International Journal of
EXERCISE SCIENCE

Original Research

Effects of a Vibrating Foam Roller on Ipsilateral and Contralateral Neuromuscular Function and the Hamstrings-to-Quadriceps Ratios

RACHEL M. RUGGIERI[†], JARED W. COBURN[‡], ANDREW J. GALPIN[‡], and PABLO B. COSTA[‡]

Exercise Physiology Laboratory, Department of Kinesiology, California State University, Fullerton, CA, USA

[†]Denotes graduate student author, [‡]Denotes professional author

ABSTRACT

International Journal of Exercise Science 14(1): 304-323, 2021. The effects of vibrating foam rolling the hamstrings on range of motion (ROM), hamstrings-to-quadriceps (H:Q) ratios, muscle activation, and peak torque (PT) of the quadriceps and hamstrings have yet to be extensively studied. The aim of this study was to investigate the effects of a vibrating foam roller on the hamstrings. Fifteen resistance trained women (mean age ± SD = 22.9 ± 2.0 years, height = 162.7 ± 4.8 cm, body mass = 66.0 ± 9.7 kgs, BMI = 24.9 ± 3.3 kg·m^2) participated in five separate testing sessions to examine pre- and post-testing PT, H:Q ratios, muscle activation of the quadriceps and hamstrings, and ROM of the hamstrings. Testing sessions consisted of a foam rolling, a vibrating foam rolling, a vibration-only, and a control condition. Hamstrings ROM increased for both limbs with the exception of the vibration condition for the untreated limb ($p = 0.003$). The untreated limb had a quadriceps PT increase from pre- to post-testing ($p = 0.014$). Concentric hamstrings PT for both limbs decreased pre- to post-testing for all conditions ($p = 0.013$). Eccentric hamstrings PT for both limbs decreased pre- to post-testing ($p = 0.026$). Conventional H:Q ratios decreased pre- to post-testing for both the treated and untreated limbs ($p < 0.001$). Functional H:Q ratios decreased for both limbs pre- to post-testing ($p < 0.001$). Although hamstrings ROM increased in both limbs, foam rolling, vibrating foam rolling, and vibration-only could possibly decrease performance measures of the ipsilateral and contralateral limbs.

KEY WORDS: Self-myofascial release, electromyography, flexibility, injury risk, vibration

INTRODUCTION

Athletic performance and risk factors can be evaluated through a variety of assessments, such as strength levels, conventional and functional hamstrings-to-quadriceps (H:Q) ratios, as well postural stability (8, 9, 10, 23). Injury risk is an important aspect in sports and recreational settings, with a significant emphasis on reducing injury incidence (23). One of the most common methods of assessing lower body injury risk, is through the use of the H:Q ratio (30). The H:Q ratio is calculated by comparing the strength of both the hamstrings and the quadriceps (22). H:Q ratios are considered within normal range when between 50-80% (23, 30), but injury risk is typically increased when H:Q ratios are lower than 60% (8, 9, 23). Low H:Q ratios are commonly influenced by weak hamstrings, or overpowering quadriceps (4, 8, 10, 23). Consequently, low H:Q ratios can increase the likelihood of lower body injuries, not only to the hamstrings, but also to the anterior cruciate ligament in the knee joint (4, 5, 8, 9, 10, 30).

A warm-up is essential to performance and is commonly performed before an exercise session is executed (20). Static stretching is one of the most common types of stretching used to increase ROM, and is often performed as part of a warm-up routine (9, 10, 11, 23). Previously, forms of stretching have been used to increase range of motion (ROM), specifically of the hamstrings (15). Although static stretching has been demonstrated to increase ROM, it has also been shown to decrease strength, power, H:Q ratios, peak torque (PT), and other performance-related measures, which can increase injury rate in athletes and recreationally active individuals (8, 9, 10, 11, 15). With the knowledge that static stretching can negatively influence performance in athletes and recreationally active individuals when performed prior to exercise or sports, research has investigated other methods that could possibly increase ROM without negatively affecting performance (22, 23).

Stretching has also been shown to influence the contralateral, or unstretched limb as well (1, 6, 12). Behm et al., (2019) and Chaouachi et al., (2017) reported increases in hip flexion ROM to both the ipsilateral and contralateral limb after static and dynamic stretching. These increases in flexibility were found without causing performance and strength impairments to the contralateral limb (1, 6). In contrast, Cramer et al., (2005) reported that although there were no stretch-specific changes to mean power output, mechanomyographic amplitude, and joint angle at PT, there were decreases in electromyography (EMG) activation and PT. Thus, Cramer et al., (2005) concluded these stretch-induced decreases to the contralateral limb, may be caused by a central nervous system inhibitory mechanism.

Self-induced myofascial release (SMR), thought to be performed through foam rolling, has become a popular research topic for increasing ROM (28). However, Behm et al., (2019) has recently suggested the term “self-myofascial release” is actually misleading when referring to foam rolling. Behm et al. (2019) stated in a recent review that foam rolling increases blood flow and reduces stiffness, but this is not actually due to the mechanism of “self-myofascial release”. Foam rollers are cylinders made up of foam of varying densities, that are combined with applied pressure or force, such as body weight, to create a massage-like effect on the fascia of muscle (23, 28). Fascia surrounds muscle, and becomes softer when moved around (5, 11, 23). Foam rolling, when thought to be SMR, has been shown to increase dilation within arteries, reduce their stiffness, restore soft tissue, increase nitrogen dioxide, and improve vascular plasticity (7, 28). Foam rolling is also believed to decrease soreness, improve ROM without impaired muscle activation and H:Q ratios, improve coordination, alleviate stress on joints, and reduce pain pressure threshold (5, 23). The most likely mechanisms of foam rolling is suggested to be from an increased stretch tolerance on ROM due to activation of global pain modulatory responses (2).

Foam rolling has also demonstrated to have a cross-over effect similar to static stretching (18, 26). Foam rolling the dominant calf has been shown to not only increase dorsiflexion ROM of the dominant rolled limb for up to 20 minutes, but has also displayed increases in dorsiflexion ROM in the contralateral unrolled limb for up to 10 minutes (19). Foam rolling the hamstrings for 60 seconds or longer, has also demonstrated to reduce fatigue resistance in knee extensions, as well as increase passive shoulder flexion and extension (26).

Vibration foam rolling has yet to be extensively studied. Vibration foam rolling adds the component of vibration therapy with foam rolling (7). Currently, vibration foam rolling has been shown to increase ankle ROM, sit-and-reach flexibility, passive hip and knee flexion, pain pressure tolerance, quadriceps muscle strength, and dynamic balance (7, 20, 29). These increases have all been shown to occur without decreases in maximal voluntary isometric knee extension, or isometric dorsiflexion and plantar flexion force. (7, 20, 29). Pain perception based on a visual analog scale also improved, indicating a greater benefit in pain tolerance (29).

Vibrating foam rolling and the effects on strength and performance, specifically on the H:Q ratio, muscle activation, PT, and hamstrings ROM, have not been researched to date. In addition, the effects of a vibrating foam roller on the contralateral, unrolled limb has yet to be studied. Therefore, the purpose of this study was to examine the effects of vibrating foam rolling on hamstrings ROM, H:Q ratios, muscle activation, and PT when compared to a normal foam roller, vibration-only, and a control condition. A secondary aim of the study was to compare the effects on ROM, H:Q ratios, and PT of the contralateral limb. It was hypothesized that the vibrating foam rolling and vibration conditions will produce similar increases to hamstrings ROM as the normal foam roller, on both the ipsilateral and contralateral limbs. It was also hypothesized that the foam rolling, vibrating foam rolling, and vibration-only will increase the H:Q ratios, PT, and muscle activation of both limbs compared to the control condition.

