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Research article

Comparison of A Single Vibration Foam Rolling and Static Stretching Exercise on the Muscle Function and Mechanical Properties of the Hamstring Muscles

Marina Maren Reiner [1], Markus Tilp [1], Gaël Guilhem [2], Antonio Morales-Artacho [2] and Andreas Konrad [1]✉
[1] Institute of Human Movement Science, Sport and Health, University of Graz, Graz, Austria; [2] Laboratory Sport, Expertise and Performance, French Institute of Sport (INSEP), Paris, France.

Abstract
Knee extension and hip flexion range of motion (ROM) and functional performance of the hamstrings are of great importance in many sports. The aim of this study was to investigate if static stretching (SS) or vibration foam rolling (VFR) induce greater changes in ROM, functional performance, and stiffness of the hamstring muscles. Twenty-five male volunteers were tested on two appointments and were randomly assigned either to a 2 min bout of SS or VFR. ROM, counter movement jump (CMJ) height, maximum voluntary isometric contraction (MVIC) peak torque, passive resistive torque (PRT), and shear modulus of semitendinosus (ST), semimembranosus (SM), and biceps femoris (BF_{lh}), were assessed before and after the intervention. In both groups ROM increased (SS = 7.7%, $P < 0.01$; VFR = 8.8%, $P < 0.01$). The MVIC values decreased after SS (-5.1%, $P < 0.01$) only. Shear modulus of the ST changed for -6.7% in both groups (VFR: $P < 0.01$; SS: $P < 0.01$). Shear modulus decreased in SM after VFR (-6.5%; $P = 0.03$) and no changes were observed in the BF_{lh} in any group (VFR = -1%; SS = -2.9%). PRT and CMJ values did not change following any interventions. Our findings suggest that VFR might be a favorable warm-up routine if the goal is to acutely increase ROM without compromising functional performance.

Key words: Shear modulus, range of motion, muscle stiffness, self-myofascial release, muscle performance, force production.

Introduction

Foam rolling (FR) and stretching are often used during warm up routines in sport settings to prepare single body parts for the following performance task. A recent meta-analysis on the effects of FR on range of motion (ROM) (i.e. used as an index reflective of joint flexibility) confirmed the positive impact of a FR exercise on joint flexibility (i.e. greater ROM) (Wilke et al., 2020). Whilst females showed greater effects than males on joint ROM following FR, the duration and the rolling speed of the FR bout did not significantly affect the outcome (Wilke et al., 2020). Moreover, the meta-analysis of Wiewelhove et al. (2019) showed a positive effect (+0.7%, Hedges´ g = 0.3, small) of FR on sprint performance (i.e. enhanced running speed) but no changes in jumping or strength performance. Concerning stretching with its various techniques similar increases in ROM were found compared to FR (Behm et al., 2016; Konrad et al., 2017; Konrad et al., 2022). However, stretching techniques may differently affect performance parameters. Static stretching (SS) and proprioceptive neuromuscular facilitation stretching (PNF) can lead to a decrease in performance parameters, especially when applied with longer durations (>60 s) without a full dynamic warm-up (i.e. initial aerobic component and followed by dynamic sport specific activities), while dynamic stretching enhanced performance (Behm et al., 2016; 2021). Comparing the effects of FR or SS on joint flexibility, increases in ROM are expected because of a greater tolerance to stretch (Magnusson et al., 1996) or a more compliant muscle-tendon-tissue (Konrad et al., 2017). Wilke et al. (2020) did not find significant differences between the two interventions regarding the rolled or stretched muscle groups (quadriceps, hamstrings, calf muscles), type of flexibility (active or passive), duration, gender, BMI, and study design (crossover vs. parallel group). Concerning functional performance a recent review (Konrad et al., 2021) reported no significant difference between a single FR and a single stretching exercise. However, subgroup analysis reported that FR with vibration should be rather performed than stretching as a warm-up when functional performance plays a role. Moreover, if the duration of the interventions (i.e., FR vs stretching) is ≥60s again FR is the better choice to optimize the subsequent performance (Konrad et al., 2021).

Changes following FR and stretching were found especially in the structures of the rear thigh, including the hamstring muscles. The hamstrings (semitendinosus (ST), semimembranosus (SM), biceps femoris long head (BF_{lh})) are flexors and stabilizers for the knee and extensors in the hip. Some studies found increased hip flexion or knee extension joint ROM when a single bout of FR was applied to the hamstring muscles (Su et al., 2017; de Benito et al., 2019; Johns and Moreside, 2020). Furthermore, performance parameters increased after a single FR bout (Su et al., 2017) or were reported to stay at the same level as pre-intervention (Killen et al., 2019). Moreover, an increased hip flexion or knee extension ROM was found after a single SS bout of the tissues of the rear thigh (Umegaki et al., 2015a; Nakao et al., 2018; Hatano et al., 2019). Palmer et al. (2019) found no changes in the performance parameters after a single session of SS but Hatano et al. (2019) reported a decreased maximal isometric muscle force (-2.5% 10 min post stretching; -2.2% 20 min post stretching; -1.8% 30 min post stretching) following SS of the hamstrings.

