©Journal of Sports Science and Medicine (2023) **22**, 180-188
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2023.180

Research article

Are Acute Effects of Foam-Rolling Attributed to Dynamic Warm Up Effects? A Comparative Study

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Abstract

Over the last decade, acute increases in range of motion (ROM) in response to foam rolling (FR) have been frequently reported. Compared to stretching, FR-induced ROM increases were not typically accompanied by a performance (e.g., force, power, endurance) deficit. Consequently, the inclusion of FR in warm-up routines was frequently recommended, especially since literature pointed out non-local ROM increases after FR. However, to attribute ROM increases to FR it must be ensured that such adaptations do not occur as a result of simple warm-up effects, as significant increases in ROM can also be assumed as a result of active warm-up routines. To answer this research question, 20 participants were recruited using a cross-over design. They performed 4x45 seconds hamstrings rolling under two conditions; FR, and sham rolling (SR) using a roller board to imitate the foam rolling movement without the pressure of the foam rolling. They were also tested in a control condition. Effects on ROM were tested under passive, active dynamic as well as ballistic conditions. Moreover, to examine non-local effects the knee to wall test (KtW) was used. Results showed that both interventions provided significant, moderate to large magnitude increases in passive hamstrings ROM and KtW respectively, compared to the control condition ($p = 0.007 - 0.041$, $d = 0.62 - 0.77$ and $p = 0.002 - 0.006$, $d = 0.79 - 0.88$, respectively). However, the ROM increases were not significantly different between the FR and the SR condition ($p = 0.801$, $d = 0.156$ and $p = 0.933$, $d = 0.09$, respectively). No significant changes could be obtained under the active dynamic ($p = 0.65$) while there was a significant decrease in the ballistic testing condition with a time effect ($p < 0.001$). Thus, it can be assumed that potential acute increases in ROM cannot be exclusively attributed to FR. It is therefore speculated that warm up effects could be responsible independent of FR or imitating the rolling movement, which indicates there is no additive effect of FR or SR to the dynamic or ballistic range of motion.

Key words: Range of motion, flexibility, passive, warm-up, hamstrings.

Introduction

To reach maximal performance output in training and competition, athletes commonly perform different types of warm-up routines to prepare the muscles for the subsequent stress and prevent injuries by increasing range of motion (ROM) (Backman and Danielson, 2011; Behm et al., 2016a; Behm et al., 2021b; Witvrouw et al., 2004). Therefore, stretching exercises have been implemented to the warm-up routines because of their beneficial acute effects in local and global increases in ROM (Behm et al., 2016a; Behm et al., 2016b; Chaouachi et al., 2017; Freitas et al., 2016; Siebert et al., 2022). However, the literature generally showed that increases in ROM with prolonged static stretching (>60-s per muscle group) without accompanying dynamic activities within a pre-event warm-up were often accompanied by impairments in maximal and explosive strength performance (Behm et al., 2021a; Behm et al., 2016a; Behm and Chaouachi, 2011; Warneke et al., 2022a). Consequently, it has been often recommended to avoid static stretching prior to training sessions and competitions (Chaabene et al., 2019; Simic et al., 2013).

Alternatively, substantial original research has highlighted an increased ROM with foam rolling (FR) (Mohr et al., 2014; Schroeder and Best, 2015; Wilke et al., 2020) without deficits in muscle performance (Healey et al., 2014; MacDonald et al., 2013; Madoni et al., 2018; Wiewelhove et al., 2019) or even improvements in performance (Bradbury-Squires et al. 2015). Accordingly, Wiewelhove et al. (2019) reviewed 21 studies pointing out significant, small magnitude, increases in flexibility (+ 4.0%, effect size = 0.34) without significant changes in strength performance (+ 1.8%, effect size = 0.12). Similarly, a recent meta-analysis reported no significant performance deficits with FR training (i.e., chronic effects) (Konrad et al. 2022a). Another meta-analysis by the same group showed no significant differences between a single bout of stretching and FR exercise immediately after the interventions as well as 10-, 15- or 20-min post-intervention (Konrad et al., 2022b). These findings are in accord with a meta-analysis by Wilke et al., (2020), who reported no significant differences in ROM gains between dynamic and static stretching compared with FR. (Kelly and Beardsley, 2016; Killen et al., 2019; Ruggieri et al., 2021).