METHODS

Participants

Fifteen subjects participated in this study (mean age ± SD = 22.9 ± 2.0 years, height = 162.7 ± 4.8 cm, body mass = 66.0 ± 9.7 kgs, BMI = 24.9 ± 3.3 kg $\cdot$m^2). This number was more than what was determined using a priori analysis on G*Power software (3.1 Dusseldorf, Germany). An alpha level of 0.05, a power of 0.80, and an effect size of 0.71, calculated from the results of a previous foam rolling study conducted by Madoni et al., (2018) was used to establish the minimum number of participants. Participants were lower body resistance trained women of collegiate age. Lower body resistance trained was defined as being active in lower body resistance training for a minimum of 3 days a week, for at least 30 minutes on each day, for the past 6 months (23). Participants were free from lower extremity injury within the past six months, and free from any previous injury or functional limitation that would prevent them from participating in any portion of the study. This study was approved by the California State University, Fullerton Institutional Review Board. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (27).

The experiment consisted of five separate visits to the laboratory (Figure 1), adapted from a previous study by Madoni et al. (2018). The first session was a familiarization day, where

Informed Consent was read and signed, the Health Status Questionnaire completed, and anthropometrics recorded. Participants practiced and became comfortable with the range of motion protocol, foam rolling and vibrating foam rolling protocols, and with the isokinetic dynamometer. The second, third, fourth, and fifth sessions were randomized sessions of control, foam rolling, vibrating foam rolling, and vibration-only conditions. Subjects participated in each session, creating a within-within experimental design. All testing was conducted by a trained, experienced, and National Strength and Conditioning Association (NSCA) certified investigator.

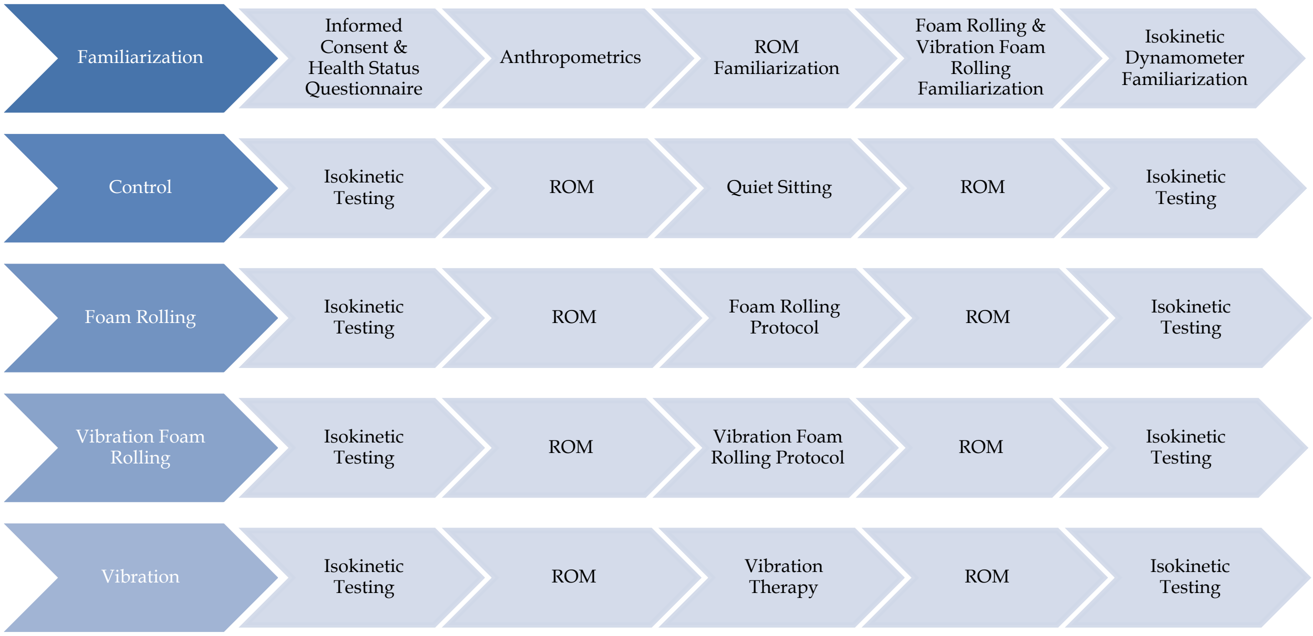

Figure 1. Research design

All testing sessions occurred in the Exercise Physiology Laboratory. The familiarization sessions lasted 75.1 ± 1.5 minutes, the foam rolling sessions lasted 85.3 ± 1.5 minutes, the vibrating foam rolling sessions lasted 86.0 ± 1.1 minutes, the vibration sessions lasted 85.1 ± 1.5 minutes, and the control sessions lasted 85.3 ± 1.7 minutes (mean session visit time in minutes ± SE). During the first visit, participants read and signed an Informed Consent, and filled out a Health Status Questionnaire. Height was measured using a stadiometer (SECA stadiometer, Chino, CA, USA,) and body mass was measured using a digital scale (Ohaus ES Series scale, Parsippany, NJ, USA). Participants then became familiar with the hamstrings range of motion assessment with the straight leg raise test. Next, the participants became familiarized with using the foam roller, the vibrating foam roller, and vibration-only setting. The roller used in this study was a VYPER 2.0 vibrating foam roller (Hyper Ice, Inc., Irvine, CA, USA), which has been used in previous studies (13, 20, 26). Participants practiced the isokinetic dynamometer protocol on each limb by performing the warm-up and protocol that was used for the remaining sessions. EMG locations were also shown and explained to the participants. Lastly, participants were shown a 10-point visual analogue scale (VAS), used to measure soreness at the beginning of each session. Measuring soreness at the beginning of each session was not the main purpose of the study, but was measured to assess any possible remaining soreness from a previous testing condition. A 0 represented no soreness, while a 10 represented the highest possible soreness.

The control, foam rolling, vibrating foam rolling, and vibration-only conditions followed a similar testing protocol, and were performed in a randomized order. A minimum of 48 hours, but no more than 72 hours separated each session. Participants were encouraged to refrain from physical activity within 24 hours of each testing session, encouraged to consume similar meals and water intake, and get adequate amount of sleep before each testing sessions. Each session occurred approximately during the same time of day (i.e., morning, afternoon, evening). The control, foam rolling, vibrating foam rolling, and vibration-only sessions first involved testing in the isokinetic dynamometer for peak torque and muscle activation using EMG, and then ROM was measured. The control group sat quietly for 10 minutes, and the other conditions sat for 7 minutes before inducing the interventions for 3 minutes. The foam rolling condition consisted of rolling without the vibration setting. For the vibration foam rolling condition, the vibration setting was turned on. For the vibration-only condition, the vibration setting was turned on, and participants only sat on the roller. After the foam rolling interventions and control condition, ROM, peak torque, and muscle activation were assessed again.

Protocol

Range of motion was measured to assess hamstrings muscle flexibility for both the dominant, or treated, and non-dominant, or untreated limb. For this test, participants laid supine on a mat with the knees fully extended. First, the treated leg was lifted up with the knee fully extended. The hip joint was flexed passively until the knee could no longer remain fully extended with the hips on the mat, until resistance of the limb was met, or until the participant expressed they were uncomfortable and their leg could not go any farther (23, 31). Then the untreated hamstrings ROM was measured with the same approach. The hip joint angle was measured using a Lafeyette Gollehon Extendable Goniometer (01135, Lafayette, IN, USA). The goniometer was aligned to the greater trochanter of the hip, the lateral epicondyle of the knee, and to the midline of the trunk. Maximal stretch for each limb was recorded in degrees.

