sufficient to cover the width of the muscle belly. To determine the doublet twitch voltage and amperage, subjects’ peak twitch torques were evoked with electrodes connected to a high-voltage stimulator (Stimulator Model DS7AH+; Digitimer, Welwyn Garden City, Hertfordshire, UK). The amperage (10 milliamps (mA) – 1amp (A)) and duration (50 micro-seconds (µs)) was kept constant throughout. Voltage ranged from 100 - 300 volts and was progressively increased until a maximum twitch torque was achieved. Once the settings for peak twitch torque were achieved it remained the same when the subject was administered the ITT.

Electromyography (EMG) activity was used as a measure of peripheral muscle activation. Surface EMG recording electrodes (MediTrace Pellet Ag/AgCl electrodes, disc shape, and 10 mm in diameter, Graphic Controls Ltd., Buffalo, NY) were placed over the muscle belly of the rectus femoris, measured by half the distance between the anterior superior iliac spine and the patella, as suggested by Mesin et al. (22). A ground electrode was secured on the fibular head. Thorough skin preparation for all electrodes included shaving hair off the desired area, removal
of dead epithelial cells from the desired area with abrasive sand paper, followed by cleansing with an isopropyl alcohol swab. EMG activity was sampled at 2000Hz, with a blackman -61 dB band pass filter between 10-500 Hz, amplified (bi-polar differential amplifier, input impedance = 2 MΩ, common mode ejection ratio > 110 dB min (50/60 Hz), gain X 1000, noise > 5 µV) and was analog-to-digitally converted (12 bit) and stored on a personal computer for analysis. EMG was measured for a one second period between the two super-imposed doublets, in order to allow generation of peak forces during the MVC (Figure 3).

Tetanic stimulation involved 100-Hz stimulation for 300 milliseconds using the same voltage, amperage and pulse duration as the doublet twitch administered during the ITT. Tetanic forces were elicited via the surface electrodes two minutes following the ITT, while the subject was told to relax. Subjects’ average tetanic force was 80% of their MVC force. Tetanic force was not much higher than this because of the pain tolerance of the subjects. Tetanic force was used to measure the mechanical integrity of the muscle to produce force as it bypasses the central nervous system. Peak tetanic force was measured.

*Range of motion (ROM)*

To assess knee joint ROM, subjects were asked to perform a modified kneeling lunge, with their torso in an upright and erect position, placing their left knee in line with their left ankle and aligning their lower left leg perpendicular to the floor (Figure 4). They were instructed to position themselves so that the right hip was stretched to the point of discomfort. The angle, to which the right hip was stretched, was measured and this hip angle was used for all subsequent ROM measurements during each experimental condition. This process was repeated in all experimental conditions. Following the hip angle measurement initial knee angle was recorded.
using a goniometer with measurements taken using the following landmarks; the lateral malleolus, the lateral epicondyle, and the center of the vastus lateralis. The subjects were then asked to maintain the stretch at the hip and were restrained by investigators across the chest to avoid any further hip flexion. Following proper positioning, subjects were told to contract the abdominal muscles to ensure maintenance of their trunk posture. The subject’s right knee was then passively flexed by investigators until the participant reached a point of discomfort. The change in the angle at the knee was the ROM measurement.

Statistical Analysis

A two-way ANOVA with repeated measures (time) was performed on all dependent variables recorded in the pre- and post-condition tests (SPSS). The two factors (2 x 3) included condition (control and foam roller) and time (pre- and post-condition tests at 2 and 10 minutes). F-ratios were considered statistically significant at the p < 0.05 levels. A Tukey Post Hoc test was performed to test for significant differences between interactions. Person product correlations were also performed to determine relationships between dependent variables. Correlations were considered statistically significant at the p <0.05 level. Descriptive statistics in text and where applicable in figures include means ± standard deviation (SD).
RESULTS

Neuromuscular performance of the quadriceps. A two-way ANOVA test revealed that there were no significant differences in any neuromuscular performance measurements (muscle force, RFD and muscle activation) between the control and foam roller conditions (see Table 1 for details). Specifically there were no force deficits seen following foam rolling (Figure 5A). MVC forces were reliably ($\rho < 0.001$, $r = 0.85$) performed within and between the control and foam rolling conditions. Furthermore, the coefficient of variation for MVC force within the control and foam rolling conditions was 5%. Thus, subjects were able to produce similar forces during both conditions and at all time points.

