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HIGHER QUADRICEPS ROLLER MASSAGE FORCES DO NOT AMPLIFY RANGE-OF-MOTION INCREASES OR IMPAIR STRENGTH AND JUMP PERFORMANCE

RUNNING HEAD: EFFECTS OF VARIED ROLLER MASSAGE FORCES

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ABSTRACT

Roller massage (RM) has been reported to increase range-of-motion (ROM) without subsequent performance decrements. However, the effects of different rolling forces have not been examined. The purpose of this study was to compare the effects of sham (RMsham), moderate (RMmod) and high (RMhigh) RM forces, calculated relative to the individuals' pain perception, on ROM, strength and jump parameters. Sixteen healthy individuals (27 ± 4 years) participated in this study. The intervention involved three 60-second quadriceps RM bouts with RMlow (3.9/10±0.64 rating of perceived pain{RPP}), RMmod (6.2/10±0.64 RPP) and RMhigh (8.2/10±0.44 RPP) pain conditions respectively. A within-subject design was used to assess dependent variables (active and passive knee flexion ROM, single-leg drop jump (DJ) height, DJ contact time, DJ performance index, maximum voluntary isometric contraction (MVIC) force, and force produced in the first 200 ms (F200) of the knee extensors and flexors). A two- way repeated measures analysis of variance (ANOVA) showed a main effect of testing time in active ($p < 0.001$, $d = 2.54$) and passive ($p < 0.001$, $d = 3.22$) ROM. Independent of the RM forces, active and passive ROM increased by 7.0% ($p = 0.03$, $d = 2.25$) and 15.4% ($p < 0.001$, d

$= 3.73$) from pre- to post measures, respectively. DJ and MVIC parameters were unaffected from pre- to post-tests ($p > 0.05$, $d = 0.33$ - 0.84). RM can be efficiently used to increase ROM without substantial pain and without subsequent performance impairments.

KEY WORDS: self-massage therapy; neuromuscular rolling; pressure; self-myofascial release

INTRODUCTION

Self-myofascial release, self-massage therapy, and neuromuscular rolling are terms that describe the use of a tool to massage muscles and connective tissues with a rolling motion (4). Applicable tools can be a foam roller (17,25,34), roller massage (RM) stick (17,21,26), or tennis ball (16). Neuromuscular rolling has been shown to increase range-of-motion (ROM) immediately after the intervention (8,17,21,25,33,34) with changes present for as long as 20 minutes (min)(22,23,27). The degree of increase in ROM reported in the literature is highly variable ranging from 2.8% (33) to 23.4% (16). Variability may be explained by the type of tool used (15,28), the target muscle group, the task instructions (17), the overall volume of neuromuscular rolling (14), and the applied rolling force (14,31,33).

A limited number of studies have suggested that the rolling forces applied to the target muscle may influence changes in ROM. Bradbury-Squires and colleagues (8) applied 25% ofthe body mass, which was equivalent to 205.9 N of RM force, to the anterior thigh. Rolling for 5 sets of 20 and 60 seconds (s) increased ROM by 10% and 16%, respectively. Another study (34) used 127.5 N of RM force applied to the hamstrings and reported an increase of 4.3% after only1 - 2 sets of 5 - 10 s. Recently, 68% of the body mass (mean force of 266.7 N) was used on a foam roller and small but significant 2.4° increase in the hip flexors and quadriceps muscles was found (30). Although a greater increase in ROM reported by Bradbury-Squries et al. (8) in comparison to that of Sullivan and colleges (34) could be the result of longer intervention, the possible effect of higher force application that would be accompanied with greater discomfort or pain cannot be excluded. While one attempt to explain this variance showed that smaller contact area and more rigid roller design would lead to greater pressure (15), the impact of rolling force that is associated with differing perception of pain (17) remains unclear. Neuromuscular rolling has been shown to increase pain threshold associated with muscle tender spots, acute electrically evoked pain, and delayed onset muscle soreness, (1,10,24). This change is also observed on the contralateral, non-rolled, limb suggesting the involvement of a central pain-modulatory system (1,10). Rolling-induced improvements in ROM could be related to an increased pain, or stretch tolerance (17). However, this relationship has not been previously examined.

Based on recent studies, neuromuscular rolling exerts global effects (1,10,23). For example, Monteiro et al. (29) showed improvements in overhead deep squat performance regardless of the area under treatment, i.e. lateral thigh, plantar surface of the foot and latissimus dorsi. This finding suggests a degree of likelihood that findings from a specific muscle (e.g. quadriceps in the present study) can be extrapolated to others (e.g. hamstrings).

While neuromuscular rolling is reported to increase flexibility, it does not appear to attenuate athletic performance (4). Several studies have shown that muscle strength, power, or balance performance remained unaffected by the self-applied treatment (5,17,18,25,26,34). To the authors' knowledge, no study has examined varied RM forces on athletic performance. Whether a high or a low intensity roll have a different impact on strength and jump parameters is of direct relevance with athletic activities that includes maximal strength and power performances.

There is a practical need to identify the optimal rolling force to achieve the greatest ROM without attenuating muscular performance. The aim of this study was to compare the effects of low (RMlow), moderate (RMmod), and high (RMhigh) RM force, calculated relative to the individual's perception of pain, applied to the anterior thigh on ROM, strength, and jump performance. With reference to the relevant literature (4,5,8,17,25,34), it was hypothesized that all interventions would enhance ROM without causing a subsequent decrease in performance. It was assumed that higher RM forces produce greater ROM improvements.