The foam rolling, vibrating foam rolling, and vibration-only protocols were designed to target the hamstrings muscle group and adapted from previous studies (14, 23, 25). Only the dominant limb was rolled for both the rolling and vibrating conditions. Rolling was performed on a mat with the roller placed under the participant's hamstrings. Hands were positioned behind the back to maintain balance. Legs were placed in front with the ankles crossed to maintain pressure on the hamstrings (23, 25). Instruction to roll from the ischial tuberosity to the popliteal space was given. One third of the hamstrings (proximal, middle, and distal) was rolled starting closest to the gluteal fold, and moving down toward the back of the knee. Participants sat for 7 minutes before foam rolling to maintain the time between control, rolling, and vibration-only days consistent, and to allow for sufficient recovery between pre- and post-tests. Each section of the hamstrings was rolled for 10 seconds, totaling 30 seconds, and this was completed 3 times. A 10-second rest in between was provided. Participants were instructed to place as much pressure as possible on the roller. Both rolling conditions used the same protocol, except the vibrating rolling condition had the medium vibration setting turned on (68 Hz). For the vibration-only session, participants sat on the foam roller without rolling and with the medium setting turned on. Participants also sat with the dominant, or treated hamstrings on the foam roller, and crossed the non-dominant, or untreated leg over the ankle. Participants sat on the foam roller for 10 seconds on each hamstrings section (proximal, middle, distal), similar to the foam rolling days, totaling 30 seconds. Participants rested for 10 seconds, and performed the vibration-only treatment 3 times similar to the rolling conditions.

Electrodes used for the EMG protocol were placed on the participant's treated and untreated thigh to assess muscle activation while using the isokinetic dynamometer. Participants had two pre-amplified bipolar surface electrodes (EL254S; Biopac Systems Inc., Santa Barbara, CA, USA) placed over the biceps femoris of the hamstrings and the vastus lateralis of the quadriceps (10, 23). The electrode placed on the biceps femoris was positioned between the ischial tuberosity and lateral epicondyle at the mid-point. The electrode for the vastus lateralis was placed at 2/3 the measurement between the anterior spina iliaca and the lateral part of the patella. EMG locations for the biceps femoris and vastus lateralis were marked during the second session to ensure EMG placement was identical for the third, fourth, and fifth session. The reference electrode was placed over the 7th cervical vertebrae. Participant's skin was shaved, abraded, and cleaned with isopropyl alcohol before EMG placement for each session. Raw EMG scores of muscle activation were recorded with the use of a Biopac data system (MP150WSW; Biopac Systems Inc). All EMG data were recorded at a frequency of 1,000 Hz while participants were on the isokinetic dynamometer. EMG values were filtered with signal bandpass at 10-500 Hz, data were measured and recorded as root square mean, and normalized to the maximum voluntary contractions (MVCs).

Using an isokinetic dynamometer, (Humac Norm CSMi, Stoughton, MA, USA) concentric peak torque was analyzed at the velocities of $60° \cdot s^{-1}$, $180° \cdot s^{-1}$, and $300° \cdot s^{-1}$, and eccentric peak torque was analyzed at the velocities of $60° \cdot s^{-1}$, and $180° \cdot s^{-1}$ (8, 23). Isometric flexion and extension were measured as well to determine MVCs for EMG normalization. Isometric flexion and extension MVCs were taken at fifty percent of the participants measured knee flexion and extension ROM. Subjects were seated in the isokinetic dynamometer, first with the treated limb strapped in, then the untreated limb. While strapped in, the shin was secured and the leg not strapped in was placed behind the stabilization bar. Straps were also placed over the participant's shoulders and across their lap to isolate the limb being tested. The isokinetic dynamometer was aligned such that the axis of the dynamometer met the knee rotation axis of the limb secured. All testing sessions started with a warm-up with kicks and pulls at increasing intensities of approximately 25%, 50%, 75%, and 100% of the participants perceived maximal output (8, 23). A 1-minute rest was provided after the warm-up (23). Participants performed three maximal repetition at each velocity, with reciprocal concentric extension and flexion actions, and separate eccentric muscle actions. The highest value of the three maximal repetitions was recorded. PT was recorded by the dynamometer at each velocity. The velocities were randomized, with a 1-minute rest in between. Verbal prompts and encouragement was provided to cue participants when to "kick," "push," "pull," and "resist" (23). Conventional H:Q ratios were calculated for each participant by dividing the highest concentric PT of the hamstrings by their highest concentric PT of the quadriceps for their respective velocity.

Functional H:Q ratios were calculated for each participant by dividing the highest eccentric PT of the hamstrings by the highest concentric PT of the quadriceps (8).

Statistical Analysis

The statistical analysis for this within-within research design experiment included seven repeated measures ANOVAs. VAS data were analyzed through a repeated measures ANOVA (condition [control vs. foam rolling vs. vibrating foam rolling vs. vibration]). Hamstrings ROM was analyzed through a three-way repeated measures ANOVA (condition [control vs. foam rolling vs. vibrating foam rolling vs. vibration] × time [pre vs. post] × limb [treated vs. untreated]). Concentric quadriceps PT, concentric hamstrings PT, conventional H:Q ratios, VL EMG, and BF EMG were analyzed using a four-way repeated measure ANOVA (condition [control vs. foam rolling vs. vibration foam rolling vs. vibration]) × velocity [$60°\cdot s^{-1}$ vs. $180°\cdot s^{-1}$ vs. $300°\cdot s^{-1}$] × time [pre vs. post] × limb [treated vs. untreated]). Eccentric hamstrings PT and functional H:Q ratios were analyzed using a four-way repeated measures ANOVA (condition [control vs. foam rolling vs. vibration foam rolling vs vibration] × velocity [$60°\cdot s^{-1}$ vs. $180°\cdot s^{-1}$] × time [pre vs. post] × limb [treated vs. untreated]). *T* tests and post hoc with a Bonferroni correction were used if necessary and appropriate, and data were reported as mean ± SE. Results were considered significant at $p \leq 0.05$. IBM SPSS Statistics version 26 was used for statistical analysis (IBM Corp., Armonk, NY, USA).

RESULTS

No significant differences were found for VAS by condition ($p > 0.05$). VAS values were 2.2 ± 0.5 (foam rolling), 1.8 ± 0.5 (vibrating foam rolling), 2.4 ± 0.6 (vibration), and 2.3 ± 0.6 (control).

Tables 1 and Table 2 display the means ± SE for treated and untreated ROM. There were no three-way interactions for hamstrings ROM for condition × time × limb, or two-way interactions for condition × time, condition × limb, or time × limb ($p > 0.05$). However, a main effect for time was found ($p = 0.003$). Hamstrings ROM increased pre- to post-testing. In addition, there was a main effect for limb ($p = 0.001$). Treated limbs ROM were greater than the untreated limbs ROM. There was no main effect for condition ($p > 0.05$).

Table 1. Means ± SE for the treated hamstrings ROM in degrees (°)

Condition	Pre-Test	Post-Test	Δ
Foam ROM	104.7 ± 4.2	108.0 ± 4.2*	3.38% Increase
VF ROM	103.4 ± 4.1	106.3 ± 4.1*	2.64% Increase
Vibration ROM	105.9 ± 4.0	107.4 ± 4.3*	1.39% Increase
Control ROM	103.1 ± 4.6	103.2 ± 4.5*	0.07% Increase

Foam ROM: Foam rolling condition ROM; VF ROM: Vibrating foam rolling condition ROM; Vibration ROM: Vibration condition ROM; Control ROM: Control condition ROM; *Denotes main effect for time

Table 2. Means ± SE for the untreated hamstrings ROM in degrees (°)

Condition	Pre-Test	Post-Test	Δ
Foam ROM	100.3 ± 3.9*	101.80 ± 4.0*	1.53% Increase
VF ROM	101.2 ± 4.3*	103.13 ± 4.2*	1.91% Increase
Vibration ROM	103.6 ± 3.8*	102.00 ± 4.1*	1.54% Decrease
Control ROM	100.7 ± 4.1*	100.87 ± 4.2*	0.2% Increase

Foam ROM: Foam rolling condition ROM; VF ROM: Vibrating foam rolling condition ROM; Vibration ROM: Vibration condition ROM; Control ROM: Control condition ROM; *Denotes main effect for time

Tables 3 and 4 display the means ± SE of the treated and untreated concentric quadriceps peak torque. There was no four-way interaction for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). In addition, no two-way interactions for condition × velocity, condition × time, condition × limb, velocity × limb, or velocity × time ($p > 0.05$) were found. However, there was a two-way interaction for limb × time ($p = 0.014$). Quadriceps PT increased pre- to post-testing for the untreated limb. There was a main effect for velocity ($p < 0.001$). PT decreased as angular velocity increased. There was a main effect for limb ($p = 0.045$). Treated limbs PT was greater than the untreated limbs PT. There were no main effects for condition or time ($p > 0.05$).