Knee joint ROM. A two-way ANOVA repeated measures test revealed that there was a significant main effect for the foam roller condition on knee joint ROM. Overall, subjects’ ROM during the control condition was significantly ($\rho < 0.001$) lower, a mean difference of approximately 10 degrees in comparison to the foam roller condition. The two-way ANOVA repeated measures test also revealed a significant ($\rho < 0.001$) interaction effect of condition X time. A post hoc analysis revealed that compared to pre-foam rolling ROM, ROM significantly increased 12.7 and 10.3% at 2 and 10 minutes, respectively, post-foam rolling. The control ROM increased but not significantly by 2.2 and 4.2% at 2 and 10 minutes, respectively post-control condition (Figure 5B). ROM was significantly ($\rho < 0.001$) higher following the foam rolling condition compared to the control condition at 2 and 10 minutes.
Delta change in ROM and FORCE. At two minutes post foam rolling every subject increased their ROM by at least 4 degrees to a maximum of almost 20 degrees (Figure 6A). Even at 10 minutes post foam rolling, subjects’ ROM was still greater than their pre-condition ROM (range 3-17 degrees). Following the control condition, subjects’ ROM showed little change and in some cases there was a slight but not significant decrease in ROM. Subjects’ change of force was similar 2 and 10 minute post foam rolling and control conditions (Figure 6B).

Correlation between quadriceps force and knee joint ROM following foam rolling. There was a significant ($\rho < 0.01$) negative correlation between dependent variables; subjects’ quadriceps force and knee joint ROM pre-test for foam rolling and control conditions. Following foam rolling subjects quadriceps force and knee joint ROM no longer correlated at 2 and 10 minutes (Figure 7, for clarity only the foam rolling correlations are shown), whereas following the control condition the significant ($\rho < 0.05$) negative correlation between quadriceps force and knee joint ROM remained at 2 and 10 minutes.
Discussion

Self-myofascial release via a foam-roller is a form of massage implemented and promoted by therapists (physical, occupation, athletic) along with functional movement and sport professionals. Foam rolling is utilized as a warm-up, recovery and maintenance technique that targets soft-tissue to improve joint ROM and optimize muscular function. The current study examined SMR as part of a warm-up protocol to potentially acutely enhance muscular performance. To our knowledge, this is the first peer-reviewed study to analyze the practical and theoretical use of foam rolling. The most important findings presented are: 1) there was a significant increase in knee joint ROM at 2 min post- (12.7%) and 10 min post-foam rolling (10.3%) of the quadriceps muscles, 2) there was no significant changes in voluntary or evoked muscle properties following foam rolling, and 3) following foam rolling the negative correlation between ROM and force production no longer existed. Our results strongly show that an acute bout of foam rolling greatly improves joint ROM with no concomitant detrimental effects on neuromuscular force production.

Foam rolling for two minutes increased knee joint ROM by approximately 11° and 9° at 2 and 10 minutes, respectively post-foam rolling. One potential theory to explain the increase in ROM following foam rolling is a change in the thixotropic property (fluid like form) of the fascia encasing the muscle (28). Fascia is made of colloidal substances and when it is disturbed, via heat and/or mechanical stress, it softens and takes on a more gel-like state, but when left undisturbed it thickens and becomes more viscous, taking on a more solid state (31). Repeated stress placed on the soft-tissue of the body due to overuse or inactivity may cause abnormal cross-links and scar tissue to form in the fascia. Subsequently, these abnormal cross-links and
scar tissue may inhibit proper biomechanics and reduce joint ROM. SMR may mechanically shear out these cross-links and breakdown scar tissue, remobilizing the fascia back to its gel-like state (34). Once the fascia is in a more gel-like state, soft-tissue compliance increases allowing for greater range of motion (5). Two important factors to increase soft-tissue compliance are the duration and force of mechanical stress application. Twomey and Taylor (38) demonstrated that long-term mechanical stress application was required to induce a gel-like state. Threlkeld (37) calculated that mechanical stress application forces of 24–115 kg was high enough to cause such changes. In the current study mechanical stress application was only applied for 2 minutes but at very high forces (average body mass 86.3 ± 7.4 kg). Perhaps the high force mechanical stress application (i.e. a combination of body mass and high-pressure foam rolling) performed in the current study was enough to induce a gel-like state in the fascia leading to increased soft-tissue compliance and subsequently greater knee joint ROM. In addition to a change in the thixotropic properties of the fascia, foam rolling involves vigorous soft-tissue to roller contact which places constant pressure on the soft-tissue. Vigorous pressure placed on the soft-tissue may overload the cutaneous receptors, possibly dulling the sensation of the stretch endpoint and increasing stretch tolerance (21), therefore increasing joint ROM.