In FR literature, ROM increases were discussed based on phenomenological results, attributing ROM increases to different factors. Authors showed an influence on passive (tissue) stiffness and hardness (Hendricks et al., 2020; Kasahara et al., 2023; Schroeder et al., 2021), reduction of pain sensitivity (Kasahara et al., 2023) or removing mechanical restrictions from myofascial tissue due to FR-induced friction (i.e., thixotropy) (Smith et al., 2018b). Physiological explanations are still not conclusive. For example, *"Despite the popularity of SMR (self-myofascial re-*

Received: 02 February 2023 / Accepted: 09 March 2023 / Published (online): 01 June 2023

lease), the physiological effects are still being studied and no consensus exists regarding the optimal program for range of motion, recovery, and performance" (Cheatham et al., 2015). However, many of the listed mechanisms are also well known from general warm-up effects, including decreased joint friction due to increased synovial fluid flow (Roberts et al., 2019), higher muscle temperature (McGowan et al., 2015), decreased viscosity of the muscles (Padua et al., 2019) and reduced tendon stiffness (Krzysztofik et al., 2023). Thixotropic effects have been attributed to result in less resistance to movement facilitating an increased ROM with dynamic warm-up activities, static stretching and FR (Behm and Wilke, 2019; Konrad et al., 2022b). Hence, attributing ROM improvements exclusively to FR may lack full validity. Since Morales-Artacho et al. (2017) showed that five minutes of ergometer cycling resulted in superior ROM increases and reduction in muscle stiffness compared to FR, it can be hypothesized that adaptations could be the result of general dynamic warm-up effects. To clearly attribute increased ROM to FR, competing parameters must be excluded. Prior studies have compared FR to control conditions where participants were not active (rested), but these studies did not compare FR to a similar active exercise. Therefore, the aim of this study was to compare the local (i.e., hip flexion ROM) as well as the remote effects (i.e., dorsiflexion ROM) effects of FR with the effects of sham rolling (SR), which was performing the same movement used for rolling the hamstrings, but without a foam roll. It was hypothesized that the muscle activity-induced thixotropic effects (associated with muscle contraction stresses and heat generation) (Behm et al., 2016a; Behm and Wilke, 2019) with SR would provide similar increases in ROM as FR compared with a control condition.

Methods

Experimental Design

A repeated measures within-subject factor design was used with three conditions performing FR and SR for the hamstrings as well as a control condition. Testing sessions were conducted on separate days with at least 48 hours of recovery between sessions. Flexibility of the hamstrings and the plantar flexors were assessed to compare the effects of both interventions on passive, active dynamic, and ballistic ROM. Plantar flexors ROM was tested to investigate non-local effects of the interventions.

Participants

Twenty (20) participants (males = 12, age: 25 ± 4.29 years, weight: 82.07 ± 9.28 kg height: 175.45 ± 3.76cm; females: age: 20 ± 0.63 years, weight: 74.87 ± 9.23 kg, height: 167.12 ± 9.07cm) participated in the study, which considering the cross-over design, incorporated 60 experimental sessions in total (i.e., three per participant). Therefore, the initially estimated sample size via G-Power of n = 24 (considering α-error of 0.05 and a power of 1-β = 0.8) was reached because of the cross-over study design (n = 20 per group). They were classified as recreationally active and healthy based on joining the physical education classes at the university leading to a minimum of three weekly training sessions. Participants who reported any injury within the last three months or increased risk of thrombosis or varicose veins in the lower extremity were excluded from the study. The participants were allocated to a FR, SR and control condition in a random order. The study protocol was reviewed by the institutional review board of the Memorial University of Newfoundland (ICEHR:20210626).

Testing procedure

Before testing, participants were instructed to perform a warm-up routine consisting of three minutes on a cycle ergometer at 60 RPM at 1kp. The intervention as well as testing was performed with the right leg. The order of the hamstrings and plantar flexors ROM testing as well as the intervention order was randomly allocated by randomization function of Excel (RAND function). As the participants were strapped into the device to measure hip flexion ROM, the passive, active dynamic, and ballistic hip flexion ROM tests were grouped together and their order randomly allocated while the order of hip flexion and ankle dorsiflexion ROM tests were also randomized.