Tables 3 and 4 display the means ± SE of the treated and untreated concentric hamstrings peak torque. There was no four-way interaction for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). There were no two-way interactions for condition × velocity, condition × time, or velocity × time ($p > 0.05$). However, two-way interactions for condition × limb ($p = 0.033$), velocity × limb ($p = 0.001$), and limb × time ($p = 0.015$) were found. The untreated limb displayed a greater PT than the treated limb in all conditions and velocities, and the treated and untreated limb decreased pre- to post-testing. In addition, a main effect for time ($p = 0.013$) and velocity ($p < 0.001$) were found. PT decreased pre- to post-testing, and PT decreased as angular velocity increased. No main effects for condition or limb were found ($p > 0.05$).

Tables 3 and 4 display the means ± SE of the treated and untreated eccentric hamstrings peak torque. No four-way interaction was found for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions for condition × velocity, condition × time, condition × limb, velocity × time, or velocity × limb ($p > 0.05$) were found for the eccentric hamstrings peak torque. However, a two-way interaction for limb × time was found ($p = 0.026$). PT decreased pre- to post-testing for both treated and untreated limb. Main effects for condition ($p = 0.021$), limb ($p = 0.020$), and time ($p = 0.023$) were found. The foam rolling condition displayed the lowest PT, while vibrating foam rolling displayed the highest PT, the untreated limb displayed a greater PT than the treated limb, and PT decreased pre- to post-testing for both limbs. No main effect was found for velocity ($p > 0.05$).

Table 3. Means ± SE for peak torque under three different velocities for the treated limb

	Pre-Test			Post-Test			
N = 15	60° $\cdot s^{-1}$	180° $\cdot s^{-1}$	300° $\cdot s^{-1}$	60° $\cdot s^{-1}$	180° $\cdot s^{-1}$	300° $\cdot s^{-1}$	Δ
PT_{Quads} (N ·m)							
Foam Rolling	131.2 ± 8.3	99.7 ± 6.2	67.2 ± 5.3	132.3 ± 6.9	99.2 ± 5.7	69.2 ± 5.0	0.82% Increase
Vibrating Foam	144.5 ± 5.4	103.2 ± 5.1	74.5 ± 4.8	139.8 ± 5.8	102.5 ± 5.6	73.1 ± 4.9	2.15% Decrease
Vibration	129.7 ± 7.6	97.2 ± 5.8	69.1 ± 5.2	125.2 ± 8.0	101.9 ± 5.9	71.7 ± 5.4	0.92% Increase
Control	133.5 ± 7.1	96.3 ± 5.7	70.9 ± 4.3	133.6 ± 7.5	98.4 ± 5.2	69.3 ± 3.9	0.22% Increase
$PT_{Hams\,(c)}$ (N ·m)							
Foam Rolling	66.1 ± 3.6*	50.9 ± 3.4*	37.3 ± 3.2*	58.7 ± 3.5*	46.5 ± 3.1*	33.7 ± 3.4*	9.94% Decrease
Vibrating Foam	65.7 ± 3.8*	49.5 ± 3.7*	36.7 ± 3.7*	62.2 ± 3.5*	48.7 ± 3.2*	32.8 ± 3.2*	5.44% Decrease
Vibration	60.4 ± 3.9*	47.6 ± 3.6*	34.9 ± 3.5*	57.1 ± 4.4*	46.9 ± 3.9*	33.3 ± 3.3*	3.92% Decrease
Control	66.6 ± 3.3*	52.1 ± 2.4*	38.1 ± 2.2*	61.9 ± 3.6*	46.7 ± 2.9*	33.1 ± 2.6*	9.57% Decrease
$PT_{Hams\,(e)}$ (N ·m)							
Foam Rolling	73.1 ± 5.8*	77.9 ± 4.5*		68.0 ± 5.0*	70.7 ± 4.2*		8.12% Decrease
Vibrating Foam	79.5 ± 5.6*	78.9 ± 4.6*		76.3 ± 4.5*	78.4 ± 4.5*		2.32% Decrease
Vibration	75.3 ± 5.9*	76.3 ± 5.5*		68.9 ± 5.6*	71.5 ± 4.9*		7.39% Decrease
Control	80.1 ± 6.0*	79.7 ± 4.6*		72.7 ± 5.0*	76.3 ± 3.9*		6.76% Decrease

PT_{Quads} (N ·m): Concentric quadriceps peak torque; $PT_{Hams\,(c)}$ (N ·m): Concentric hamstrings peak torque; $PT_{Hams\,(e)}$ (N ·m): Eccentric hamstrings peak torque; *Denotes significant changes pre- to post-testing

Table 4. Means ± SE for peak torque under three different velocities for the untreated limb

	Pre-Test			Post-Test			
N = 15	60° $\cdot s^{-1}$	180° $\cdot s^{-1}$	300° $\cdot s^{-1}$	60° $\cdot s^{-1}$	180° $\cdot s^{-1}$	300° $\cdot s^{-1}$	Δ
PT_{Quads} (N ·m)							
Foam Rolling	124.7 ± 6.4*	93.3 ± 5.6*	65.9 ± 5.2*	124.7 ± 6.1*	94.1 ± 5.2*	71.0 ± 4.8*	2.09% Increase
Vibrating Foam	128.1 ± 7.0*	98.0 ± 5.3*	68.4 ± 5.3*	135.0 ± 6.0*	98.0 ± 5.2*	73.7 ± 4.8*	4.12% Increase
Vibration	124.4 ± 7.2*	92.2 ± 5.3*	66.5 ± 4.8*	129.9 ± 5.7*	97.2 ± 4.4*	69.3 ± 4.5*	4.71% Increase
Control	124.3 ± 6.7*	90.0 ± 4.3*	65.0 ± 4.2*	128.3 ± 6.4*	96.9 ± 4.6*	71.2 ± 4.2*	6.13% Increase
$PT_{Hams\ (c)}$ (N ·m)							
Foam Rolling	66.0 ± 4.0*	49.7 ± 3.6*	35.9 ± 3.0*	63.1 ± 3.5*	48.2 ± 3.0*	35.3 ± 3.0*	3.34% Decrease
Vibrating Foam	67.3 ± 3.7*	50.3 ± 3.1*	33.0 ± 3.5*	64.9 ± 3.5*	48.2 ± 3.2*	35.4 ± 2.8*	1.13% Decrease
Vibration	66.4 ± 3.8*	46.7 ± 3.3*	37.1 ± 3.6*	66.1 ± 3.9*	50.1 ± 2.9*	35.2 ± 2.9*	0.76% Increase
Control	68.3 ± 3.4*	48.0 ± 2.4*	34.5 ± 3.2*	65.7 ± 3.5*	48.6 ± 2.8*	34.9 ± 2.7*	1.10% Decrease
$PT_{Hams\ (e)}$ (N ·m)							
Foam Rolling	76.5 ± 5.3*	79.5 ± 5.4		75.7 ± 4.8*	76.7 ± 4.5*		2.27% Decrease
Vibrating Foam	81.4 ± 5.0*	82.5 ± 5.7		82.9 ± 6.6*	83.7 ± 4.3*		1.67% Increase
Vibration	80.7 ± 4.3*	79.1 ± 4.4		78.5 ± 6.1*	77.7 ± 4.5*		2.29% Decrease
Control	78.3 ± 5.1*	81.8 ± 4.4		83.5 ± 5.9*	80.7 ± 4.9*		2.54% Increase

PT_{Quads} (N ·m): Concentric quadriceps peak torque; $PT_{Hams\ (c)}$ (N ·m): Concentric hamstrings peak torque; $PT_{Hams\ (e)}$ (N ·m): Eccentric hamstrings peak torque

Tables 5 and 6 display the means ± SE of the treated and untreated conventional H:Q ratios. No four-way interaction was found for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions for condition × velocity, condition × time, condition × limb, velocity × time, or limb × time ($p > 0.05$) were found. However, a two-way interaction for velocity × limb was found ($p = 0.025$). The untreated limb displayed a greater PT at each velocity. A main effect for time ($p < 0.001$) was found, demonstrating the pre-testing conventional H:Q ratios were greater than the post-testing conventional H:Q ratios in all conditions. No main effects were found for condition, velocity, or limb ($p > 0.05$).