In the recent years, the combination of a FR and vibration (VFR), has become popular. In general, local vibration therapy has positive effects on muscle performance (Cochrane, 2016; Alghadir et al., 2018), ROM (Pamukoff

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et al., 2014; Konrad et al., 2020), and increases muscle activity (Mischi and Cardinale, 2009; Pamukoff et al., 2014). Adding vibration to a FR led to similar effects in ROM (Wilke et al., 2020) and increased performance parameters in the quadriceps muscles (Reiner et al., 2021) if compared with the effects of a FR bout. Findings on performance parameters in the hamstrings are contradictory. Lee et al. (2018) found an increase in maximal voluntary knee flexion peak torque after using a VFR but Ruggieri et al. (2021) documented a decreased knee flexor peak torque and Tsai and Chen (2021) found no changes in performance parameters after the VFR. Furthermore, there are expectations about superior effects of VFR on other muscle-tendon-tissue parameters such as muscle stiffness, i.e. an indicator for the extensibility of the muscle tissue. Previous studies investigated changes in the muscle shear modulus after SS (Umegaki et al., 2015a; Nakamura et al., 2017) and FR (Morales-Artacho et al., 2017; Mayer et al., 2019) but the effects of a VFR intervention was not investigated on the hamstrings yet.

Up to date, no study compared the effects of the common warm-up strategies comprising VFR and SS on functional (ROM, performance) and structural parameters (muscle stiffness, i.e. localized muscle shear modulus) in the hamstrings.

Therefore, the aim of this study was to compare the effects of a two min SS and a two min VFR bout on ROM, PRT, functional performance parameters (jumping height, maximal voluntary isometric contraction (MVIC) peak torque), and the muscle shear modulus of the hamstring muscles ST, BF_{lh}, and SM. We hypothesized a similar increase in ROM in both intervention groups. We expected a decrease in functional performance parameters in the SS group but not in the VFR group. Moreover, we hypothesized similar changes for the muscle shear modulus of the hamstring muscles in both groups.

Methods

Study Design

Each participant visited the laboratory on two sessions, separated by 48h, to complete both interventions (SS or VFR). The intervention was randomized by picking cards. A 5-min warm-up on a stationary bike (Monark, Ergomedic 874 E, Sweden) at 60 rev·min^{-1} and 60 W was performed at both appointments. Before (pre) and after (post) the interventions hip extension ROM, counter movement jump (CMJ), MVIC, and PRT (functional parameters) and shear modulus of ST, SM, and BF_{lh} (muscle mechanical properties) of the hamstring muscles in the right leg were examined. Muscle activation level was measured with surface electromyography on BF_{lh} during shear wave elastography (SWE) testing, MVIC, and PRT before and after the intervention. To avoid any possible interference between the tests they were performed in the order listed in Figure 1. SWE assessment was done in the order ST, BF_{lh}, and SM.

Participants

A necessary group size of at least 15 participants (alpha = 0.05, beta = 0.8, f = 0.4) was suggested by an a priori sample size calculation (primary outcome variable: ROM) for a repeated-measures ANOVA based on data by Lee et al. (2018). To cover possible drop outs we recruited 25 physically active male participants (age: 27.6 ± 6.6 years; body mass: 83.7 ± 11.7 kg; height: 184. 4 ± 7.6 cm). They had no injuries at the lower extremities and were informed about the test procedure, benefits, and risks before they signed a written informed consent form. The ethical approval was obtained by the ethical commission of the university of Graz (approval code GZ. 39/68/63 ex 2020/21) and conformed to the standards of the Declaration of Helsinki. All measurements were done without shoes in socks.

Procedures

Muscle shear modulus

An ultrasound scanner (Aixplorer V12.3, Supersonic Imaging, Aix-en-Provence, France) coupled with a linear transducer array (4 - 15 MHz, SuperLinear 10-2; Vermon, Tours, France) was used to measure muscle shear modulus of the ST, BF_{lh} and SM by SWE. in shear wave elastography mode (musculoskeletal preset, penetration mode, smoothing level 5, persistence off, scale 0–450 kPa). A handheld technique, based on reliability measurements in previous studies (Lacourpaille et al., 2012)· was used to scan the muscles. The participant was positioned right next

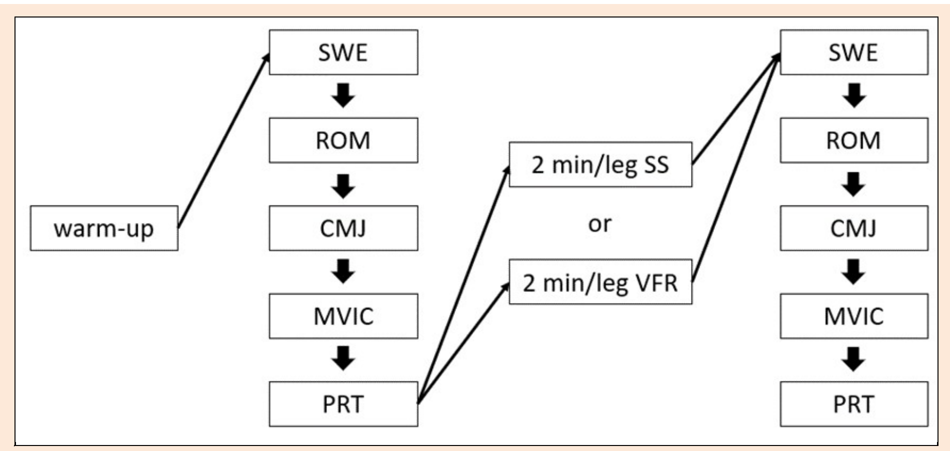

Figure 1. A schematic illustration of the order of measurements. SWE= shear wave elastography; ROM = range of motion; CMJ= counter movement jump; MVIC = maximal voluntary isometric contraction; PRT = passive resistive torque; SS= static stretching; VFR = vibration foam rolling.

to the dynamometer in a supine position with a hip angle of 90° and knee angle of 120° (180° = full hip and knee extension) to achieve a slightly stretched position of the hamstring muscles (Lacourpaille et al., 2017). The similar probe placement for each participant at all measurements was ensured by using a reusable foil marked with the scars and birthmarks of the participant's skin and the probe placement of the first, and combined with a B-Mode ultrasound image of the first measurement. (Figure 2) (see Reiner et al., 2021).