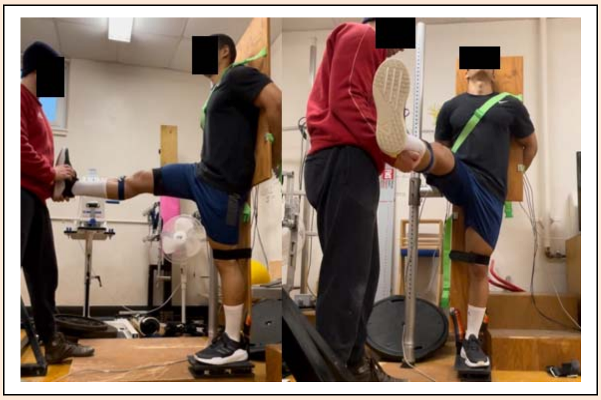

Figure 1. Passive range of motion testing using a goniometer for standing hip flexion range of motion measurement

Hip flexion ROM testing

For the starting position, participants were fixed in the measuring device used previously in this laboratory (Behm et al., 2019; Caldwell et al., 2019) (see Figure 1). Therefore, an electronic goniometer (Technical Services Memorial University of Newfoundland, St. John's, Newfoundland, Canada) and associated software (BioPac AcqKnowledge data acquisition and analysis system: DA 150: analog-digital converter MP100WSW, Holliston, MA) were used. The knee joint was fixed in an extended position in the measuring device. Passive ROM was investigated by passively lifting the leg vertically upward by the investigator until the participant pointed out maximal discomfort in the hamstrings. To measure active dynamic ROM, the participant was instructed to lift the leg vertically until no movement was possible, while for ballistic ROM a maximal hip flexion was performed explosively. Therefore, the participant was instructed to kick as high and as fast as possible. Each ROM test was performed until the difference between the best and the second-best trial was <5% with a maximum of three attempts. One minute of recovery was allocated between each ROM test. High reliability has been previously reported with ICC of 0.79 - 0.91 (Caldwell et al., 2019).

Dorsiflexion ROM testing

Dorsiflexion ROM was determined using the knee to wall test (KtW). For this purpose, the participant was instructed to stand upright in front of the wall and place the right foot flat on the floor. A piece of paper was placed under the heel of the foot. Then, the participant was asked to touch the wall with the right knee without losing contact to the paper. The left foot had to be lifted up from the ground, while the participant was allowed to stabilize the body weight with the hands using the wall (see Figure 2). The distance between the second toe of the foot and the wall was determined using a measuring tape. Failed attempts were considered as trials where the paper could be removed from underneath the heel, signifying losing contact between the heel and the ground. Afterwards, the participant would be instructed to move their feet closer to the wall, until the paper could not be removed. Reliability of the knee to wall test is stated to be high with ICC of 0.944 (Warneke, et al., 2022b).

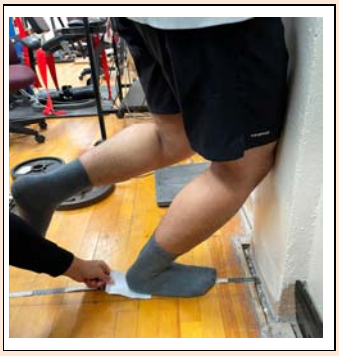

Figure 2. Knee to wall testing using a measuring tape.

Intervention

Based on prior results and recommendations (Behm et al., 2020; Hendricks et al., 2020), the optimal FR dosage is approximately 120 seconds. FR was performed for the hamstrings of the right leg for 4x45 seconds with a rest of 30 seconds to ensure an effective stimulus. The participants were instructed to use a cadence of 1 second for the length of the hamstrings in each direction without resting at the end position. To increase the pressure on the roll, the left leg was placed on the right leg while rolling, with only the hands were allowed to touch the floor (see Figure 3). Therefore, the arms had to push the body weight upward while performing FR. SR was performed in a similar manner, however, instead of using a foam roll, the same movement was performed on a rolling board (small dolly with four wheels for moving equipment) with a foam pad on the board to reduce the pressure (see Figure 4). In the control condition, the participants were instructed to sit in a relaxed position in a chair for five minutes.