The increase in ROM following foam rolling was similar to that found following other forms of soft-tissue manipulation. Massage of the of the plantar flexors (21) and hamstrings musculotendinous junction (9) significantly increases ankle and hamstring ROM, respectively. Crossman et al. (14) showed an increase in ROM at the hip joint following massage of the hamstrings. Arabaci (2) showed that Swedish massage significantly increased sit & reach flexibility. However, Wiktorsson-Moller et al. (39) demonstrated that massage improved ROM, but that static stretching resulted in significantly greater hip, knee and ankle ROM than that
obtained by massage, warming up, or warming up and massage combined. Currently, there is no research directly comparing SMR via foam rolling and static stretching-induced changes to ROM. Based on the current SMR study and previous static stretching studies (6-8, 16, 30) ROM appears to increase by a similar percentage following SMR and static stretching. McKechnie et al. (21) showed a 9-14% (5min post) increase in ROM post static stretching which was similar to the percentage increase in ROM following foam rolling in the present study.

Foam rolling for two, one minute bouts did not impede voluntary muscle activation, force or evoked contractile properties. Currently, there are no other studies demonstrating the effects of foam rolling on muscle force. Wiktorsson-Moller et al. (39) found that massage induced a decrease in quadriceps isometric force and hamstrings isokinetic force, which was contradictory to the results found in the present study. A key difference between the current study and Wiktorsson-Moller et al. (39) was massage time (2 minutes versus 7-15 minutes, respectively) and massage type (foam rolling versus a massage therapist, respectively). Others have found that short duration massage increases joint ROM while maintaining muscular power (21).

Based on studies demonstrating the effects of massage on EMG and spinal cord excitability, it was surprising to find no change in muscle force. Arroyo-Morales et al. (3) demonstrated a significant decrease of vastus medialis EMG during 40 minutes of massage on the quadriceps. Thus, a transient loss in muscle strength may be seen following massage, although this was not tested. In the current study, myofascial release was for 2 minutes as opposed to 40 minutes. No changes in EMG levels were seen following the short duration SMR implemented in the present study. Perhaps there is an EMG versus massage-time relationship. Shorter massage times may cause no change in EMG and subsequent force production (21). Several studies (17, 24, 35) have found that massage decreases spinal motoneuron excitability
along with a depression in H-reflex amplitude following a short bout of massage. H-reflex size was dependent on the massage pressure. A deeper massage induced greater inhibition of the spinal motoneuron. The H-reflex depression was not dependent on mechanical stimulation of cutaneous mechanoreceptors, but may have been due to the involvement of deep mechanoreceptors (17, 24, 35). Unfortunately, we were unable to determine the amount of pressure between the quadriceps muscle and foam roller and nor was H-reflex measured. Each subject placed most or all of their body mass on the foam roller during rolling, which should be comparable or greater in intensity than that of a deep massage. In the previous studies, the H-reflex was recorded during the massage itself. Perhaps in those studies, if muscle force and activation were measured directly following the massage there may have been decreases. In the current study, activation and force were tested 2 minutes and 10 minutes post foam rolling. The two-minute rest period may have allowed for a reduction in deep mechanoreceptor activation, leading to a restoration of the H-reflex, allowing for normal force production.

Although static stretching increases ROM, it is being eliminated from the traditional pre-event warm-up because prolonged static stretching impairs neuromuscular performance (6-8, 30). Decreased neuromuscular performance (6-8, 30) following static stretching may be attributed to the potential static stretching-induced sarcomere damage. Thus, static stretching may cause tremendous stress during muscle lengthening, potentially damaging the sarcomere (25) and subsequently reducing muscle force. However, recent research demonstrating the effects of acute (26) and chronic (27) static stretching on muscle-tendon unit (MTU) stiffness has shown that decreased MTU stiffness following static stretching was not do to changes in fascicle length but rather a combination of muscle stiffness and changes to the surrounding connective tissue (i.e. fascia). Whereas, a decrease in MTU stiffness may lead to decreased force (20) it is unknown
how static stretched-induced changes in connective tissue affects muscle force. The physiological mechanism by which SMR enhances ROM is very different than static stretching. Instead of placing pressure on the origin and insertion points of the muscle, which leads to increase sarcomeres in series, SMR may enhance the thixotropic nature of the fascia enveloping the muscle (see above for more details). Foam rolling is thought to enhance soft-tissue pliability which allows increased joint ROM (5), and potentially without causing any damage to the cross-bridges and sarcomeres of the muscle and subsequently not impacting muscle force production.