Figure 2. An example of the reusable foil put on the backside of the right leg with marked birthmarks (blue dots) and probe positions (red lines).

The measuring order for SWE was the same in all sessions: ST, BF_{lh}, and SM. ST was measured proximal the tendinous insertion (Morales-Artacho et al., 2017), the SM near the ST but more medial and slightly more distal close the mid-thigh (Morales-Artacho et al., 2017), and the BF_{lh} was measured about mid-thigh more lateral than the ST (Morales-Artacho et al., 2017). Care was taken to put minimal pressure on the skin during shear modulus measurements to avoid deformation of structures and muscle tissue (according to Kot et al., 2012). Positioning the range of interest (ROI) on the muscle tissue in maximal size any aponeurosis was excluded. The transducer was aligned in plane with the muscle fascicles and the same position during the whole process was held (according to (Le Sant et al., 2017). To guarantee the same muscle conditions during the SWE pre-measurements a conditioning (a passive movement with the dynamometer at 5 °/s from 90° to 140° knee angle for 5 cycles prior the pre- shear modulus testing) was done. The EMG was used as a visual check for the participants´ passivity during the shear modulus measurement. Three videos of 15 s each were collected for each muscle. The mean of the five consecutive frames with the lowest standard deviation of the shear modulus averaged over the ROI within a video was considered for further analysis. The two closest mean values per muscle from the three videos taken for each muscle were used to calculate the mean passive stiffness per muscle (Morales-Artacho et al., 2017).

Hip Flexion Range of Motion (ROM)

The maximal hip flexion ROM, assessed with the Sit and Reach test, was done with a Sit -n´ Reach Trunk Flexibility Box (Fabrication Enterprises; Baseline Model 12-1086, New York, USA). Positioned on the ground, hip flexed and knees parallel and fully extended, the participants fit their feet solidly against the Sit n´ Reach box with the ankle joints in a neutral position (90°). Moreover, the participants sat in an upright position, holding both arms parallel to the ground in front of the trunk and the index fingers were touching each other. For the testing procedure the participants were asked to bend forward and move the stretch indicator on the Sit n' Reach test box with their fingertips of both hands as far away as possible. A bending movement with the knees or pushing the stretch indicator with just one hand was not allowed. The trial was repeated if any evasive movement with legs or trunk was detected. Furthermore, to avoid a reflexive muscle activation the participants were asked to move at a slow speed (Kubo et al., 2002). The test was done three times with a 15 s break in between the trials. The average of the three trials was taken for further analysis.

Countermovement Jump (CMJ)

To test the CMJ height a mobile force platform (Quattro Jump, Kistler GmbH, Winterthur, Switzerland) with a sampling frequency of 500 Hz was used. The participants were positioned on the plate in an upright hip wide stand and the hands holding on the hips to prevent any acceleration impulse during the movement. Starting on command, the participants were asked to bend their knees and hips to a personal choice (Heishman et al., 2019). Reaching the individual deepest position, the participants were asked to jump as explosive and high as possible. Three jumps were performed and a one-minute break was in between each attempt. The jumping height values (in cm), measured and generated by the Kistler software, were saved and the highest attempt was taken for further analysis.

Maximum Voluntary Isometric Contraction (MVIC) peak torque

Positioned on a dynamometer (Con Trex MJ, CMV AG, Dübendorf, Switzerland) with the hip and knee angle of the right leg (test leg) at 80° and 110° (Hatano et al., 2019), respectively, the participants performed MVIC knee flexor peak torque measurements. The center of rotation of the knee joint axis and the dynamometer was aligned with a custom-made laser device. The participants´ exact position during the first MVICs was recorded to ensure the same positioning for all following assessments on the dynamometer. To minimize evasive movements the trunk and test leg were fixed with straps and the leg was fixed to the lever arm about 2 cm above the medial malleolus (Morales-Artacho et al., 2017). Crossing the arms in front of the chest each participant was asked to perform three knee flexor MVICs for 5 s each with a 1 min rest in between the trials. The participants received strong verbal encouragement during the measurement while pushing as hard as possible. The attempt with the highest torque value was considered for further analysis.

Passive Resistive Torque (PRT)

Keeping the same sitting position as described for the MVIC peak torque measurement the PRT measurement was done. At an angular velocity of 5 °. s^{-1} from 90° to max. 180° the knee joint was passively moved for five cycles while the participants were asked to be completely relaxed. The angle velocity of 5 °.s^{-1} was chosen to avoid any reflexive muscle activity, according to previous studies (Kubo et al., 2002). For further analysis the lowest torque value of the last three cycles in the extension phase was taken.