Data analysis

The analysis was performed with SPSS 28 (IBM, Armonk, New York, USA), graphical illustration was performed using "R"(R Core Team, 2021). Data are provided as mean (M) ± standard deviation (SD) for the pre-post values. The Shapiro Wilk test was used to check normal distribution. Reliability was determined and is provided in intraclass correlation coefficient, coefficient of variability and 95% confidence interval (CI) for aforementioned tests (see Table 1). Moreover, Levene's test for homogeneity in variance was performed. A one-way ANOVA was used to confirm no significant condition differences in the pre-test values. A two-way ANOVA with repeated measures (3 conditions x 2 times) was performed for each sex to investigate the changes from pre- to post-test with the three conditions. The Scheffé test was performed as the post-hoc test to investigate the differences in increases between the intervention conditions and the control condition. Effect sizes are presented as Eta squares (η^2) and categorized as follows: small effect $\eta^2 < 0.06$, medium effect $\eta^2 = 0.06$-0.14, high effect $\eta^2 > 0.14$ (Cohen, 1988). Additionally, effect sizes for group comparisons are reported with Cohen's d (Cohen, 1988) and categorized as: trivial: <0.2, small: $d < 0.5$, medium: $d = 0.5$-0.8, and large magnitude effects: $d > 0.8$. The level of significance was set to $p < 0.05$. Furthermore, sex-related differences were investigated by performing a separated calculation for males and females with some subsequent statistics to detect potential differences between sexes.

Figure 3. Participant performing foam rolling for the hamstrings.

Figure 4. Participant performing sham rolling (SR) using a rolling board (dolly) with a foam pad on top to reduce pressure.

Table 1. Reliability assessed with ICC (95% CI) and CV (±SD) for the ROM tests.

Parameter	ICC (95% CI)	CV ± SD
Passive ROM testing	0.988 (0.980 – 0.993)	1.33 ± 0.1%
Active Dynamic ROM testing	0.983 (0.972 – 0.990)	1.22 ± 0.1%
Ballistic ROM testing	0.978 (0.964 – 0.987)	1.35± 0.1%
KtW	0.991 (0.985 – 0.995)	1.40 ± 0.2%

ROM = range of motion, KtW = knee to wall, ICC = intraclass correlation coefficient, CV = coefficient of variance.

Results

Data were normally distributed ($p = 0.2$). Intra-day reliability using the best and the second-best trials was classified as excellent with all correlations over 0.978 (Table 1). The one-way ANOVA revealed no significant pre-test difference for any parameter with $p = 0.92$ for the ballistic, active dynamic ($p = 0.73$), passive ROM ($p = 0.97$) conditions and $p = 0.97$ for the KtW. The results of the two-way ANOVA for each parameter are provided in Table 2.

Results show large magnitude increases in passive ROM with a significant main effect for time (data collapsed/combined over conditions) (p 0.003, $\eta^2 = 0.149$) and a significant Condition*Time interaction ($p = 0.004$, $\eta^2 = 0.182$). The post-hoc testing demonstrated no difference between the increases in the FR and SR conditions ($p = 0.801$, $d = 0.156$). However, there were significant increases with both intervention conditions when compared to the control condition ($p = 0.007$-0.041, $d = 0.615$-0.772).

Results showed no significant effects of the intervention regarding active dynamic ROM ($p = 0.121$ and $p = 0.655$). For ballistic ROM measurement, there was a significant Time-effect ($p < 0.001$, $\eta^2 = 0.473$) showing a decrease in ROM, however, no significant Condition*Time interaction was observed ($p = 0.248$).

In contrast, for KtW there was a large magnitude increase in ROM from pre-to post-test with a Time-effect ($p < 0.001$, $\eta^2 = 0.273$) and a Condition*Time interaction ($p < 0.001$, $\eta^2 = 0.238$). Post-hoc testing determined no significant difference between FR and SR condition ($p = 0.933$, $d = 0.09$), however, there was a significant increase with the intervention conditions versus the control condition ($p = 0.002$-0.006, $d = 0.79$-0.878). The results of passive ROM and the KtW are illustrated in Figure 5.

Table 2. Pre- and post-test values as well as the results of the two-way ANOVA providing the time-effect and the time*group interaction