However, it remains unknown whether foam rolling causes damage to the muscle fibers of the involved muscle.

The present results, illustrating that foam rolling diminished the significant negative correlation between ROM and MVC force production are interesting. Prior to foam rolling, subjects who had the least ROM produced the greatest amount of force and vice versa. In accordance with the correlation coefficient, ROM could explain 31% of the factors related to force prior to foam rolling, which decreased to 5.4% and 3.5% at 2 and 10 minutes post-foam rolling, respectively. Similar to foam rolling, the pre-test control ROM could explain 28% of the factors related to force however, unlike foam rolling, the correlation coefficient at 2 and 10 minutes post-control remained above 22%. The relationship between ROM and force production could have implications in sporting and rehabilitation settings. In clinical rehabilitation settings, individuals who have joint mobility injuries generally receive therapy to increase mobility while still maintaining stability within a given joint, as was seen with the functional movement screen (19). A technique that can enhance ROM without inhibiting force production could be of value in treating joint mobility injuries. The present study showed a $10.6^\circ \pm 6.7^\circ$ (2 min post) and an $8.8^\circ \pm 5.5^\circ$ (10 min post) increase in ROM post SMR via foam rolling without a subsequent loss.
in force output, making SMR via foam rolling an applicable technique to enhance ROM prior to a muscular performance event.

One potential limitation in the study was the difficulty to find a knee joint ROM test for knee flexion. Part of the difficulty was that most individuals can flex their knee until their heel touches the buttocks. Thus, to assess knee joint ROM, each participant was asked to conform a kneeling lunge position so that the right hip was stretched to the point of discomfort followed by the participant’s right knee being passively flexed to the point of discomfort. Even using this standardized technique, 4 of the 11 subjects minimally increased ROM because their heel touched the buttocks. Thus, the ROM mean values reported here were probably an underestimation of the overall effect foam rolling has on quadriceps flexibility.

Based upon this initial investigation, future research may endeavor to examine a post foam rolling time line to determine how long ROM remains enhanced beyond 10 minutes. Furthermore, the foam rolling duration in the current study was only 2 minutes. It would be interesting to determine the effects of longer durations of foam rolling on ROM and muscle performance. In future studies that test knee joint ROM for the quadriceps; it may be optimal to recruit participants who are inflexible. This may reduce the number of participants who are able to touch their heel off the buttocks in the ROM test employed here.

**PRACTICAL APPLICATIONS**

In conclusion, the data presented in this study suggest that an acute bout (only 2 minutes) of slow undulating foam rolling of the quadriceps on a high-pressure foam roller significantly increases quadriceps ROM. In fact, foam rolling for only two minutes enhances quadriceps muscle ROM to a similar degree as previously reported in other static stretching studies. More importantly, acute foam rolling had no significant impact on quadriceps muscle force or
activation. Although the results apply to static ROM and isometric force production, which may or may not have application to dynamic movements, the results give supporting evidence to the potential benefits of employing a foam rolling program to increase joint ROM prior to a physical activity that requires substantial force production.
References


FIGURE 1: Experimental design. The chart illustrates the experimental set-up, conditions, and independent variables that were measured pre-condition and post-condition at 2 and 10 minutes.

FIGURE 2: Picture illustrating foam rolling procedure. Subjects placed all or almost all of their body mass on the high density foam roller and only the quadriceps muscles of the right leg were in contact with the foam roller. Foam rolling started at the most proximal portion of the quadriceps and the subjects foam rolled down the quadriceps using short kneading like motions until the foam roller was just above the patella. This was repeated throughout two, one minute repetitions.

FIGURE 3: Maximum voluntary contraction force, evoked twitches and electromyography raw data from one participant.

FIGURE 4: Picture illustrating the quadriceps and knee joint ROM test. Subjects performed a modified kneeling lunge. They positioned themselves so that the right hip was stretched to the point of discomfort. Following proper positioning, the subject’s right knee was passively flexed until the participant reached a point of discomfort. The change in the angle at the knee was the ROM measurement.

FIGURE 5: Knee extension force and knee joint ROM during the control and foam rolling conditions. A) Force was not affected by the control or foam rolling conditions. Forces were similar for each condition and at all time points. B) Knee joint ROM did not change in the
control condition but significantly increased following foam rolling. * represents a statistical significance at $\rho < 0.001$. All data are presented as mean $\pm$ one standard deviation.