Surface Electromyography (EMG)

During SWE; MVIC, and PRT measurements the muscle activity was monitored by EMG (myon 320, myon AG, Zurich, Switzerland) at a sample rate of 2000 Hz. According to "European Recommendations for Surface ElectroMyoGraphy" (SENIAM) (Hermens et al., 1999), after skin preparation, surface electrodes (Blue Sensor N, Ambu A/S, Ballerup, Denmark) were placed on the distal third of the muscle belly of the BF_{lh}. The trial was repeated if muscle activation during passive measurements exceeded an individual indicator placed at 5% of the maximum EMG-values. Detecting muscle activation during passive measurements in the analyzing process, the EMG signal was high-pass filtered (10 Hz, Butterworth) and the root-mean square (RMS, 50 ms window) values were calculated. If necessary, to ensure that the participant was relaxed, i.e., did not show EMG activity exceeding 5% of muscle activity recorded during MVIC (Gajdosik et al., 2005), a post-hoc analysis was performed for the PRT and SWE.

Foam rolling intervention

For the intervention a foam roller with additional vibration (Blackroll Standard foam roll in combination with a Blackroll Booster Set, Bottighofen, Switzerland) was used. The vibration booster is located along the longitudinal hole in the middle of the foam roll and was switched on with a vibration intensity of 32 Hz (according to Lim and Park, 2019). The rolling duration was 2 min with a rolling frequency of 15 repetitions per minute (2 s from distal to proximal and 2 s from proximal to distal) (Behm et al., 2020), applied on each posterior face of the thigh, and the left leg rolled first. Rolling start was proximal to the knee and the turn point was close to the ischial tuberosity. The participants rolled with their own body weight and were asked to add as much pressure as possible (i.e. initial point of discomfort) on the middle part of the thigh while moving linearly for- and backward. A metronome provided auditory signals to pace the movement. (Figure 3).

Stretching intervention

For the stretching intervention, the straight leg raise exercise was used. Participants laid in a supine position on a mat on the ground and were asked to flex the hip and move one leg upwards till the initial point of discomfort was reached. It is a combination of passive static stretching in the extended leg (knee joint angle = 180°) and active movements with the arms and hands to maintain the stretching position/intensity for the hamstring muscles. Moreover, the participants´ ankle joint at the stretched leg was kept in neutral position (90°). The other leg remained on the ground in a relaxed and extended position. The left leg was stretched first, followed by the right leg. The stretching duration was 2 min per leg and the participants were asked to stretch at the initial point of discomfort and increase the flexion during the whole duration to maintain the same stretch intensity (constant torque stretching) (Figure 4). The 2 min intervention duration was chosen to likely induce changes in performance parameters after static stretching (Behm et al., 2016).

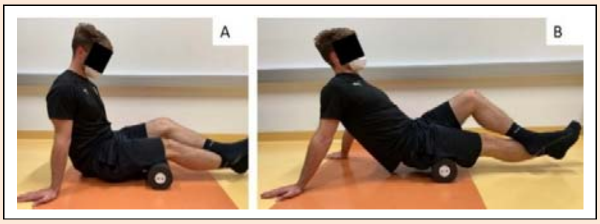

Figure 3. Starting position (and turn point) proximal the knee (A) and turn point distal the ischial tuberosity (B) during the vibration foam roll intervention. The participants were supervised to reach the turn points according the auditory signals of the metronome.

Figure 4. Schematic illustration of the stretching position (straight leg raise exercise). The participants were supervised during stretching to maintain an extended knee during the whole stretching duration.

Statistical analyses

For statistical analyses SPSS (version 26.0, SPSS Inc., Chicago, Illinois) was used. SWE Intra-day and inter-rater reliability of the pre- measurements were determined calculating the intraclass correlation coefficients (ICC, 2-way mixed-effects model, single rater, absolute agreement definition) (Koo and Li, 2016). The standard error of measurement for shear modulus values was calculated as the standard deviation multiplied by the square root of one minus the ICC and the coefficient of variation (CV) was calculated using the pre-values of both SWE measurements. For each participant and muscle the values were calculated separately. The CV was done dividing the standard deviation by the mean multiplied by 100. The mean of all CV´s per muscle was calculated (Atkinson and Nevill, 1998).

Shear modulus of the ST, SM and BF_{lh}, hip flexion ROM, CMJ height, MVIC knee flexor peak torque, and PRT were the tested variables. A Shapiro-Wilk test was used to verify the normal distribution of the data. If variables showed normal distribution, a two-way repeated-measures ANOVA [factors: time (pre vs. post) and intervention (VFR vs. SS)] was performed. Otherwise, a Friedman test was used to test the effects of the two different interventions (SS and VFR). A paired t-test or a Wilcoxon test was performed, if there were significant results in the ANOVA with repeated measures or the Friedman test, respectively. Moreover, a three-way repeated measures ANOVA [factor: time (pre vs. post), intervention (SS vs. VFR), and muscle (ST vs. SM vs. BF_{lh})] was performed.

To check the baseline conditions (pre-values) of all parameters in both interventions (VFR and SS) for similarity, paired t-tests (normally distributed) or Wilcoxon (nor not normally distributed) tests were performed. Paired t-tests or Wilcoxon tests between the delta values (post-pre) within a parameter were used to test possible differences between interventions (VFR vs. SS). The effect size Cohen's d was calculated following the suggestions of Cohen (1988) and d was defined as 0.2, 0.5, and 0.8 for a small, medium, and large effect, respectively. The alpha level was set to 0.05.