Parameter	Pre-test (M ± SD) in N	Post-test (M ± SD) in N	% Pre-Post Differences	Time effect	Time * condition
FRpassive	127.40 ± 16.95	130.29 ± 17.17	+2.45	$p = 0.003$	$p = 0.004$*
SRpassive	126.13 ± 16.95	130.03 ± 17.12	+3.22	$F_{54.1} = 9.423$	$F_{54.2} = 5.995$
CGpassive	126.27 ± 17.86	125.19 ± 19.23	-0.97*	$\eta^2 = 0.149$	$\eta^2 = 0.182$
FRdyn	95.69 ± 13.05	93.97 ± 12.34	-1.65	$p = 0.121$	$p = 0.655$
SRdyn	95.86 ± 9.00	93.55 ± 8.45	-2.28	$F_{54.1} = 2.485$	$F_{54.2} = 0.426$
CGdyn	98.61 ± 11.18	97.99 ± 19.98	-0.89	$\eta^2 = 0.044$	$\eta^2 = 0.016$
FRballistic	124.80 ± 15.31	120.08 ± 15.91	-3.83	$p < 0.001$	$p = 0.248$
SRballistic	125.92 ± 13.76	120.20 ± 14.82	-4.59	$F_{54.1} = 48.564$	$F_{54.2} = 1.43$
CGballistic	124.08 ± 13.34	121.01 ± 14.43	-2.53	$\eta^2 = 0.473$	$\eta^2 = 0.05$
FRKtW	10.87 ± 2.99	11.37 ± 2.86	+5.15	$p < 0.001$	$p < 0.001$*
SRKtW	10.83 ± 3.12	11.40 ± 3.00	+5.84	$F_{54.1} = 20.256$	$F_{54.2} = 8.416$
CGKtW	11.04 ± 3.00	10.95 ± 2.89	-0.61*	$\eta^2 = 0.273$	$\eta^2 = 0.238$

FR=foam rolling, SR=sham rolling, CG=control group, passive=passive ROM testing in the hip flexor, dyn=active dynamic hip flexor ROM testing, ballistic=ballistic hip flexor ROM testing, KtW=knee to wall test to evaluate the ankle joint ROM. Asterisks (*) illustrate a time * group interaction significant difference between the control condition versus the other two intervention conditions (FR and SR).

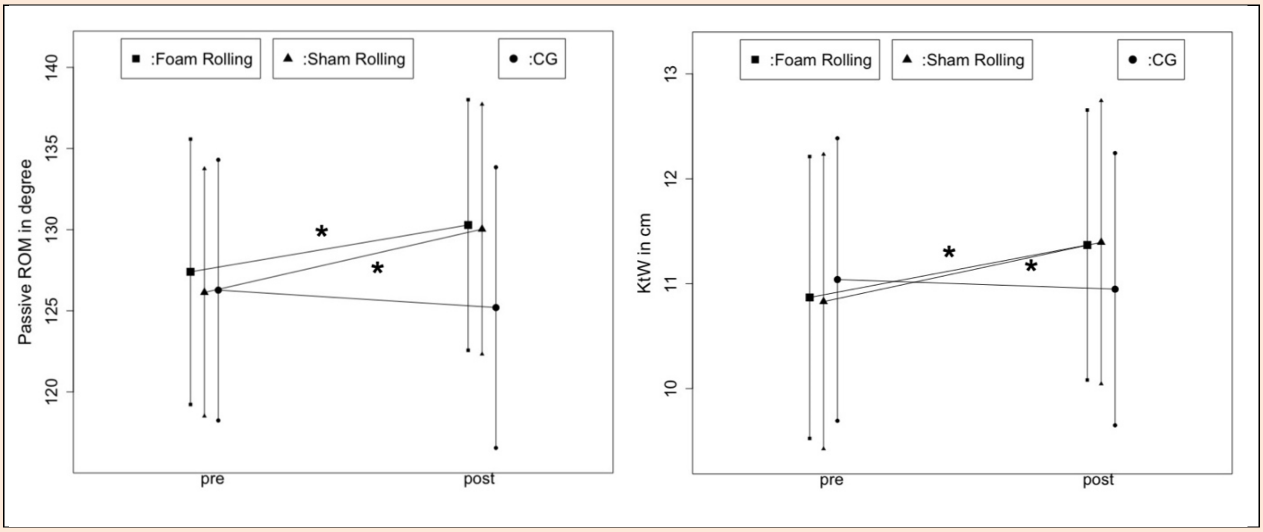

Figure 5. **Comparison of ROM progressions dependent on group for the passive hip flexion ROM testing (a) and for the dorsiflexion ROM testing via the KtW (b).** Asterisks (*) illustrate a time * group interaction significant difference between the control condition versus the other two intervention conditions (FR and SR).

Males

For male participants, no significant main effect for Time for passive ROM testing was observed ($F_{32.1} = 2.757$, $p = 0.107$, $\eta^2 = 0.079$), however, the interaction effect displayed a significant Time*Group interaction ($F_{32.2} = 3.387$, $p = 0.046$, $\eta^2 = 0.175$). Post-hoc testing revealed a significant difference between the SR and the control condition ($p = 0.037$), while the difference between FR and the control condition missed the level of significance with $p = 0.06$). No significant difference could be determined between the SR and FR ($p = 0.974$).