METHODS

Experimental Approach to the Problem

A randomized (https://www.randomizer.org/) within-subject design was used to investigate the effects of three conditions; RMlow, RMmod, and RMhigh forces applied to the anterior thigh on active and passive knee flexion ROM, single-leg drop jump (DJ) performance and MVIC measures (Figure 1). At the beginning of each session, the subject's maximum point of discomfort was re-evaluated to control for daily variations of the individual's rating of perceived pain (RPP). After the warm-up, (5 min warm-up on a Monark cycle ergometer at 60-70 revolutions per minute and 1 kilopond of resistance) dependent measures were tested which included active and passive knee flexion ROM, two single-leg DJs, two knee extension, and two knee flexion MVICs. After the pre-tests, subjects sat quietly for 10 min followed by another set of dependent variable measures. Following the pre-tests, the intervention consisted of three 60 s RM bouts either at RMlow, RMmod, or RMhigh rolling intensities. To monitor effects of repeated bouts, and thus determine possible effects of the RM volume; knee flexion ROM, and single-leg DJ performance were measured after each RM set. Immediately after (INTpost) and ten minutes after the last bout of RM (INTpost10), all measures (ROM, DJ, and MVIC) were performed again.

Figure 1 could be placed here

Participants

A statistical power analysis was calculated based on related prior publications (8,17,24,25,34) which determined that 16 participants would be needed to achieve an alpha of

0.05 and a power of 0.8. Thus, 16 young, healthy individuals (eight males, 27 ± 5 years, 178 ± 5 cm, 87 ± 9 kg and eight females, 26 ± 2 years, 170 ± 4 cm and 69 ± 8 kg) were recruited to participate in this study. All participants were either resistance and/or aerobically physically trained (minimum 3 sessions x 20 min/week) and reported no prior experience with RM. Exclusion criteria included any history of neurological or musculoskeletal injuries in the past year. Participants were instructed to refrain from vigorous physical activity and to abstain from alcoholic beverages 24 hours prior to testing.

All subjects completed the Physical Activity Readiness Questionnaire form (PAR-Q; Canadian Society for Exercise Physiology 2011) and signed a written letter of consent prior to testing. A brief explanation of the study was given during the familiarization. Additionally, participants were accustomed to the RM device. This orientation allowed participants to experience the force of RM necessary to elicit their maximum point of discomfort prior to thefirst testing session. The maximum tolerable pain was considered equivalent to a 10/10 on a visual analogue scale reaching from 0 (no pain or discomfort) to 10 (maximum tolerable pain) as perceived by the participant. Participants were encouraged to practice single-leg DJs several times from a platform set at a height corresponding to 50% of the length of the tibial tuberosity. This study was approved by the Newfoundland and Labrador Human Research Ethics Board (reference # 15.226). All procedures were in accordance with the Declaration of Helsinki (2013).

Procedures

Interventio

n

The Theraband® RM (The Hygenic Corporation, Akron, OH, USA) composed of dense foam wrapping around a solid plastic cylinder was used for this study. The ridged design is supposed to allow for both superficial and deep-tissue massage when performing RM on the muscle (8,34). The RM was placed in a specially designed constant pressure roller apparatus (Custom designed by Technical Services, Memorial University of Newfoundland, St John's, Newfoundland and Labrador, Canada: Figure 2), which was previously used in this laboratory (8,34). This device allowed for consistent force application and frequency of rolling, thereby eliminating variations that would be typical if each individual applied the roller action to their own limb (Figure 3). A pilot study on experienced individuals was conducted beforehand. It revealed that the average force that a person would exert while rolling a muscle was strongly dependent on the day and the individual. Weighted plates were added to the vertical poles until the load of the apparatus for one full cycle of rolling reached the individual's 10/10 RPP on the specific testing day. The evaluation of the highest point of discomfort on each day was conducted prior to the warm-up. The maximum weight put on the apparatus was calculated relatively for 50% (RMlow: 116.7 ± 27.5 N; 15% of body mass), 70% (RMmod, 160.6 ± 29.4 N; 21% of body mass), and 90% (RMhigh, 205.9 ± 34.3 N; 27% of body mass) of the participants maximum (10/10) rating of perceived pain (RPP), respectively. These relative loads were chosen since most of our prior publications (1,8,10,17,24,25) used rolling pressures at 7/10 on a pain scale. While 70% (7/10) provides moderate discomfort, the choice of 90% and 50% would provide a spectrum of either extreme discomfort or minimal discomfort while still providing varying pressure on cutaneous, fascial and muscle sensory receptors.

One full cycle (distal to proximal and return) was completed by the researcher in 4 s, as conducted in previous studies (8,30). The pace was monitored with a metronome. Each roll commenced at the distal end of the quadriceps superior to the patellar tendon and continued tothe proximal end of the quadriceps (hip crease) and was then reversed. After each of the 60 s bouts of rolling, the participant performed active and passive knee flexion ROM as well as two single-leg DJs. The between RM bout measures were conducted to control for possible changes dependent on RM volume. The between set interval was two minutes. RM was performed for three sets of 60 s irrespective of the RM force. To determine the individuals' RPP during each RM bout, participants were asked to mark three separate, blank 10 cm lines that represented the visual analogue scale after 5, 30, and 60 s of RM. After 60 s of rolling, RM caused low (3.9/10 ± 0.64 RPP), moderate (6.2/10 ± 0.64 RPP) and intense (8.2/10 ± 0.44 RPP) pain in RMlow, RMmod, and RMhigh, respectively. The individual pain scores at 60 s were further used to investigate possible pain-related ROM increases.