SWE reliability, baseline measurement quality, and normal distribution

Of both test days the SWE ICC values between the pre-measurements (VFR vs. SS) for the ST, BF_{lh}, and SM were 0.93, 0.82, and 0.9, respectively. The standard errors of measurement for the ST, BF_{lh}, and SM shear modulus values were 0.85, 1.96, and 1.87 kPa with confidence intervals of 0.83 - 0.97, 0.58 - 0.92, and 0.78 - 0.91 kPa and a coefficient of variation (CV) of 4.6%, 6.5%, and 6.1%, respectively. Moreover, on both test days baseline characteristics for the pre-measurements showed no significant difference in ST shear modulus (P = 0.38), BF_{lh} shear modulus (P = 0.47), SM shear modulus (P = 0.73), ROM (P = 0.3), CMJ (P = 0.66), MVC peak torque (P = 0.76), and PRT (P = 0.2). Only data from MVIC peak torque and the PRT measurements were not normally distributed.

The results of the three-way repeated measures ANOVA was not different to the results of the simpler two-way repeated measures ANOVA and therefore, for a better understanding, the results of the two-way repeated measures ANOVA will be presented in the following results.

Results

Shear modulus values

A significant time effect of the shear modulus of ST (P = 0.001; F = 15.4; r = 0.6; df = 24) was revealed by a two-way repeated measures ANOVA but no group (P = 0.24; F = 1.438; r = 0.2; df = 24) or group × time interaction effect (P = 0.745; F = 0.11; r = 0.1; df = 24) were observed. A significant decrease following VFR (P = 0.005; d = 0.6, medium effect) and SS (P = 0.003; d = 0.7, medium effect) was shown after pairwise comparison of the shear modulus data of the ST (Figure 5A) (Table 1).

Two-way repeated measures ANOVA revealed no effects in group (*P* = 0.55; F = 0.4; r = 0.1; df = 24), time (*P* = 0.61; F = 0.3; r = 0.1; df = 24), or group × time interaction (*P* = 0.64; F = 0.2; r = 0.1; df = 24) for the shear modulus of the BF_{lh} (Table 1) (Figure 5B).

A significant time effect of the shear modulus of the SM (*P* = 0.008; F = 8.4; r = 0.5; df = 24) was revealed by a two-way repeated measures ANOVA, but no group (*P* = 0.86; F = 0.03; r = 0.04; df = 24) or group x time interaction effect (*P* = 0.73; F = 0.1; r = 0.1; df = 24) was seen. A significant decrease following VFR (*P* = 0.03; d = 0.45; small effect), but no change following SS (*P* = 0.09; d = 0.36; small effect) was detected after a pairwise comparison of the shear modulus values of the SM (Table 1) (Figure 5C).

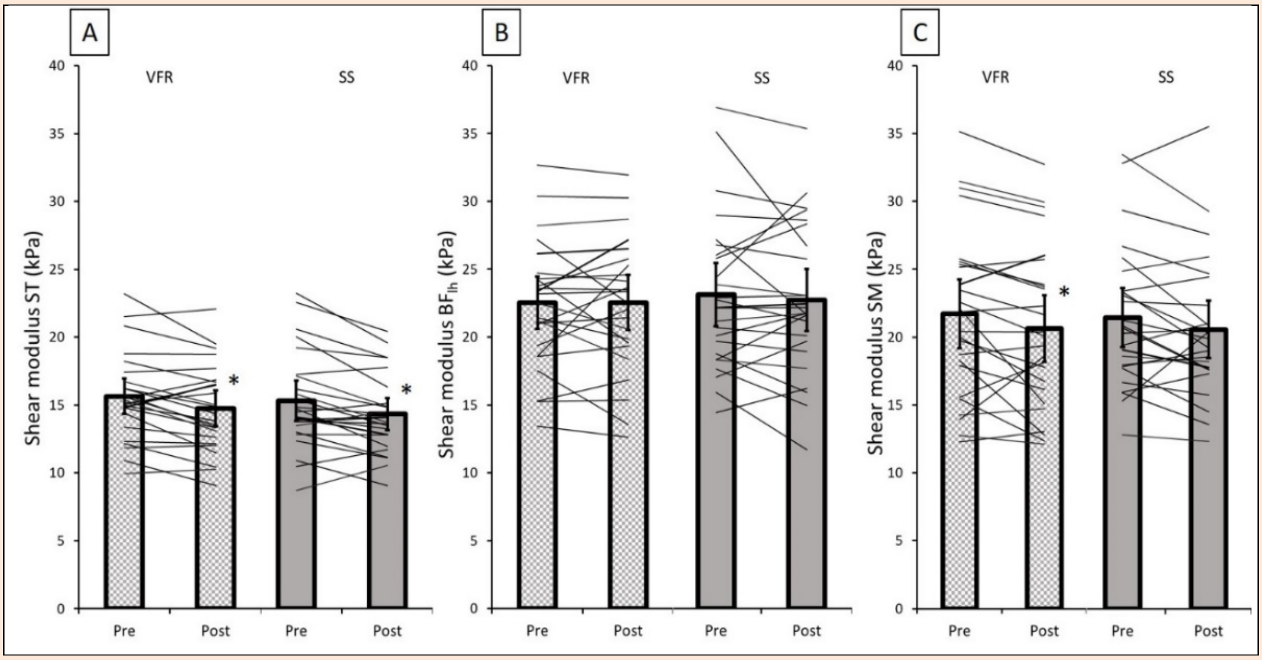

Figure 5. Pre and post mean shear modulus values of both groups (VFR and SS) and the individual changes of each muscle A= shear modulus of ST; B= shear modulus of BF_{lh}; C= shear modulus of SM; *=Significant change between pre and post values

Table 1. Results of the tested parameters pre and post intervention.