Tables 5 and 6 display the means ± SE of the treated and untreated functional H:Q ratios. No four-way interaction was found for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions for condition × velocity, condition × time, condition × limb, velocity × time, velocity × limb, or limb × time ($p > 0.05$)

were found. However, main effects for velocity ($p < 0.001$), limb ($p = 0.001$), and time ($p < 0.001$) were found. Functional H:Q ratios increased as angular velocity increased, untreated limbs H:Q ratios were greater than the treated limbs, and the pre-testing ratios were greater than the post-testing ratios. No main effect for condition was found ($p > 0.05$).

Table 5. Means ± SE of the treated conventional and functional H:Q ratios

	Pre-Test			Post-Test			
N = 15	$60° \cdot s^{-1}$	$180° \cdot s^{-1}$	$300° \cdot s^{-1}$	$60° \cdot s^{-1}$	$180° \cdot s^{-1}$	$300° \cdot s^{-1}$	Δ
$H: Q\ Ratio_{(c)}$							
Foam Rolling	0.523 ± 0.038*	0.518 ± 0.027*	0.562 ± 0.030*	0.452 ± .030*	0.478 ± 0.030*	0.499 ± 0.041*	10.87% Decrease
Vibrating Foam	0.456 ± 0.022*	0.477 ± 0.024*	0.474 ± 0.031*	0.448 ± 0.021*	0.483 ± 0.026*	0.452 ± 0.033*	1.64% Decrease
Vibration	0.484 ± 0.042*	0.491 ± 0.024*	0.505 ± 0.034*	0.475 ± 0.047*	0.458 ± 0.027*	0.471 ± 0.039*	5.13% Decrease
Control	0.507 ± 0.023*	0.557 ± 0.030*	0.551 ± 0.030*	0.478 ± 0.034*	0.486 ± 0.030*	0.490 ± 0.037*	10.01% Decrease
$H: Q\ Ratio_{(f)}$							
Foam Rolling	0.590 ± 0.068*	0.794 ± 0.036*		0.528 ± 0.048*	0.733 ± 0.048*		8.87% Decrease
Vibrating Foam	0.551 ± 0.036*	0.773 ± 0.036*		0.552 ± 0.036*	0.775 ± 0.038*		0.27% Increase
Vibration	0.608 ± 0.063*	0.795 ± 0.047*		0.579 ± 0.062*	0.709 ± 0.042*		8.20% Decrease
Control	0.612 ± 0.048*	0.860 ± 0.068*		0.548 ± 0.039*	0.709 ± 0.039*		14.59% Decrease

$H: Q\ Ratio_{(c)}$: Concentric H:Q ratios; $H: Q\ Ratio_{(f)}$: Functional H:Q ratios; *Denotes significant changes pre- to post-testing

Table 6. Mean ± SE of the untreated conventional and functional H:Q ratios

	Pre-Test			Post-Test			Δ
N = 15	$60° \cdot s^{-1}$	$180° \cdot s^{-1}$	$300° \cdot s^{-1}$	$60° \cdot s^{-1}$	$180° \cdot s^{-1}$	$300° \cdot s^{-1}$	
$H: Q\ Ratio_{(c)}$							
Foam Rolling	0.536 ± 0.031*	0.539 ± 0.036*	0.554 ± 0.030*	0.515 ± 0.031*	0.516 ± 0.023*	0.503 ± 0.030*	5.89% Decrease
Vibrating Foam	0.541 ± 0.038*	0.517 ± 0.025*	0.483 ± 0.039*	0.482 ± 0.017*	0.497 ± 0.026*	0.484 ± 0.028*	5.14% Decrease
Vibration	0.549 ± 0.035*	0.511 ± 0.026*	0.548 ± 0.036*	0.512 ± 0.026*	0.518 ± 0.024*	0.511 ± 0.035*	4.47% Decrease
Control	0.560 ± 0.026*	0.545 ± 0.029*	0.546 ± 0.043*	0.530 ± 0.037*	0.507 ± 0.024*	0.500 ± 0.032*	6.95% Decrease
$H: Q\ Ratio_{(f)}$							
Foam Rolling	0.633 ± 0.053*	0.869 ± 0.053*		0.623 ± 0.047*	0.825 ± 0.039*		3.64% Decrease
Vibrating Foam	0.660 ± 0.053*	0.860 ± 0.063*		0.614 ± 0.040*	0.827 ± 0.048*		5.70% Decrease
Vibration	0.678 ± 0.052*	0.883 ± 0.046*		0.610 ± 0.450*	0.807 ± 0.043*		9.21% Decrease
Control	0.641 ± 0.041*	0.921 ± 0.047*		0.672 ± 0.057*	0.850 ± 0.061*		2.55% Decrease

$H: Q\ Ratio_{(c)}$: Concentric H:Q ratios, $H: Q\ Ratio_{(f)}$: Functional H:Q ratios
*Denotes significant changes pre- to post-testing

Tables 7 and 8 display the means ± SE of the treated and untreated concentric vastus lateralis muscle activation. No four-way interaction was found for condition × velocity × time × limb (p

> 0.05). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions were found for condition × velocity, condition × time, condition × limb, velocity × time, velocity × limb, or limb × time ($p > 0.05$). No main effects were found for time, limb, or condition ($p > 0.05$). However, a main effect for velocity was found ($p = 0.007$). The 180° $\cdot s^{-1}$ muscle activation was the greatest for both the treated and untreated vastus lateralis.

Table 7 and 8 display the means ± SE of the treated and untreated concentric biceps femoris muscle activation. No four-way interaction was found for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions were found for condition × velocity, condition × time, condition × limb, velocity × time, or velocity × limb ($p > 0.05$). However, a two-way interaction was found for limb × time ($p = 0.011$). The treated limb's muscle activation decreased pre- to post-testing, and the untreated limb muscle activation increased pre- to post-testing. No main effects were found for condition, velocity, time, or limb ($p > 0.05$).

Tables 7 and 8 display the means ± SE of the treated and untreated eccentric biceps femoris muscle activation. No four-way interaction was found for condition × velocity × time × limb ($p > 0.05$). There were no three-way interactions for condition × velocity × time, condition × velocity × limb, condition × limb × time, or velocity × limb × time ($p > 0.05$). No two-way interactions for condition × velocity, condition × time, condition × limb, velocity × time, velocity × limb, or limb × time ($p > 0.05$) were found. In addition, no main effects for condition, limb, or time were found ($p > 0.05$). However, a main effect for velocity was found ($p = 0.029$). The 180° $\cdot s^{-1}$ eccentric biceps femoris muscle activation was the greatest for both the treated and untreated limbs.