Figures 2 and 3 could be placed here

Dependent Variables

Two pre-tests were analyzed to determine possible effects of repeated measures (2). The second set of measures prior to the intervention (INTpre) was used as a baseline for comparison to the intervention. To monitor effects of repeated bouts, and thus determine possible effects of the RM volume; knee flexion ROM, and single-leg DJ performance were measured after each RM set. Immediately after (INTpost) and ten minutes after the last bout of RM (INTpost10), all measures (ROM, DJ, and MVIC) were performed again. The three experimental sessions were conducted at similar times during the day to minimize diurnal effects. A minimum of 48 hours and maximum of four days was scheduled between each session.

Knee flexion ROM was assessed using a slight modification of the kneeling lunge position published previously (24,25). With their torso upright in an erect position, participants were asked to position their malleolus of the non-dominant leg over a horizontal line on the floor with their tibia perpendicular to the floor. A rectangular frame over the horizontal line served to visualize the position of the non-dominant limb and support the erect position. The dominant knee was then moved back until the participant felt a maximal tolerable stretch in the dominant hip flexor without deviating from the initial position. The position of the dominant knee was marked and kept for all subsequent ROM measurements for each session, respectively. All measures were performed barefoot and on the dominant leg as identified by the lateral preference inventory (13). Knee joint ROM was assessed by the same researcher with an analogue goniometer placed in accordance with MacDonald at al. (24,25) at the following landmarks: the lateral malleolus, the lateral epicondyle, and the center of the vastus lateralis. The participants were instructed to engage their abdominal muscles to maintain trunk posture. By actively contracting the hamstrings, active knee flexion ROM was then measured. For the passive knee flexion ROM assessment, one researcher passively flexed the individual's knee until the participant reached the maximal point of discomfort (Figure 4).

Figure 4 could be placed here

All DJ trials were performed on a force platform (AMTI, 400x600 x83 mm, model BP400600 HF-2000 - Watertown, MA02472-4800 USA) and amplified at a gain of 1000. Vertical ground reaction forces (GRF) were measured. Participants stood on a platform set at a height corresponding to 50% of the length of their tibial tuberosity, and with their hands placed akimbo. They were instructed to drop onto the force plate with their dominant leg, to then vertically jump at the maximal effort with as little ground contact time as possible and land

on

their dominant leg. A trial was considered valid when the foot was placed on the force plate and when participants maintained a stable landing position for two seconds. GRF was used to determine contact time and jump height. Jump height was calculated using the formula: *jump height = 0.5 x g x* t^2 in which *g* refers to the acceleration due to gravity and *t* is the flight time. In addition, given that ground contact time is a relevant parameter for DJ performance, a performance index was calculated according to the following formula: *performance index = jump height / contact time* (35).

Participants performed unilateral MVICs by flexing or extending the knee joint against a strap attached to the ankle while sitting on a padded table. In order to prevent hip extension, the subjects were fastened to the table at the proximal part of the thigh while the upper body was fastened to a back rest. The ankle strap was secured by a high-tension wire to a Wheatstone bridge configuration strain gauge (Omega Engineering Inc., Don Mills, Ont.), which was connected to a metal plate on the opposing wall for knee flexion and to the table for knee extension. Differential voltage from the strain gauge was amplified (Biopac Systems Inc., DA 100), A/D converted (MP100WSW, Holliston, MA), and monitored on a computer (Dell Inspiron 6000) at a sampling rate of 2500 Hz. The subjects were shown how to perform an MVIC with their arms crossed and then instructed to flex or extend their knee as fast and as strong as possible for hamstring or quadriceps MVIC. Verbal encouragement was given during the 4 s trials to ensure maximal force production. Two trials per movement were separated by a1 min rest. The order of knee flexion or extension was randomized. The maximal force level and F200 were taken into consideration for further analysis. F200 was considered an indicator of how rapidly force can be produced (20).

Statistical Analyses

SPSS software (Version 22.0, IBM) was used to analyze the data. The Shapiro-Wilk test confirmed a normal distribution. To determine the effects of the RM intervention on MVIC force and F200 a 3 (RMlow, RMmod, RMhigh) x 3 (INTpre, INTpost, INTpost10) analysis of variance (ANOVA) was used. Effects on ROM and DJ parameters were calculated in a 3 x 5 ANOVA because measures were also taken between RM bouts. Differences were considered significant at $p \leq 0.05$. When the condition x time interaction was significant, post-hoc paired t- tests were used to identify the statistically relevant comparisons. Moreover, effect sizes were assessed to determine the pertinence of differences by computing Cohen's *d*. Classifications of the effect sizes were in accordance with the literature (12) (small: $d < 0.5$; medium: $0.5 \leq d < 0.8$; large: $d \geq 0.8$). Additionally, Spearman's correlation coefficients between pain and ROM increases were determined. Intersession reliability was calculated using an Intraclass Correlation Coefficient (ICC) Cronbach's alpha. Data were presented as mean and standard deviations (SD).

RESULTS

ICC reliability scores were classified as acceptable to high for active (0.70) and passive (0.71) ROM, DJ height (0.70), contact time (0.76), performance index (0.74), knee extension MVIC forces (0.97), and F200 (0.94) as well as knee flexion MVIC forces (0.89) and F200 (0.91).

Active Range-of-Motion

A significant main effect ($p < 0.001$, $d = 2.54$) for testing time was found for active ROM. Both INTpost (Δ 7.0%, $p = 0.029$, $d = 2.25$) and INTpost10 (Δ 6.9%, $p = 0.026$, $d = 2.38$) measures showed significantly more active ROM than INTpre measures in all intervention groups (Figure 5). No significant main effects for different intensities (load) of rolling force or interactions for rolling force with testing time were found.