**FIGURE 6:** Each data point represents the $\Delta$ change in A) ROM ($\degree$) and B) force (N) for each subject at 2 and 10 minutes post baseline. Overall, subjects’ ROM significantly increased at 2 and 10 minutes post foam rolling but not post control. There was no difference between subjects’ force following the foam rolling and control conditions.

**FIGURE 7:** Correlation between subjects ROM and force. Following foam rolling there was no longer a significant correlation between ROM and force. Each data point represents force and ROM of one participant. * represents a significant ($\rho < 0.01$) negative correlation between subjects quadriceps force and knee joint ROM prior to the foam rolling condition.
TABLE 1: Raw data presented as means ± SD. ** Represents a significant ($\rho < 0.001$) main effect between foam rolling and control.

§ Represents a significant ($\rho < 0.001$) difference between foam rolling and control at 2 and 10 minutes.

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<td>3.4</td>
</tr>
<tr>
<td>Force (N)</td>
<td>704</td>
<td>123.1</td>
<td>677.4</td>
<td>103.6</td>
</tr>
<tr>
<td>Muscle Inactivation (%)</td>
<td>8.616</td>
<td>3.2</td>
<td>10.5</td>
<td>4.7</td>
</tr>
<tr>
<td>EMG (mV/s)</td>
<td>0.181</td>
<td>0.11</td>
<td>0.19</td>
<td>0.10</td>
</tr>
<tr>
<td>Tetanus (N)</td>
<td>571.5</td>
<td>131.7</td>
<td>557.0</td>
<td>131.9</td>
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<tr>
<td>RFD (N/s)</td>
<td>498.1</td>
<td>202.1</td>
<td>504.9</td>
<td>124.3</td>
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<tr>
<td>Twitch Force (N)</td>
<td>150.9</td>
<td>35.6</td>
<td>137.8</td>
<td>32.4</td>
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<tr>
<td>½ Relaxation Time (ms)</td>
<td>0.07</td>
<td>0.02</td>
<td>0.07</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>SMR</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM (°)</td>
<td>77.6</td>
<td>10.2</td>
<td><strong>88.2§</strong></td>
<td>8.5</td>
</tr>
<tr>
<td>ROM (Δ)</td>
<td>0</td>
<td>0</td>
<td><strong>10.6§</strong></td>
<td>6.7</td>
</tr>
<tr>
<td>Force (N)</td>
<td>727.5</td>
<td>101.3</td>
<td>692.8</td>
<td>98.5</td>
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<tr>
<td>Muscle Inactivation (%)</td>
<td>8.3</td>
<td>3.4</td>
<td>9.2</td>
<td>5.22</td>
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<tr>
<td>EMG (mV/s)</td>
<td>0.25</td>
<td>0.17</td>
<td>0.24</td>
<td>0.14</td>
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<tr>
<td>Tetanus (N)</td>
<td>567.9</td>
<td>125.6</td>
<td>541.3</td>
<td>123.4</td>
</tr>
<tr>
<td>RFD (N/s)</td>
<td>566.3</td>
<td>99.7</td>
<td>496.2</td>
<td>171.3</td>
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<tr>
<td>Twitch Force (N)</td>
<td>151.2</td>
<td>38.1</td>
<td>140.6</td>
<td>33.5</td>
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<tr>
<td>½ Relaxation Time (ms)</td>
<td>0.072</td>
<td>0.021</td>
<td>0.07</td>
<td>0.022</td>
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</tbody>
</table>
ROM = range of motion, EMG = electromyography, RFD = rate of force development
**EXPERIMENTAL DESIGN**

Figure 1

- **Warm-Up**
  - Bicep (5 min/75 kp)

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**INDEPENDENT VARIABLES**

- **Condition 1**
  - Control ROM
  - 5 Minute Rest

- **Condition 2**
  - Foam-Rolling ROM
  - Two, 1 minute bouts of foam rolling
  - With 30s rest between bouts

- **Condition 3**
  - Control Force
  - 5 Minute Rest

- **Condition 4**
  - Foam Rolling Force
  - Two, 1 minute bouts of foam rolling
  - With 30s rest between bouts

---

**DEPENDENT VARIABLES MEASURED**

**PRE-CONDITION AND POST-CONDITION AT 2 AND 10 MINUTES**

- **Control and Foam Rolling ROM**
  - 1. Rom

- **Control and Foam Rolling Force**
  - 1. MVC
  - 2. Tetanus
  - 3. EMG
  - 4. Muscle Inactivation
  - 5. Twitch Force and ½ Relaxation Time
  - 6. Rate of Force Development
Figure 3
Figure 4
Figure 6