Table 7. Means ± SE of the treated EMG muscle activation

	Pre-Test			Post-Test			
N = 15	60° ·s^{-1}	180° ·s^{-1}	300° ·s^{-1}	60° ·s^{-1}	180° ·s^{-1}	300° ·s^{-1}	Δ
EMG_{VL} (MV)							
Foam Rolling	71.7 ± 3.4	91.7 ± 2.3	82.1 ± 4.3	69.9 ± 4.0	87.2 ± 3.0	78.9 ± 4.1	3.86% Decrease
Vibrating Foam	77.7 ± 4.5	90.5 ± 2.1	86.4 ± 3.2	75.1 ± 3.6	89.0 ± 2.6	83.7 ± 4.2	2.69% Decrease
Vibration	71.7 ± 3.7	91.5 ± 2.0	80.9 ± 4.1	71.0 ± 3.9	92.8 ± 2.4	87.2 ± 3.1	2.85% Increase
Control	73.1 ± 3.9	86.5 ± 1.8	90.1 ± 2.7	74.3 ± 4.3	88.5 ± 2.4	85.7 ± 2.9	0.51% Decrease
$EMG_{BF\ (c)}$ (MV)							
Foam Rolling	78.4 ± 3.4*	84.94 ± 3.9*	76.4 ± 4.7*	78.6 ± 5.3*	76.6 ± 3.9*	70.4 ± 6.9*	5.91% Decrease
Vibrating Foam	81.5 ± 4.9*	83.0 ± 3.5*	78.3 ± 4.9*	77.1 ± 4.4*	83.9 ± 3.6*	75.0 ± 4.3*	2.79% Decrease
Vibration	81.8 ± 4.1*	81.8 ± 3.5*	75.5 ± 4.4*	76.6 ± 5.6*	72.9 ± 4.5*	69.3 ± 4.8*	8.55% Decrease
Control	84.3 ± 2.6*	80.9 ± 3.2*	85.61 ± 3.4*	76.3 ± 3.2*	79.9 ± 3.0*	76.6 ± 4.0*	7.18% Decrease
$EMG_{BF\ (e)}$ (MV)							
Foam Rolling	74.0 ± 5.0	78.8 ± 3.90		71.4 ± 4.7	78.8 ± 4.2		1.64% Decrease
Vibrating Foam	74.8 ± 4.1	76.9 ± 4.6		75.6 ± 3.9	77.5 ± 3.5		0.91% Increase
Vibration	74.0 ± 4.5	73.1 ± 3.9		65.0 ± 4.6	74.2 ± 4.9		5.34% Decrease
Control	73.2 ± 2.4	77.8 ± 3.5		74.8 ± 4.1	76.6 ± 4.4		0.28% Increase

EMG_{VL}: Vastus lateralis EMG muscle action; $EMG_{BF\ (c)}$: Concentric biceps femoris EMG muscle activation; $EMG_{BF\ (e)}$: Eccentric biceps femoris EMG muscle activation; *Denotes significant changes pre- to post-testing

Table 8. Means ± SE of the untreated EMG muscle activation

	Pre-Test			Post-Test			
N = 15	60° ·s^{-1}	180° ·s^{-1}	300° ·s^{-1}	60° ·s^{-1}	180° ·s^{-1}	300° ·s^{-1}	Δ
EMG_{VL} (MV)							
Foam Rolling	74.1 ± 4.8	87.6 ± 3.0	7.7 ± 5.5	77.6 ± 3.6	92.2 ± 2.9	82.2 ± 3.0	5.63% Increase
Vibrating Foam	75.8 ± 4.8	89.8 ± 2.8	84.1 ± 4.4	80.6 ± 3.3	91.7 ± 2.8	80.4 ± 3.9	1.16% Increase
Vibration	72.1 ± 3.9	84.7 ± 3.6	77.8 ± 4.5	77.6 ± 4.2	85.6 ± 3.7	81.9 ± 3.8	4.45% Increase
Control	68.6 ± 3.7	80.4 ± 4.5	75.4 ± 5.8	72.7 ± 4.6	85.7 ± 3.1	86.0 ± 4.3	8.89% Increase
$EMG_{BF\,(c)}$ (MV)							
Foam Rolling	80.2 ± 4.3*	79.9 ± 3.5*	73.8 ± 5.7*	81.8 ± 4.0*	80.9 ± 3.8*	74.4 ± 5.6*	1.33% Increase
Vibrating Foam	73.6 ± 4.5*	79.20 ± 4.1*	65.8 ± 6.6*	74.0 ± 2.9*	76.4 ± 4.3*	74.3 ± 5.4*	1.16% Increase
Vibration	72.7 ± 4.3*	76.1 ± 3.5*	72.7 ± 5.1*	83.5 ± 3.2*	82.9 ± 3.2*	72.4 ± 3.5*	1.14% Increase
Control	78.4 ± 4.9*	79.7 ± 4.3*	67.8 ± 3.5*	77.0 ± 4.0*	84.2 ± 3.9*	76.8 ± 3.7*	1.21% Increase
$EMG_{BF\,(e)}$ (MV)							
Foam Rolling	71.0 ± 5.0	75.9 ± 3.5		73.3 ± 3.7	75.8 ± 3.3		1.55% Increase
Vibrating Foam	71.8 ± 2.9	77.6 ± 4.1		72.8 ± 3.6	78.2 ± 4.0		1.03% Increase
Vibration	72.8 ± 4.4	73.5 ± 4.5		79.6 ± 2.9	78.5 ± 4.1		8.01% Increase
Control	71.5 ± 3.5	74.9 ± 4.5		81.0 ± 4.1	76.0 ± 4.7		7.24% Increase

EMG_{VL}: Vastus lateralis EMG muscle action; $EMG_{BF\,(c)}$: Concentric biceps femoris EMG muscle activation; $EMG_{BF\,(e)}$: Eccentric biceps femoris EMG muscle activation; *Denotes significant changes pre- to post-testing

Table 9. Summary of results

Variable	Condition	Treated Limb	Untreated Limb
ROM	Foam Rolling	↑	↑
	Vibrating Foam	↑	↑
	Vibration	↑	↓
	Control	↑	↑
Concentric Quadriceps PT	Foam Rolling		↑
	Vibrating Foam		↑
	Vibration		↑
	Control		↑
Concentric Hamstrings PT	Foam Rolling	↓	↓
	Vibrating Foam	↓	↓
	Vibration	↓	↑
	Control	↓	↓
Eccentric Hamstrings PT	Foam Rolling	↓	↓
	Vibrating Foam	↓	↑
	Vibration	↓	↓
	Control	↓	↑
Conventional H:Q Ratios	Foam Rolling	↓	↓
	Vibrating Foam	↓	↓
	Vibration	↓	↓
	Control	↓	↓
Functional H:Q Ratios	Foam Rolling	↓	↓
	Vibrating Foam	↑	↓
	Vibration	↓	↓
	Control	↓	↓
Concentric VL MA	Foam Rolling		
	Vibrating Foam		
	Vibration		
	Control		
Concentric BF MA	Foam Rolling	↓	↑
	Vibrating Foam	↓	↑
	Vibration	↓	↑
	Control	↓	↑
Eccentric BF MA	Foam Rolling		
	Vibrating Foam		
	Vibration		
	Control		

↑: Indicates a significant increase pre- to post-testing. ↓: Indicates a significant decrease pre- to post-testing.