Weak but significant correlations were found between the pain of each bout of RM and the ROM changes from INTpre to measures after the first ($r = -0.29$, $p = 0.04$), second ($r = -0.308$, $p = 0.03$), and third (INTpost) ($r = -0.321$, $p = 0.02$) RM application. Regarding the separate rolling forces, the changes in active ROM from INTpre to INTpost correlated with the recorded pain values during the first ($r = 0.565$, $p = 0.023$) and second ($r = 0.633$, $p = 0.008$) RMlow force application. There were no correlations with RMmod. Significant correlations with RMhigh were evident between pain during second and third RM bout and the changes in active ROM from INTpre to testing after the second ($r = 0.500$, $p = 0.048$), and third RM bout (INTpost) ($r = 0.620$, $p = 0.010$), respectively (Table 1).

Table 1 and Figure 5 can be placed around here

Passive Range-of-Motion

There was a significant main effect for testing time ($p < 0.001$, $d = 3.22$) with significantly greater passive ROM after the second RM treatment (Δ 9.3%, $p = 0.007$, $d = 2.40$), for INTpost (Δ 15.4%, $p = 0.000$, $d = 3.73$), and INTpost10 (Δ 11.9%, $p = 0.000$, $d = 2.90$) measures in comparison to INTpre measures. The increases in passive ROM from one bout to another was significant from the first to the second bout (Δ 4.6%, $p = 0.049$, $d = 1.12$) and from the second RM bout to INTpost (Δ 7.3%, $p = 0.029$, $d = 1.57$) measures. Additionally, there wasa 7.4% increase in ROM from the first pre-test to the INTpre-test ($p = 0.000$, $d = 1.96$) (Figure

6). There was no significant effect for the intervention or the interaction of rolling force application and testing time. There was a small effect size between the greater ROM increases from INTpre to INTpost performance of RMsham and RMmod (d = 0.43) and a moderate effect size of RMlow compared to RMhigh measures (d = 0.55)(Table 1).

There were small but significant correlations between the pain of each bout of rolling and the changes in knee flexion passive ROM between the second and INTpost measures (painin the first: r = 0.407, p = 0.004; second: r = 0.419, p = 0.003; and third RM bout: r = 0.427, p = 0.002). The pain of the third 60 s RMsham bout correlated with the INTpost increases in passive ROM (r = 0.713, p = 0.002). There were no correlations for RMmod and RMhigh.

Figure 6 can be placed around here

Drop Jump Performance

There were no significant effects on DJ height, DJ contact time, and DJ performance index (Table 2).

Table 2 can be placed here

Knee Flexion and Extension MVIC Force and F200

Significant main effects for testing time (p < 0.001, d = 1.53) showed 6% higher forces in the first pre-test compared to INTpre performance in knee flexion MVIC (p = 0.038, d = 1.74). Main effects for testing time in knee flexion MVIC F200 (p = 0.029, d = 0.94) showed that forces achieved in the first pre-test were 11.8% higher than INTpost force (p = 0.048, d =

1.5)(Table 3). Knee extension MVIC force showed main effects for testing time (*p* = 0.009, *d* = 1.08). Participants produced 4.8% more force in in the initial measures than in INTpre trials (*p* = 0.003, *d* = 0.75). No further significant differences were present (Table 4).

Table 3 and 4 can be placed here

DISCUSSION

The most important findings of the present study were that, besides the overall increase in active and passive ROM, there was no significant effect of varied rolling forces. Although higher forces elicited greater pain, participants could roll without substantial discomfort and still increase ROM. Secondly, strength (MVIC) and power (DJ) parameters remained unaffected regardless of the rolling forces. Finally, the second pre-test (INTpre) was significantly different than the initial pre-test for knee flexion passive ROM, knee flexion, and knee extension MVIC force, emphasizing the impact of initial pre-tests on subsequent measures.

Without any effect of the varied force application, RM treatment induced 7.0% and 15.4% greater active and passive ROM respectively. The significant increases persisted for 10 min. Previous literature reported highly varying significant greater ROM after neuromuscular rolling (4,31). No significant findings were reported by Mikesky et al. (26) who did not controlfor any parameters possibly influencing RM treatment. Vigotsky and colleagues (37) did not find increases in knee flexion ROM (modified Thomas test) after two 60 s bouts of foam rolling. The Thomas test only uses the weight of the leg and force of gravity to determine any length changes. Contrary, the present kneeling lunge test was dependent on the biceps femoris strength for active ROM and on the researcher's force for passive ROM assessment. Therefore, the different outcomes might be due to different ROM assessment. Vigotsky et al. (37) neither considered rolling intensity nor pain. Both variables were taken into consideration for explaining varying ROM increases caused by neuromuscular rolling theoretically in previous studies (8,15,24,25,34) and practically (direct measurement) in the present study.