	VFR		SS		VFR	SS	VFR	SS
	Pre	Post	Pre	Post	Effects size d or r t-test/ Wilcoxon test		Pre (%)	Post (%)
Shear modulus ST (kPa)	15.6 (±3.2)	14.8* (±3.2)	15.3 (±3.6)	14.3* (±2.9)	0.6	0.7	-6.7 (±10.1)	-6.7 (±10.7)
Shear modulus BFlh (kPa)	22.5 (±4.7)	22.5 (±4.9)	23.1 (±5.6)	22.7 (±5.5)			-1.0 (±12.3)	-2.9 (±10.7)
Shear modulus SM (kPa)	21.7 (±6.2)	20.6 * (±6.0)	21.5 (±5.3)	20.6 (±5.2)	0.45	0.36	-6.5 (±15.4)	-4.9 (±11.9)
ROM (°)	29.3 (±7.2)	32.0* (±6.9)	30.0 (±7.1)	32.2* (±6.9)	1.6	1.4	8.8 (±5.6)	7.7 (±5.5)
CMJ (cm)	47.6 (±5.2)	48.2 (±6.0)	47.4 (±5.9)	46.8 (±5.4)			0.9 (±3.9)	-1.4 (±5.4)
MVIC (Nm)	172.2 (±24.8)	173.6 (±25.9)	175.3 (±20.7)	165.8* (±25.3)	0.05	0.37	0.6 (±6.0)	-5.1 (±8.4) #
PRT (Nm)	51.8 (±7.9)	51.7 (±8.1)	52.7 (±8.3)	52.8 (±8.2)			-0.4 (±5.8)	0.0 (±5.4)

VFR= vibration foam rolling, SS= static stretching, ST= semitendinosus, BF_{lh} = biceps femoris long head; SM = semimembranosus; ROM = maximal hip flexion range of motion; CMJ = counter movement jump; MVIC = maximal voluntary isometric contraction peak torque; PRT = passive resistive torque; * = significant difference between pre- and post-measurement data; # = significant difference between delta values of each group; mean (±SD)

Range of Motion (ROM)

A significant time effect (P = 0.00; F = 71.8; r = 0.87; df = 24) of the mean values of the ROM tests was revealed by a two-way repeated measures ANOVA, but no group (P = 0.38; F = 0.8; r = 0.2; df = 24) or group x time interaction effect (P = 0.35; F = 0.9; r = 0.2; df = 24) was detected. A significant increase following both groups; VFR (P = 0.0; d = 1.6, large effect) and SS (P = 0.0; d = 1.4, large effect), was shown with a pairwise comparison of the ROM pre and post data (Table 1) (Figure 6).

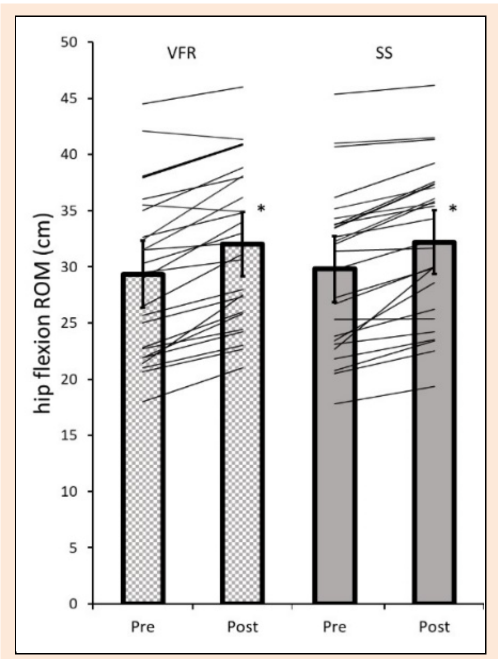

Figure 6. Pre and post mean hip flexion ROM values of both groups (VFR and SS) and the individual changes. *=Significant change between pre and post values

Counter movement jump (CMJ) height

No significant time (P = 0.08, F = 3.4; r = 0.35; df = 24), group (P = 0.9; F = 0.02: r = 0.03; df = 24) or group × time interaction effect (P = 0.13; F = 2.5; r = 0.3; df = 24) was revealed by a two-way repeated measures ANOVA of the maximum values of the counter movement jump (Table 1).

MVIC peak torque

Significant differences (P = 0.003; χ^2 = 13.8; N = 25; df = 3) were revealed by a Friedman test for the MVIC peak torque values. A significant decrease in the SS group (P = 0.009; r = 37; medium effect) but not in VRF group (P = 0.7; r = 0.05; no effect) was detected by a pairwise comparison with a Wilcoxon-test. A comparison of the delta values showed a significant difference between the changes in the two groups (P = 0.003; d = 0.66, medium effect) (Table 1) (Figure 7).

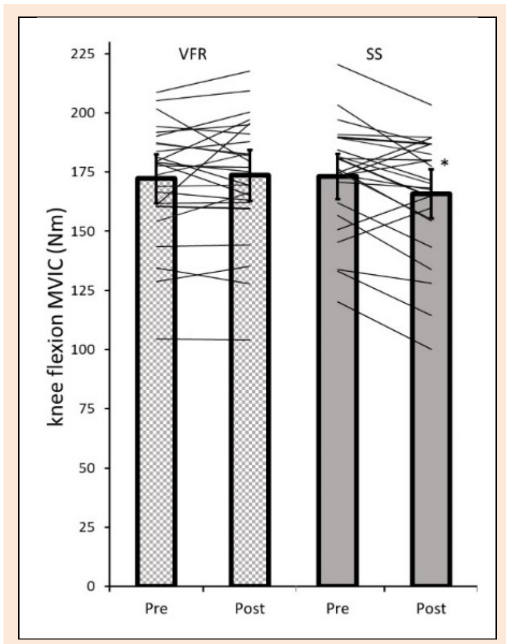

Figure 7. Pre and post mean knee flexion MVIC peak torque values of both groups (VFR and SS) and the individual changes. *=Significant change between pre and post values

Passive Resistive Torque (PRT) values

No significant changes (P = 0.52; χ^2 = 2.28; N = 23; df = 3) were revealed by a Friedman test for the pre and post PRT values of the VFR and the SS group (Table 1).