For the dynamic testing condition, there was a significant ROM decrease ($F_{32.1} = 24.447$, $p < 0.001$, $\eta^2 = 0.433$) without a significant Time*Group interaction ($F_{32.2} = 0.178$, $p = 0.838$, $\eta^2 = 0.011$). There was a significant main effect for time ($F_{32.1} = 26.993$, $p < 0.001$, $\eta^2 = 0.458$) showing a significant ROM decrease in the ballistic ROM test from pre- to post-test. However, no significant time*group interaction was observed ($F_{32.2} = 0.738$, $p = 0.486$, $\eta^2 = 0.044$). For the KtW, a significant main effect for Time showed significant increases ($F_{32.1} = 15.012$, $p < 0.001$, $\eta^2 = 0.319$), however, the Time*Group interaction failed reaching the level of significance ($F_{32.2} = 2.517$, $p = 0.097$, $\eta^2 = 0.136$).

Females

For female participants a significant main effect for Time showed a pre-post-test increase ($F_{18.1} = 7.303$, $p = 0.015$, $\eta^2 = 0.289$). The Time*Group interaction effect did not reach the level of significance ($F_{18.2} = 3.189$, $p = 0.065$, $\eta^2 = 0.262$). In the dynamic testing condition, there was neither a significant Time effect ($F18.1 = 0.226$, $p = 0.64$, $\eta^2 = 0.012$) nor a Time*Group interaction ($F_{18.2} = 0.5$, $p = 0.615$, $\eta^2 = 0.053$). In the ballistic ROM test, there was a significant Time effect reported ($F_{18.1} = 19.315$, $p < 0.001$, $\eta^2 = 0.518$), without a significant Time*Group interaction ($F_{18.2} = 0.420$, $p = 0.663$, $\eta^2 = 0.045$). In contrast, testing the KtW, the females showed a significant Time effect ($F_{18.1} = 4.587$, $p = 0.046$, $\eta^2 = 0.203$) with a significant Time*Group interaction ($F_{18.2} = 8.873$, $p = 0.002$, $\eta^2 = 0.496$). The Scheffé test revealed significant differences between SR and CG ($p = 0.004$), and FR and CG ($p = 0.012$), while no significant difference could be observed between SR and FR ($p = 0.899$).

Sex-related differences

For passive ROM, the direct comparison between male and female participants showed a significant increase in ROM ($F_{34.1} = p < 0.001$, $\eta^2 = 0.347$), however, no significant interaction effect was obtained ($F_{34.3} = 0.533$, $p = 0.663$, $\eta^2 = 0.045$), showing no sex-related difference. For the dynamic ROM testing, there was also a significant Time effect ($F34.1 = 6.615$, $p = 0.015$, $\eta^2 = 0.163$) showing a significant decrease from pre to post-test without a significant interaction ($F_{34.3} = 1.159$, $p = 0.340$, $\eta^2 = 0.093$), showing no significant sex-related difference. Similarly, for ballistic ROM testing there was a significant Time effect ($F_{34.1} = 35.446$, $p < 0.001$, $\eta^2 = 0.51$) highlighting a significant decrease in ROM, but no significant Time*Group interaction could be found ($F34.3 = 0.140$, $p = 0.935$, $\eta^2 = 0.012$). In the KtW, there was also a significant Time effect ($F34.1 = 25.161$, $p < 0.001$, $\eta^2 = 0.425$) showing a significant pre-post-test ROM increase, however, no significant Time*Group interaction was observed ($F34.3 = 0.094$, $p = 0.963$, $\eta^2 = 0.008$). Therefore, overall, no significant sex-related differences were observed.

Discussion

Since the current literature does not distinguish between the effects of FR and mimicking the FR movement (without a foam roller), it is difficult to attribute the acutely measured ROM increases after FR exclusively to the intervention. Hence, this study aimed to compare the effects of hamstrings FR with SR on hip flexion and ankle dorsiflexion ROM. The results of the present study determined a significant, large magnitude increase in passive hamstrings ROM as well as in KtW in response to 4x45 seconds of FR. However, the SR condition also resulted in significant, large magnitude increases, without a significant difference between FR and SR. Therefore, the ROM increases cannot exclusively be attributed to FR (the pressure of the foam roll) since only performing the dynamic movement required for FR demonstrated similar results. Therefore, using a foam roller on the hamstrings does not provide any additional increase in ROM to just executing (mimicking) the action associated with hamstrings FR.