Overall, differing levels of pain associated with RMlow (3.9/10), RMmod (6.2/10) and RMhigh (8.2/10) had similar effects upon knee flexion ROM. According to these findings, individuals can roll without substantial discomfort or pain but still achieve significant ROM increases. However, small overall correlations revealed that increasing pain and active knee flexion ROM could be related ($0.29 < r < 0.321$). Conversely, RMmod-dependent active ROM changes and pain did not significantly correlate. Differing correlations between pain and ROM increases might be due to a very individual response to both the perception of pain and neuromuscular rolling, which was also elucidated previously (37). Small effect sizes between each INTpost result of active ROM, a small effect size between RMlow and RMmod as well asa moderate (d = 0.55) effect size between INTpost passive ROM outcomes of RMlow and RMhigh indicate that there are practical relevant differences that need to be further investigated. Even though this study was the first to focus on the impact of varied force application,

few studies mentioned possible force-related mechanisms. Curran et al. (15) compared a multilevel rigid roller with a bio-foam roller and strongly encouraged further research in pressure-related neuromuscular rolling mechanisms. The authors hypothesized that higher forces and less cutaneous contact time, consequent higher pressure, might be beneficial for facilitating movement. Their theory was not supported in this study. Bradbury Squires et al. (8) suggested that rolling force and duration could possibly amend viscoelasticity and thixotropic properties of fascia (32). However, this theory has been rejected since forces outside of human physiological range would be required to induce mechanical deformation in firm tissues, including fascia (11). If fascial ground substance were altered to a more gel-like constitution, it would more likely bea long-term effect (3,36). Noticeably, Bradbury-Squires et al. (8) found 7%

M. vastus lateralis (VL) and 8% M. biceps femoris (BF) activation, relative to the maximum activation during

MVIC, at 20 and 60 seconds during one 60-second RM bout, regardless of the increasing pain. They indicated that the co-contraction while rolling would protect the musculature from RM forces. Secondly, heat might be generated which would result in reduced muscle and connective tissue viscoelasticity, further leading to greater ROM. An observation in the present study was that participants began to sweat during RM application, irrespective of the force. Muscular co-contractions cannot be excluded as a possible mechanism contributing to ROM increases.

Another possible neuromuscular mechanism involved might be related to a greater stretch tolerance as the extrafusal and intrafusal (muscle-spindle) muscle length alters when muscles contract, similarly to the contract-relax proprioceptive neuromuscular facilitation (CR-PNF, 19). An increased pain pressure threshold (decreased pain sensitivity) over tender spots in the plantar flexors after ipsilateral and contralateral heavy RM, and massage treatments was reported (1), thus, supporting neural mechanisms. Increased stretch tolerance (increased resilience against the pain or discomfort of stretching) might be attributed to the diffuse noxious inhibitory control mechanism (9). Pain transmission would be inhibited due to monoamine transmitters when nociceptive stimuli are evoked and ascend to the brain. The highly variable individual RPP indicate that further research with greater populations is needed to determine whether force-induced pain affects ROM outcomes of neuromuscular rolling.

That varied forces did not cause impairments in muscle strength or jump performance parameters is in alignment with previous research (17,25,34). These findings put emphasis on different working mechanisms from traditional static stretching. Possible static stretching mechanisms include a reduction in active or passive stiffness in musculotendinous unit or a reduced crossbridge overlap (6). Considering that static stretching has been reported to lead to decrements in performance (6), RM, even when applied with high forces, may be an alternative treatment to increase ROM in an athletic field that involves maximum performances.

Finally, this study showed significantly different results between the two pre-tests. These findings put emphasis on the impact of the initial pre-test on subsequent measures. While Atha and Wheatley (2) reported mobilizing effects of repeated measures, Bergh and Ekblom (7) found that higher muscle temperature enhances muscle strength and power output. Bradbury-Squires et al. (8) suggested VL and BF co-contractions might generate additional intramuscular heat; however, an impact of one 60 s bout of quadriceps foam rolling on muscle temperature has not been found in a different study (30). Since MVIC force in the present study only substantially changed from the initial pre-test to all subsequent measures, it is likely that the warm-up resulted in more muscle hyperthermia than possible RM-induced co-contractions. Therefore, multiple pre-tests or warm-ups involving MVICs, and ROM measures should be performed to prevent testing effects.

The most important limitation is that the present study did incorporate a low intensity RM (RMlow) rather than a control group. The RMlow condition provided a similar environmental condition with negligible force application. However, while the RMlow condition could have activated cutaneous receptors, the lack of pre- to post-intervention force-dependent RM changes suggests the RMlow condition was a suitable control replacement. Another limitation of this study may concern whether an individual's upper body strength might not produce sufficiently high forces. However, the present findings indicate that intense forces do not need to be reached to substantially increase ROM. Finally, participants did not have prior experience with neuromuscular rolling. The results of the present study may not necessarily be extrapolated to a population that uses RM regularly.

In conclusion, the increase in ROM was not dependent upon the intensity (pressure or load) of the RM. Fortunately for rolling enthusiasts, higher levels of pain or discomfort are not necessary to achieve an increased ROM. Furthermore, the intensity of rolling did not have differential effects on strength or power measures. Moreover, the second pre-test (INTpre) was significantly different than the initial pre-test for knee flexion passive ROM, knee flexion, and knee extension MVIC force, emphasizing the impact of initial pre-tests on subsequent measures.

PRACTICAL APPLICATION

Previous literature suggested that the forces at which neuromuscular rolling is performed might have an impact on rolling-induced ROM increases (4,15). The present results suggest that the intensity of rolling forces (50-90% of maximum discomfort) do not differentially affect strength and jump performance nor do they substantially amplify ROM. Pain with rolling is not necessary for increasing ROM. While prior studies have shown increased ROM with as little as 5-10 s of RM (34), the research tends to show higher ROM with longer durations and thus 2-3 sets of 30-60 s of rolling per muscle group (1,8,10,17,24,25) below a level of significant pain or discomfort would be suggested. These findings are of clinical relevance as practitioners do not need to roll to the point of discomfort or pain to achieve improvements in flexibility.