Discussion

The aim of the present study was to investigate the effects of 2 min of SS and 2 min of VFR on the hip joint flexibility, muscle performance and tissue stiffness of the hamstring muscles. As expected, the results of the present study show changes in hip joint flexibility following both 2 min of SS and 2 min VFR and the maximal force-generating capacity decreased after the bout of SS but was unchanged after the VFR. In contrast to our hypothesis, muscle stiffness was significantly decreased in the ST after both interventions but in the SM only in the VFR group. BF_{lh} shear modulus was not changed after any of the two interventions.

In accordance with previous studies (Umegaki et al., 2015b; Lee et al., 2018; Nakao et al., 2018; Ruggieri et al., 2021) similar significant increases in hip joint flexibility were found following both interventions, VFR (+8.8%) and SS (+7.7%). Lee et al. (2018) (6 min rolling duration) and Ruggieri et al. (2021) (3 × 30 s rolling duration) found significant increases in tissue extensibility of the rear thigh after a VFR intervention (+6% and +2.6%, respectively). The rolling duration in the present study and in Ruggieri et al. (2021) met the prescriptions of Behm et al. (2020) for increases in ROM using a FR. Behm et al. (2020) analyzed the findings of 128 measures and found large effect sizes for 30-120 s of rolling but only small ones for 300 s. In contrast, Lee et al. (2018) reported a large effect size (1.1) after 6 min of VFR. Therefore, the additional vibration while rolling might influence the tissue in a different way and might be beneficial for increases in rear thigh tissue extensibility even after longer rolling durations. The main possible mechanisms behind changes in ROM after using a FR might be changes in pain sensitivity and stretch tolerance (Behm and Wilke, 2019; Nakamura et al., 2021). One consideration is the manipulation of Ruffini cylinders and Pacinian corpuscles in the skin layers that might lead to an inhibition of the sympathetic activation and a muscle relaxation (Behm and Wilke, 2019). Moreover, the applied rolling pressure might lead to a pain reduction (i.e. decrease in pain sensitivity) due to changes in afferent inputs in the central nervous system initialized from Golgi tendon organs and other receptors (Cheatham et al., 2019). Another consideration for increased ROM values is the impact of the rolling pressure on thixotropy. Cell fluids might get more viscous due to the applied pressure and reduce the resistance to movements (Behm and Wilke, 2019). These effects might be even enhanced with the additional vibration in a VFR intervention, as vibration therapy alone seems to lead to improvements in muscle activation, functional performance parameters, and ROM (Germann et al., 2018).

Although the intervention time was shorter in the present study (2 min) compared to 5 min SS applied on the hamstrings by Umegaki et al. (2015a) and Hatano et al. (2019), a significant increase in ROM could have been detected. An increase in maximal ROM after an intervention is often accompanied by an increase in PRT values. Such finding would indicate adaptations in stretch tolerance (neural adaptations i.e. reduced pain sensitivity; (Magnusson et al., 1996)) as a possible cause for changes in joint flexibility. Following SS of the rear thigh a decreased PRT at a higher maximal hip flexion joint ROM, was reported (Umegaki et al., 2015a; Hatano et al., 2019) which rather indicates a reduction in tissue stiffness as a possible explanation. The PRT values in the present study did not change despite a significant increase in ROM. We assume that this was a consequence of the applied hip angle of 80° (with 180° in the neutral position) which allowed nearly all participants to reach a full knee extension. Therefore, a more flexed hip angle would be necessary to increase passive tension and detect changes in PRT. The measured values might be still in the toe region of the force-length-curve because not enough tension is applied to the tissue in the maximal possible knee extension. It would be necessary to reach the linear region in the force-length-curve to see possible changes but due to mechanical limitations of the dynamometer, a hip angle <80° could not be obtained.

A decreased PRT at an increased maximal joint ROM after a stretching or FR intervention might be due to a decrease in muscle stiffness which can be assessed by the muscle shear modulus. Umegaki et al. (2015a) reported a decrease in muscle shear modulus in three hamstring muscles (ST, SM, and BF_{lh}) and Hatano et al. (2019) observed changes in the calculated muscle stiffness of the hamstrings combined with a decrease in PRT following SS which indicates mechanical changes. However, this was not the case in the present study where decreases in shear modulus of single muscles of the hamstrings were observed without any changes in PRT values. While both SS and VFR led to significant changes in ST, only VFR decreased shear modulus of the SM. No changes occurred in the BF_{lh} shear modulus values in any group. Comparing the location of the muscles, the ST and SM are positioned medial in the posterior thigh and the BF_{lh} lateral (Balius et al., 2019). Due to a possible light inward rotation of the leg for core stability during the rolling procedure of the central part of the rear thigh the ST and SM might receive a more intense stimulus than the lateral-positioned BF_{lh}. The muscle shear modulus of the ST and SM decreased for 6.7% and 6.5%, respectively, while the non-significant decrease in the values of the BF_{lh} was 1% in the VFR group. In contrast, the muscle shear modulus changed slightly different in the SS group. The only significant change (-6.7%) was seen in shear modulus of the ST, the most central muscle of the three, while the shear modulus of the SM changed by -4.9% and the BF_{lh} for -2.9% (both not significant). Miyamoto et al. (2017) found shear modulus changes in all three hamstring muscles (ST, SM, BF_{lh}) after the knee extension stretching intervention, while stretching the hamstrings during a hip flexion maneuver lead to changes in ST and SM only. Furthermore, Miyamoto et al. (2017) stretched for a longer duration (3x90 s) which might have led to significant decreases. In the present study SS (2 min) resulted in a significant decrease in the ST, however, a meaningful percental change of almost 5% was also observed in the SM. A slightly longer stretching duration might have led to significant changes in shear modulus in the SM as well. A possible explanation for the differences in stiffness changes might be different lengths and orientations of the fascicles in the three measured muscles. The ST has the longest fascicles and the lowest pennation angle compared to the BF_{lh}, and the SM (Kellis et al., 2012). Therefore, the fascicle orientation of the ST might have a favorable position for the greatest impact during the SS intervention.