Overall, there are a high number of studies reporting ROM increases with FR (Behara and Jacobson, 2017; Cheatham and Stull, 2018; de Benito et al., 2019; Konrad et al., 2022b; Konrad et al., 2022c; Nakamura et al., 2021b; Park et al., 2021; Reiner et al., 2023; Su et al., 2017; Wilke et al., 2020). In a recent meta-analysis Konrad et al., (2022a) reported similar ROM increases with the acute effects of one bout of FR versus static stretching, postulating similar mechanism (i.e., increased pain tolerance, reduced soft-tissue compliance, thixotropic effects) (Cheatham and Baker, 2017). Interestingly, Warneke et al. (2022a) also pointed out a significant acute increase of ROM after 5x12 repetitions of calf raises performed in the leg press, which did not differ significantly from ROM increases after stretching. Morales-Artacho et al. (2017) compared the effects of FR with ergometer cycling on ROM increases and showed even higher acute ROM increases after performing five minutes of ergometer cycling compared to FR, which were accompanied by reduced muscle stiffness. Accordingly, Krzysztofik et al. (2023) also pointed out decreased Achilles tendon stiffness and quadriceps stiffness with increased skin temperature acutely after performing different squat variations. Even though, no ROM measurement was performed in this study (Krzysztofik et al. 2023), Yu et al. (2022) pointed out significantly higher muscle stiffness in males compared with females, which was accompanied by lower flexibility in males. Furthermore, Hirata et al (2020) showed that stretching-induced ROM increases were accompanied by a reduction in muscle stiffness. Therefore, a link between ROM and muscle stiffness could be hypothesized. Therefore, acute ROM increases are not exclusively attributable to specific training interventions such as stretching and FR but are also observed after performing dynamic exercise. Previous FR studies typically included a passive control group (no activity) but did not compare to a group or condition that performed a comparable sliding or rolling movement but without a foam roll. Consequently, it cannot be excluded that the effects found from previous studies could be attributed to warm-up effects, instead of the foam roll intervention.

The present findings do not suggest that FR is devoid of positive effects on ROM. Prior studies reported increased lower limb ROM with roller massagers, which has the individual roll the muscle with a similar FR device, but the arms provide the resistance without movement of the lower body (Bradbury-Squires et al., 2015; Halperin et al., 2014; Hodgson et al., 2019). Furthermore, a device constructed to provide external resistance on a foam roller that was moved by the researcher was also shown to increase knee flexion ROM (Grabow et al., 2018), however, potential warm-up effects because of muscle contractions versus the induced pressure have not been measured in those studies as well. Grabow et al. (2018) did examine the effects of low, moderate, and high levels of perceived pain with the roller massager reporting the increase in ROM was not dependent on the intensity (pressure or load) of the roller. Hence, FR in the present study may have contributed to the increased ROM, but its effect was not significant enough to substantially augment the activity-induced increases in ROM.

Accordingly, underlying mechanisms in FR literature are similar to those described for warm-up effects (Gutierrez-Coronado et al., 2022; Morales-Artacho et al., 2017; Padua et al., 2019; Roberts et al., 2019). Morales-Artacho et al. (2017) showed decreased stiffness after ergometer cycling warm-up, while Gutierrez-Coronado (2022) compared static and dynamic warm up routines pointing out that both routines improved (stretching) pain perception. Padua et al. (2019) and Roberts et al. (2019) referred to reduced joint friction due to increased synovial fluid and decreased muscle viscosity (thixotropic effects) as a result of an increased muscle temperature.