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FIGURE LEGENDS:

Figure 1: Flow chart of the experimental design (ROM = range-of-motion; DJ = drop jump; MVIC = maximum voluntary isometric contraction

Figure 2: Custom designed constant rolling pressure apparatus

Figure 3: Roller massage procedure

Figure 4: Kneeling lunge position for measurement of knee flexion range of motion (ROM) **Figure 5:** Changes in active knee flexion ROM based on two-way repeated measures ANOVA(main effect of time); significance level set at p ≤ 0.05; significant (*) findings of 5 and 6 arerelative to the second pre-test (2), significant difference of 2 is relative to 1.

Note. ROM = range-of-motion, RM = roller massage, mod: moderate, 1 = first pre-test, 2 = second pre-test (INTpre), 3 = after the first RM bout, 4 = after the second RM bout, 5 = after the intervention (INTpost), 6 = 10 min after the intervention (INTpost10)

Figure 6: Changes in passive knee flexion ROM based on two-way repeated measures ANOVA (main effect of time); significance level set at p ≤ 0.05; significant (*) findings of 5 and 6 are relative to the second pre-test (2), significant difference of 2 is relative to 1.

Note. ROM = range-of-motion, RM = roller massage, mod: moderate, 1 = first pre-test, 2 = second pre-test (INTpre), 3 = after the first RM bout, 4 = after the second RM bout, 5 = after the intervention (INTpost), 6 = 10 min after the intervention (INTpost10).

TABLE LEGENDS:

Table 1: Effects of three roller massage (RM) forces on active and passive range of motion (ROM)

Table 2: Effects of three roller massage (RM) forces on drop jump (DJ) measures

Table 3: Effects of three roller massage (RM) forces on MVIC knee flexion measures

Table 4: Effects of three roller massage (RM) forces on MVIC knee extension measures

Table 1: Effects of three roller massage (RM) forces on active and passive range of motion (ROM)

Variable	Cond.	Pre	INT Pre	RM 1	RM 2	INT Post	INT Post 10	Δ (%) pre-post	Main effect p-value (d)		
									Time	Cond.	Time x Cond.
Active ROM (°) Mean (SD)	RM low	62.4 (9.0)	59.1 (7.6)	57.8 (8.2)	56.7 (7.8)	55.3 (8.0)	54.8 (7.4)	-6.4	.000 (2.54)	.805 (0.20)	.301 (0.36)
	RM mod	62.6 (8.6)	59.2 (10.4)	56.9 (9.8)	55.1 (7.9)	53.7 (9.7)	54.2 (7.8)	-9.3			
	RM high	61.5 (7.4)	57.6 (8.3)	57.4 (6.3)	55.1 (7.2)	54.8 (6.5)	54.9 (6.4)	-4.9			
Passive ROM (°) Mean (SD)	RM low	46.3 (2.0)	42.7 (2.0)	39.8 (1.8)	38.9 (1.8)	37.8 (1.9)	38.5 (2.0)	-11.5	.000 (3.22)	.504 (0.43)	.540 (0.46)
	RM mod	47.4 (2.6)	43.3 (2.7)	41.9 (2.0)	39.5 (1.7)	35.7 (2.2)	37.6 (2.3)	-17.6			

	RM high	48.4 (2.3)	45.6 (2.2)	43.1 (2.2)	40.9 (2.2)	37.7 (2.2)	29.8 (2.3)	-17.3			

Note. RM = roller massage; mod = moderate; M = mean; SD = standard deviation; Cond. = condition; Pre = first pre-test (controls for repeated measures); INT pre = pre-test prior to intervention (base for comparison); RM 1 = test after first RM bout; RM 2 = test after second RM bout; INT post = post-test; INT post 10 = test 10 min after the intervention; Δ (%) = difference from INT pre – post-test; d= effect size Cohen's d*;*

Table 2: Effects of three roller massage (RM) forces on drop jump (DJ) measures											
Variable	Cond.	Pre	INT Pre	RM 1	RM 2	INT Post	INT Post 10	Δ (%) pre-post	Main effect p-value (d)		
									Time	Cond.	Time x Cond.
DJ height (m) Mean (SD)	RM low	0.121 (0.259)	0.135 (0.705)	0.116 (0.029)	0.122 (0.347)	0.116 (0.031)	0.113 (0.271)	-4.1	0.201 (0.68)	0.206 (0.67)	0.286 (0.59)
	RM mod	0.120 (0.036)	0.108 (0.035)	0.111 (0.033)	0.112 (0.034)	0.115 (0.033)	0.107 (0.030)	6.5			
	RM high	0.126 (0.032)	0.119 (0.028)	0.119 (0.028)	0.123 (0.029)	0.117 (0.028)	0.120 (0.034)	-1.7			

Tables Varied RM Forces

DJ contact time (s) Mean (SD)	RM low	0.354 (0.047)	0.367 (0.073)	0.388 (0.101)	0.373 (0.077)	0.367 (0.067)	0.375 (0.077)	0.0	0.147 (0.67)	0.667 (0.33)	0.237 (0.61)
	RM mod	0.368 (0.079)	0.352 (0.070)	0.364 (0.071)	0.376 (0.077)	0.362 (0.054)	0.376 (0.073)	2.8			

	RM high	0.358 (0.067)	0.365 (0.054)	0.352 (0.069)	0.368 (0.067)	0.370 (0.065)	0.361 (0.058)	1.4			
DJ performance index (m/s) Mean (SD)	RM low	0.388 (0.203)	0.417 (0.254)	0.366 (0.231)	0.382 (0.228)	0.377 (0.248)	0.364 (0.240)	-9.6	0.068 (0.84)	0.249 (0.62)	0.420 (0.50)
	RM mod	0.387 (0.245)	0.372 (0.263)	0.370 (0.263)	0.339 (0.178)	0.367 (0.233)	0.346 (0.263)	-1.3			
	RM high	0.409 (0.223)	0.391 (0.257)	0.404 (0.247)	0.388 (0.217)	0.369 (0.229)	0.391 (0.216)	-5.6			