DISCUSSION

Results indicated a pre- to post-testing increase in hamstrings ROM for both limbs, with the exception of the vibration condition for the untreated limb. The treated hamstrings also displayed a greater ROM than the untreated hamstrings. Concentric quadriceps PT for the treated limb was greater than the untreated limb, the untreated limb had a PT increase pre- to post-testing, and PT decreased as angular velocity increased for both the treated and untreated limbs. Concentric hamstrings PT for both limbs decreased pre- to post-testing for all conditions, with the exception of the vibration condition for the untreated hamstrings PT, which increased. Concentric hamstrings PT also decreased as angular velocity increased for both limbs. The untreated concentric hamstrings PT displayed a greater PT pre- to post-testing than the treated limb, and displayed a higher PT at each velocity. Eccentric hamstrings PT of the treated and untreated limb decreased pre- to post-testing, with the exception of the vibrating foam condition and control condition of the untreated limb. The foam rolling condition displayed the lowest eccentric hamstrings PT, the vibrating foam rolling condition displayed the highest eccentric hamstrings PT. The untreated limb displayed a higher eccentric hamstrings PT than the treated limb. Conventional H:Q ratios decreased pre- to post-testing for both the treated and untreated limbs, and the untreated limb displayed greater ratios at each velocity. For both the treated and untreated limbs, functional H:Q ratios decreased pre- to post-testing, with the exception of the vibrating foam rolling condition, which increased for the treated limb. Functional H:Q ratios also increased as angular velocity increased, and the untreated limb had greater ratios than the treated limb. For the treated and untreated VL muscle activation, a main effect for velocity was found, meaning the $180°\cdot s^{-1}$ velocity displayed the greatest muscle activation. The treated hamstrings concentric BF muscle activation decreased pre- to post-testing, and the untreated limb increased pre- to post-testing. Muscle activation increased as angular velocity increased for the eccentric BF.

Increases in the treated hamstrings ROM was consistent with previous research. Madoni et al., (2018) showed increases in hamstrings ROM after foam rolling the hamstrings using the same protocol on 22 recreationally active women. Cheatham et al., (2018) found increases in passive ROM after vibrating foam rolling the quadriceps. Although the study done by Cheatham et al., (2018) foam rolled the quadriceps, increases in ROM were consist with the current study. Another study examining the effects of 45 seconds of vibration from a 35Hz power plate also found an increase in hamstrings ROM (18). The 45 seconds of vibration from the power plate, however, was combined with static stretching, while the current study did not examine the effects combined with static stretching (18). A study done on female gymnasts found increases in split ROM for only the non-dominant limb, after 30Hz of vibration was applied to the hamstrings and quadriceps while simultaneously performing static stretching (24). An increase in knee flexion ROM was found after six minutes of vibrating foam rolling in a study done by Lee et al., 2018, which is consistent with the current study. While Lee et al., (2018) found an increase in knee flexion after vibrating foam rolling, a decrease in knee flexion ROM was found after 6 minutes of foam rolling, which is not consistent with the increased ROM after foam rolling in the current study. Increases in the treated ROM of the present study can possibly be explained by Behm & Wilke (2019), who suggest foam rolling increases stretch tolerance on ROM due to the activation of global pain modulatory responses. The global pain modulatory responses suggested to contribute to the increases of ROM are diffuse noxious inhibitory control, gate control theory, and increased parasympathetic nervous system relaxation (2).

The foam rolling protocol from the current study produced increases in ROM for the contralateral/untreated limb. Chaouachi et al., (2017), also reported increases in hip flexion ROM for the stretched and non-stretched limb. Chaouachi et al., (2017), used 14 male rowers in their study, and performed static and dynamic stretching, unlike the current study. Behm et al., (2019) also found increases in hip flexion ROM of both the dominant and nondominant limb after stretches to the dominant hamstrings and quadriceps were performed with a Theraband. Foam rolling performed on the ipsilateral calves were found to have crossover effects on the contralateral limb (19). Increases were reported by Kelly & Beardsley, (2016) and García-Gutiérrez et al., (2018), after performing vibrating foam rolling on the calves. Increases in both ipsilateral and contralateral dorsiflexion ROM were found in both studies, similar to the increases in the contralateral/untreated limb of the current study. These results support the concept of cross-over effects on ROM (13, 19).

The current study found increases pre- to post-testing for the untreated concentric quadriceps, decreases in the treated and untreated concentric hamstrings PT, and treated and untreated eccentric hamstrings PT, while finding increases in concentric hamstrings PT in the vibration condition, and increases in eccentric hamstrings PT in the vibrating foam rolling and control conditions. Lee et al., (2018), reported increases in knee extension PT after a foam rolling and vibrating foam rolling condition, and increases in knee flexion PT were also found after the vibrating foam rolling condition (20). Chaouachi et al., (2017), found no impairments in hip flexion PT after performing static and dynamic stretching, unlike the current study. Contrary to Chaouachi's findings, the foam rolling study conducted by Madoni et al., (2018) reported decreases pre- to post-testing in concentric hamstrings peak torque, which is consistent with the current study. Decreases in PT as angular velocity increased was also found for the concentric quadriceps and hamstrings, which is similar to the present study (23). Madoni et al., (2018) used recreationally active women, and the current study used resistance trained women, which could be a possible reason for similar results. Chaouachi et al., (2017), however, studied male rowers, and Lee et al., (2018) used collegiate aged males. Using male subjects in the studies, could be a possibility as to why the subjects' PT did not decrease, as men have been shown to have greater stiffness than women (16). The current investigation, and a study by Madoni et al., (2018) displayed decreases in PT. Another study examining the effects of local vibration at 15Hz on the calves, reported plantar flexion increased without decreasing plantar flexion strength (17). This investigation, although performed on the calves, did not show a decrease in strength, and used male subjects as well (17). Differences in results could possibly be due to different testing protocols and rolling interventions, location of implemented rolling conditions, or to using a more highly trained male population.

The concentric and functional H:Q ratios for the current study decreased pre- to post-testing for both the treated and untreated limb. In a study by Costa et al., (2009) decreases in H:Q ratios pre- to post-testing were reported after static stretching of the posterior thigh, which is consistent with the current study. Costa et al., (2013) also demonstrated static stretching the hamstrings only, decreased the conventional H:Q ratios similarly to the current study, but found that static stretching of both the hamstrings and quadriceps decreased the functional H:Q ratios. The current study only induced conditions to the treated hamstrings and found decreases of the functional H:Q ratios for both contralateral and ipsilateral limbs. Madoni et al., (2018) reported concentric H:Q ratios decreased pre- to post-testing, and the functional H:Q ratios increased as velocity increased after foam rolling. These findings were similar to the current investigation's findings. The effects of vibrating foam rolling studied by Lim et al., (2019) demonstrated isometric MVCs of the VL, VM, and RF increased after the rolling. While the current study found increases in the untreated quadriceps strength, decreases in concentric and eccentric hamstrings strength were also found. Decreases in strength might be due to the amount of dynamometer tests executed, possibly resulting in fatigue regardless of the session condition.

Decreases in BF activation after foam rolling of the quadriceps were reported by Cavanaugh et al., (2017), with no decreases to the VL or VM. A decrease from pre- to post-testing for the treated limb's BF was found in the current study, but not in the untreated BF which increased, or eccentric BF muscle activation in either limb. The treated and untreated VL muscle activation did not show a decrease or increase. Madoni et al., (2018) also demonstrated decreases in BF muscle activation in the treated limb after foam rolling using the same protocol, suggesting the induced hamstrings stretch from the foam roller used in both studies may decrease BF activation. Costa et. al., (2009) however, found no differences in muscle activation after performing static stretching, which suggests decreases in muscle activation may be specific to the mode of intervention being performed. An article by Bradbury-Squires et al., (2015) also suggests decreases in EMG amplitude after a bout of foam rolling may be caused by a suppression of H-reflexes. It is important to note that the BF and VL are not the only muscles used in knee flexion and extension. Perhaps, different responses in muscle activation could have been observed if a different muscle was assessed.

Future research could follow a similar protocol to investigate differences between men and women, or perhaps women who meet specific strength requirements. For this study, the women were required to be lower-body resistance trained, 3 days a week for 30 minutes, for the past 6 months. Although participants had to meet the lower-body resistance training requirement, they were not required to meet an explicit strength requirement. Investigating a population that would be highly trained, could possibly reveal different results. Another future alternative could be to investigate how vibrating foam rolling of the quadriceps, or how a combination of rolling, would affect the same variables. One strength of the present investigation was the repeated measures crossover design. In addition, the current study was the first to compare foam rolling, vibrating foam rolling, and vibration-only, on the treated as well as contralateral limb. In summary, the hamstrings ROM increased in all conditions for both limbs, but at the expense of decreasing the treated concentric and eccentric hamstrings PT, the treated and untreated conventional H:Q ratios and functional H:Q ratios, and the treated concentric BF muscle activation. Overall, vibration, vibrating foam rolling, and foam rolling of the hamstrings may increase hamstrings ROM, but with the possible risk of decreasing performance measures to the ipsilateral and contralateral limbs.