Our KtW test showed significant improvements in dorsiflexion ROM without rolling the plantar flexors. This improvement may also be attributed to the aforementioned dynamic warm up-related mechanisms. The plantar flexors and hamstrings are assumed to be linked via myofascial chains (Wilke et al., 2016). Accordingly, Cheatham et al (2015) described altered muscle-spindle length or stretch perception with FR. FR-induced friction is proposed to break down scar tissue, remobilizing the fascia to reduce myofascial restrictions and restore a gel-like state of the fascia. However, the underlying physiological mechanisms to improve overall flexibility by reducing remote trigger points and myofascial restrictions with FR can be reasonably questioned (Behm and Wilke, 2019). Hence, interpreting changes in ROM performance as warm-up effects would also explain the remote (non-local) effects of FR, showing improved flexibility in non-rolled body regions (Konrad et al., 2023; Monteiro et al., 2019; Nakamura et al., 2021b), (Kasahara et al., 2023; Konrad et al., 2023) and decreased pain perception (Cheatham and Baker, 2017). Since warm-up effects as a result of movement/exercise are well-known, this would relate to Monteiro et al.'s (2019) comment "This work may have important clinical (rehabilitation) implications, as it demonstrates global effects of FR on functional outcomes". Hence, the global effect of warm-up exercise should not be surprising.

Furthermore, the results clarify the limited relevance in the practice of sports and the clinical relevance of foam-rolling to improve the ROM, since the intervention only produced significant improvements in passive ROM, which might be of minor importance for sports practice. Moreover, there were decreases in ballistic ROM (incorporating the stretch-shortening cycle) and no effect in active dynamic ROM. While the decrease in ballistic ROM in the control condition can possibly be explained by cooling down effects from 5 minutes of sitting, the results showed that FR was not effective in preventing those decreases. Another explanation would include the activation of the stretch-shortening cycle and increased co-activation due to repeated ballistic movements exceeding the extensibility of the muscle. These movements, performed in the pre-test at least two times could therefore cause an activation of the (spinal and/or H) stretch reflex (Augé and Morrison, 2000; Budini and Tilp, 2016; Jaggers et al., 2008). Consequently, ballistic movements have been speculated in some studies to be ineffective to influence the ROM positively (Mahieu et al., 2007; Opplert and Babault, 2018). The ballistic hip ROM testing movements could be perceived as ballistic stretches.

Limitations

The results of the study compared the effects of FR and SR on hip flexion ROM and ankle dorsiflexion ROM, however, no underlying physiological parameters such as pain tolerance, muscle- or tendon stiffness or body temperature were assessed. Therefore, the underlying mechanisms remain speculative, however, opening another research gap. Furthermore, some previous studies reported increased ROM in the upper limbs after FR muscles in the lower extremity, referring to "global" or "remote" effects (Monteiro et al., 2019; Nakamura, et al., 2021a). The phenomenon of non-local ROM increases is also well known in stretching literature (Chaouachi et al., 2017; Killen et al., 2019; Ruggieri et al., 2021). In this study, no ROM testing in the upper limbs was performed. This would be of high interest, as it can be assumed that warm up effects would also influence upper limb ROM, especially because of the isometric contraction of the arms and shoulders to stabilize the bodyweight while performing FR and SR the hamstrings. Including another comparison group performing different kinds of stretching or an ergometer cycling group to extend the intervention to other muscle groups and movements would be interesting for further research. Finally, no sex-related ROM differences were observed, however a relatively small sample size may have affected the ability to detect possible differences when considering condition, time, and sex interactions.

Conclusion

Our results show no significant difference in passive hamstrings ROM increases in response to the FR or SR intervention (although both interventions were effective in increasing ROM), while both interventions showed no significant flexibility increase in the active dynamic and ballistic ROM testing. Therefore, the common conclusion, attributing acute ROM increases exclusively to FR seems to be questionable, especially since the listed adaptations and suggested underlying mechanisms can be assumed to be present after warming up in general. Consequently, the statement made by Wiewelhove et al. (2019) *"Evidence seems to justify the widespread use of foam rolling as a warm-up activity rather than a recovery tool"* should be questioned, since FR did not induce additional ROM increases compared to the SR condition. Further research investigating differences in the underlying mechanisms (e.g., muscle/tendon/muscle-tendon stiffness, pain perception) is required to clarify differences between FR and SR.

Acknowledgements

The experiments comply with the current laws of the country in which they were performed. The authors have no conflict of interest to declare. The datasets generated and analysed during the current study are not publicly available but are available from the corresponding author, who was an organizer of the study.

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Key points

- This study demonstrated a significant increase in passive hip flexion range of motion and ankle dorsiflexion range of motion in response to 4x45 seconds of foam rolling, but also for sham rolling
- There were no significant increases in active dynamic as well as ballistic hip flexion range of motion in response to the intervention
- There was no significant difference in responses between the foam rolling and sham rolling interventions, therefore, it is concluded that acute range of motion increases cannot be exclusively attributed to the foam rolling intervention.

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