Note. RM = roller massage; mod = moderate; M = mean; SD = standard deviation; Cond. = condition; Pre = first pre-test (controls for repeated measures); INT pre = pre-test prior to intervention (base for comparison); RM 1 = test after first RM bout; RM 2 = test after second RM bout; INT post = post-test; INT post 10 = test 10 min after the intervention; Δ (%) = difference from INT pre – post-test; d= effect size Cohen's d;

Tables Varied RM Forces

Table 3: Effects of three roller massage (RM) forces on MVIC knee flexion measures									
Variable	Cond.	Pre	INT Pre	INT Post	INT Post10	∆ (%) pre-post	Main effectp-value (d) Time	Cond.	Time xCond.
Knee flexion MVIC force (N) Mean (SD)	RM low	301.7 (37.4)	282.6 (38.7)	285.8 (40.8)	279.5 (48.5)	1.1	0.000 (1.53)	0.865 (0.20)	0.769 (0.38)
	RM mod	301.3 (44.8)	287.8 (53.9)	291.2 (49.0)	286.1 (45.5)	1.2			
	RM high	307.5 (43.4)	285.2 (48.0)	287.4 (51.3)	277.0 (55.2)	0.8			
Knee flexion MVIC F200(N)	RM low	180.1 (43.8)	158.9 (50.2)	151.2 (40.9)	158.4 (58.7)	-4.8	0.029	0.450	0.594
	RM mod	174.6 (57.3)	156.4 (60.6)	144.9 (40.4)	153.1 (62.0)	-7.4			

Mean (SD)							(0.94)	(0.47)	(0.45)
	RM high	156.5 (57.1)	156.2 (43.7)	152.2 (34.9)	135.5 (33.2)	-2.6			

Note. RM = roller massage; MVIC: maximum voluntary isometric contraction; mod = moderate; M = mean; SD = standard deviation; Cond. = condition; Pre = pre-test; INT pre = base for comparison; INT post = post-test; INT post 10 = test 10 min after the intervention; Δ (%) = difference from INT pre - post; *d* = effect size Cohen's *d.*

Table 4: Effects of three roller massage (RM) forces on MVIC knee extension measures

Variable	Cond.	Pre	INT Pre	INT Post	INT Post 10	Δ (%) pre-post	Main effect p-value (d)		
							Time	Cond.	Time x Cond.
Knee extension MVIC force	RM low	554.3 (140.4)	520.7 (135.2)	534.0 (133.1)	503.9 (122.2)	2.6			
		556.8 (164.3)	538.8 (141.2)	531.8 (155.2)	544.3 (142.3)	-1.3			

(N) Mean (SD)	RM mod RM high	551.2 (126.7)	523.6 (130.1)	499.9 (127.3)	534.2 (142.0)	-4.5	0.009 (1.08)	0.336 (0.55)	0.061 (0.75)
Knee extension MVIC F200 (N)	RM low	319.3 (128.5)	284.6 (93.0)	299.3 (88.7)	275.3 (91.5)	5.2			

Tables Varied RM Forces

Mean (SD)	RM mod	289.5 (119.9)	297.4 (104.8)	278.8 (96.1)	284.2 (98.3)	-3.2	0.412 (0.51)	0.786 (0.26)	0.325 (0.56)
	RM high	295.8 (96.1)	288.1 (86.6)	280.3 (93.6)	274.5 (93.0)	-2.7			

Note. RM = roller massage; MVIC: maximum voluntary isometric contraction; mod = moderate; M = mean; SD = standard deviation; Cond. = condition; Pre = pre-test; INT pre = base for comparison; INT post = post-test; INT post 10 = test 10 min after the intervention; Δ (%) = difference from INT pre - post; *d* = effect size Cohen's *d.*

Figure 1: Flow chart of the experimental design (ROM = range-of-motion; DJ = drop jump; MVIC = maximum voluntary isometric contraction