ACKNOWLEDGEMENTS

The authors would like to thank Hyper Ice, Inc. (Irvine, CA) for donating the vibrating foam rollers used in this study.

REFERENCES

1. Behm D, Lau R, O'leary J, Rayner M, Burton E, & Lavers, L. Acute effects of unilateral self-administered static stretching on contralateral limb performance. J Perform Health Res 3(1): 1-7, 2019.

2. Behm DG, & Wilke J. Do Self-myofascial release devices release myofascia? Rolling mechanisms: A narrative review. Sports Med (Auckland, N.Z.) 49: 1173–1181, 2019.

3. Bradbury-Squires D, Noftall J, Sullivan K. Roller-massager application to the quadriceps and knee-joint range of motion and neuromuscular efficiency during a lunge. J Athl Train 50(2): 133-140, 2015.

4. Carlson C. The natural history and management of hamstring injuries. Current reviews in musculoskeletal medicine 1(2): 120-123, 2008.

5. Cavanaugh, TM, Aboodarda, JS, Hodgson, DD, & Behm, GD. Foam rolling of quadriceps decreases biceps femoris activation. J Strength Cond Res 31(8): 2238-2245, 2017.

6. Chaouachi A, Padulo J, Kasmi S, Othmen AB, Chatra M, & Behm DG. Unilateral static and dynamic hamstrings stretching increases contralateral hip flexion range of motion. Clin Physiol Funct Imaging 37(1): 23, 2017.

7. Cheatham SW, Stull KR, & Kolber MJ. Comparison of a vibration roller and a nonvibration roller intervention on knee range of motion and pressure pain threshold: A randomized controlled trial. J Sport Rehabil 28(1): 1, 2018.

8. Costa PB, Ryan ED, Herda TJ, Walter AA, Defreitas JM, Stout Jr, & Cramer JT. Acute effects of static stretching on peak torque and the hamstrings-to-quadriceps conventional and functional ratios. Scand J Med Sci Sports 23(1): 38-45, 2013.

9. Costa PB, Ruas CV, & Smith CM. Effects of stretching and fatigue on peak torque, muscle imbalance, and stability. J Sports Med Phys Fitness 58(7-8): 957, 2018.

10. Costa PB, Ryan ED, Herda TJ, Defreitas JM, Beck TW, & Cramer JT. Effects of static stretching on the hamstrings-to-quadriceps ratio and electromyographic amplitude in men. J Sports Med Phys Fitness 49(4): 401, 2009.

11. Couture G, Karlik D, Glass SC, & Hatzel BM. The effect of foam rolling duration on hamstring range of motion. Open Orthop J 9: 450-455, 2015.

12. Cramer JT, Housh TJ, Weir J, Johnson G, Coburn JW, & Beck T. The acute effects of static stretching on peak torque, mean power output, electromyography, and mechanomyography. Euro J Appl Physiol 93(5): 530-539, 2005.

13. García-Gutiérrez MT, Guillén-Rogel P, Cochrane DJ, & Marín P J. Cross transfer acute effects of foam rolling with vibration on ankle dorsiflexion range of motion. J Musculoskelet Neuronal Interact 18(2): 262, 2018.

14. Halperin I, Aboodarda SJ, Button DC, Andersen LL, & Behm DG. Roller massager improves range of motion of plantar flexor muscles without subsequent decreases in force parameters. Int J Sports Phys Ther 9(1): 92, 2014.

15. Herda JT, Costa BP, Walter AA, Ryan DE, Hoge MK, Kerksick MC, Cramer TJ. Effects of two modes of static stretching on muscle strength and stiffness. Med Sci Sports Exerc 43(9): 1777-1784, 2011.

16. Hoge KM, Ryan ED, Costa PB, et al. Gender differences in musculotendinous stiffness and range of motion after an acute bout of stretching. J Strength Cond Res 24(10): 2618-2626, 2010.

17. Ikeda N, Inami T, & Kawakami Y. Stretching combined with repetitive small length changes of the plantar flexor muscles enhances their passive extensibility for longer duration than conventional static stretching, while not compromising strength. BioRxiv 1-24, 2018.

18. Jemni AM, Mkaouer AB, Marina AM, Asllani AA, & Sands AW. Acute static vibration-induced stretching enhanced muscle viscoelasticity but did not affect maximal voluntary contractions in footballers. J Strength Cond Res 28(11): 3105-3114, 2014.

19. Kelly S, & Beardsley C. Specific and cross-over effects of foam rolling on ankle dorsiflexion range of motion. Int J Sports Phys Ther 11(4): 544, 2016.

20. Lee CL, Chu IH, Lyu BJ, Chang WD, & Chang NJ. Comparison of vibration rolling, nonvibration rolling, and static stretching as a warm-up exercise on flexibility, joint proprioception, muscle strength, and balance in young adults. J Sports Sci 36(22): 2575-2582, 2018.

21. Lim JH, Park CB, K BG. The effects of vibration foam roller applied to hamstring on the quadriceps electromyography activity and hamstring flexibility. J Exerc Rehabil 15(4): 560-565, 2019.

22. Macdonald G, Penney M, Mullaley M, Cuconato A, Drake C, Behm D, & Button D. An acute bout of self-myofascial release increases range of motion without a subsequent decrease in muscle activation or force. J Strength Cond Res 27(3): 812, 2013.

23. Madoni SN, Costa PB, Coburn JW, & Galpin AJ. Effects of foam rolling on range of motion, peak torque, muscle activation, and the hamstrings-to-quadriceps strength ratios. J Strength Cond Res 32(7): 1821-1830, 2018.

24. McNeal JR, Edgerly S, Sands WA, & Kawaguchi, J. Acute effects of vibration-assisted stretching are more evident in the non-dominant limb. Eur J Sport Sci 11(1): 45-50, 2011.

25. Miller KL, Costa PB, Coburn JW, & Brown LE. The effects of foam rolling on maximal sprint performance and range of motion. JASC 27(01): 15-26, 2019.

26. Monteiro ER, Costa PB, Corrêa Neto VG, Hoogenboom BJ, Steele JD, & Silva Novaes JD. Posterior thigh foam rolling increases knee extension fatigue and passive shoulder range-of-motion. J Strength Cond Res 33(4): 987-994, 2019.

27. Navalta JW, Stone WJ, Lyons TS. Ethical Issues Relating to Scientific Discovery in Exercise Science. Int J Exerc Sci 12(1): 1-8, 2019.

28. Peacock CA, Krein DD, Silver TA, Sanders GJ, & Von Carlowitz K-PA. An acute bout of self-myofascial release in the form of foam rolling improves performance testing. Int J Exerc Sci 7(3): 202, 2014.

29. Romero-Moraleda B, González-García J, Cuéllar-Rayo Á, Balsalobre-Fernández C, Muñoz-García D, & Morencos E. Effects of vibration and non-vibration foam rolling on recovery after exercise with induced muscle damage. J Sports Sci Med 18(1): 172, 2019.

30. Rosene J, Fogarty T, & Mahaffey B. Isokinetic hamstrings: quadriceps ratios in intercollegiate athletes. J Athl Train 36(4): 378-383, 2001.

31. Ylinen J, Kautiainen H, & Häkkinen A. Comparison of active, manual, and instrumental straight leg raise in measuring hamstring extensibility. J Strength Cond Res 24(4): 972-977, 2010.