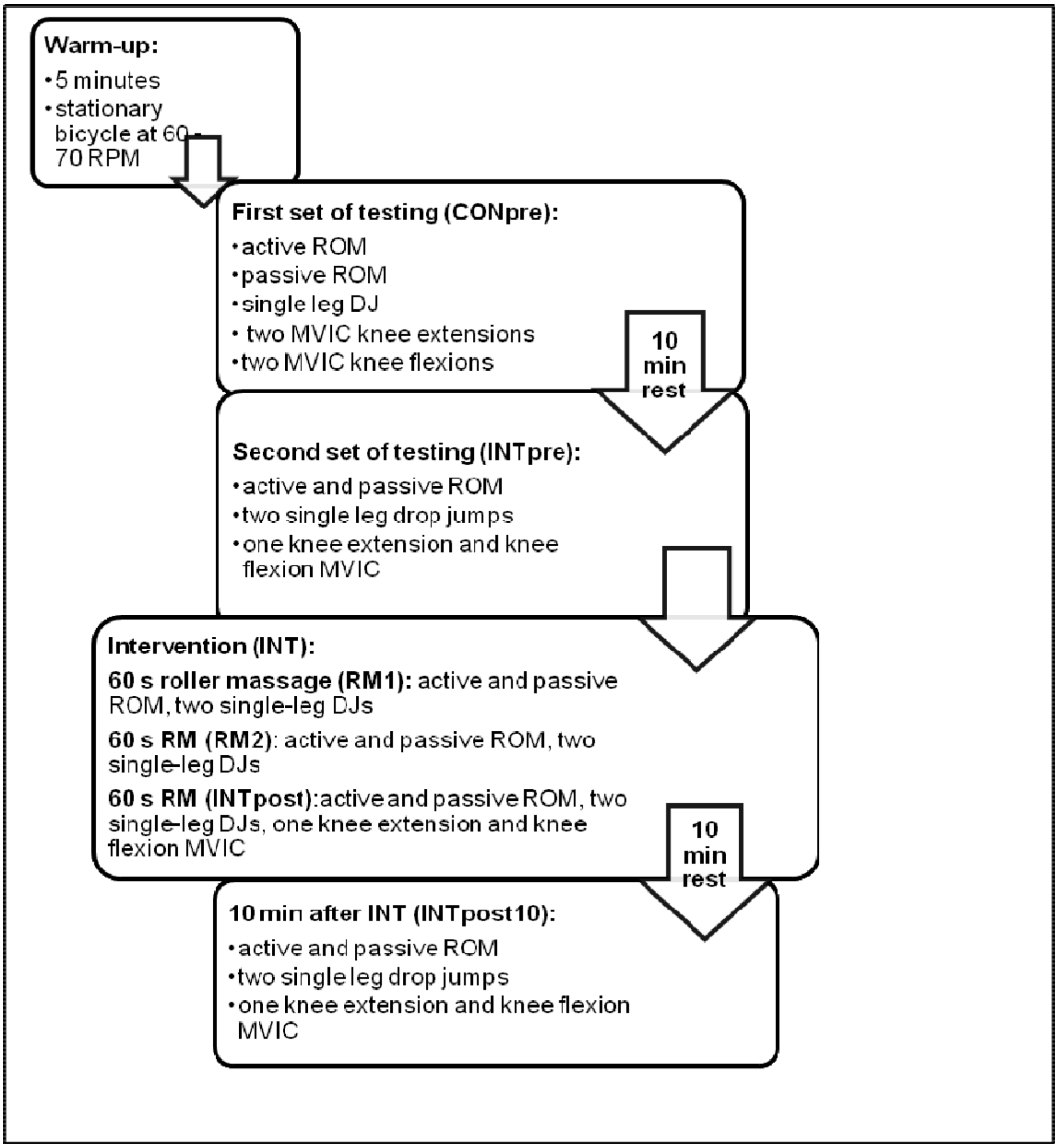
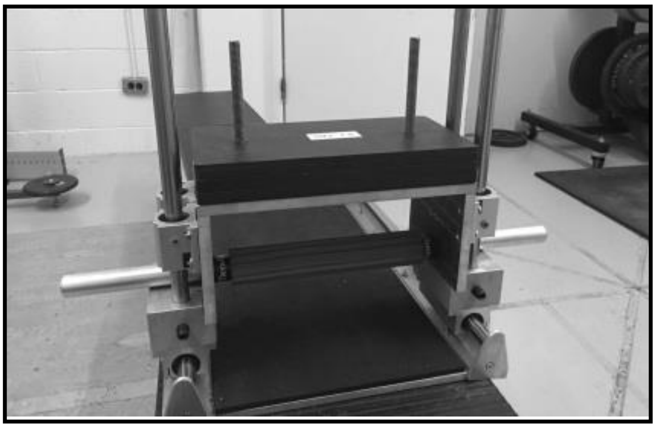


Figure 2: Custom designed constant rolling pressure apparatus



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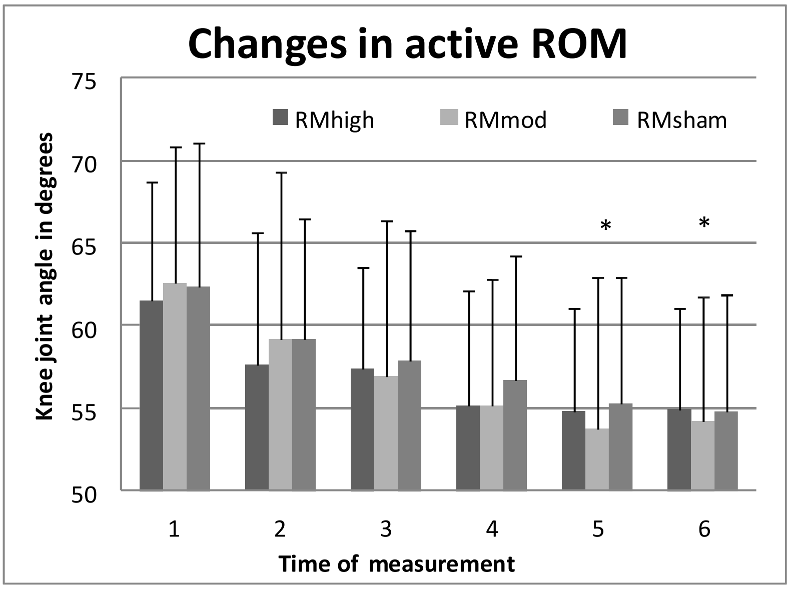

Figure 6: Changes in passive knee flexion ROM based on two-way repeated measures ANOVA (main effect of time); significance level set at $p \leq 0.05$; significant (*) findings of 5 and 6 are relative to the second pre-test (2), significant difference of 2 is relative to 1.

Note. ROM = range-of-motion, RM = roller massage, mod: moderate, 1 = first pre-test, 2 = second pre-test (INTpre), 3 = after the first RM bout, 4 = after the second RM bout, 5 = after the intervention (INTpost), 6 = 10 min after the intervention (INTpost10)