There was a clear finding in the isometric muscle performance parameter. As hypothesized, the MVIC torque values decreased after the SS intervention while we observed no changes after the VFR intervention. Previously, other studies reported that SS may impair performance parameters (Hatano et al., 2019) in knee flexion task but also in other muscles after static stretching durations ≥ 60 s (Kay and Blazevich, 2012; Behm et al., 2016), if no dynamic activity is added to the warm-up procedure (Behm et al., 2021). The intervention duration in the present study was 2 min and therefore we expected a decrease in maximal force generating capacity after SS. This reduction might be due to a more compliant muscle tendon complex and a reduced stiffness of tissues in the muscle-tendon-unit concomitant with an impairment in force transmission (Markovic and Mikulic, 2010). Another reason for the loss in isometric performance parameters might be an inhibition in muscle activation due to the prolonged stretching (Cramer et al., 2005) or changes in cross bridge length after the static stretching (Proske and Morgan, 1999). The MVIC peak torque values after the VFR stayed the same. Therefore, the VFR intervention might inhibit the loss in performance, even the stiffness of two muscles was significantly reduced. The additional vibration might lead to a greater motor unit recruitment by stimulating more muscle receptors of different types (Fallon and Macefield, 2007; Germann et al., 2018). This likely leads to a greater availability of prepared muscle fibers and possibly a higher force-generating capacity and muscle performance (Germann et al., 2018). Moreover, it can be assumed that the added vibration stimulate the tissue to adapt the tonicity of the muscle to manage the vibration waves (Germann et al., 2018). Another reason are possible hormonal changes after the vibration therapy and induced muscle tonicity adaptations can lead to increased neuromuscular performance. These mechanisms might counteract the effects caused by stiffness reductions.

In contrast to the loss in MVIC peak torque values, no changes were found in jump performance in any group. No changes in jumping height, MVIC peak torque values, or 20-m sprints were detected after short durations of stretching (15s or 60, Stafilidis and Tilp, 2015) or longer ones (5 min, de Oliveira and Rama, 2016). Additionally, 5 min of FR or VFR of the rear thigh tissue of both legs did not change jumping height (Lim and Park, 2019), while Sağiroğlui (2017) reported increased jumping height after 1 min of foam rolling each muscle group in the legs (hamstrings and gluteus, quadriceps, and gastrocnemius muscles). FR interventions might lead to contradictory results but comparing the different static stretching durations no changes in CMJ height were found after any of the interventions. Therefore, we assume that the CMJ height is independent of stretching durations and possible decreased MVIC values while there might be changes after short applications of FR or VFR even we could not detect any. Moreover, jumps are complex movements and muscle coordination, muscle volume, inter joint coordination etc. likely have a larger influence on jump performance than mechanical properties. Looking from a different perspective, a more compliant muscle tendon unit may delay the rebound effect with the stretch-shortening cycle (SSC) with activities that need very short amortization periods like sprinting, CMJ SSC durations are much longer than with sprinting and thus a more compliant muscle may actually better match the SSC reflex and mechanical rebound effects contributing to a better performance (Gleim et al., 1990; Trehearn and Buresh, 2009).

There are some limitations of the present study. The participants were young active males and therefore a generalization of the results for women or other populations need to be done with caution. Moreover, the results are based on the structure and functionality of the hamstring muscles and a generalization for other body parts is not possible. Another limitation is the chosen test for the hip flexion ROM. The Sit and Reach test might be limited by the extensibility of the lower back muscles and is not exclusively a test for the hamstring's extensibility.

Conclusion

The present study evidences that VFR leads to a greater hip flexion ROM and a decreased muscle stiffness in the medial positioned hamstring muscles ST and SM, while the force production capacity stays the same. Therefore, VFR may be a more favorable warm-up strategy for the hamstring muscles than SS. Despite similar increases in ROM and no effect on CMJ height after both interventions, SS led to a loss of isometric muscle force. While a reduction in muscle stiffness of some muscles can be expected following both interventions, its negative effect on muscle force seems to be counteracted by the vibrations induced by VFR, probably due to increased stimulation of different muscle receptors.

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Key points

- Both interventions (vibration foam rolling and static stretching) lead to the similar increase in hip flexion range of motion.
- Vibration foam rolling of the hamstrings reduces muscle stiffness of the Semitendinosus (ST) and Semimembranosus (SM) muscles, while static stretching lead to a reduction in muscle shear modulus of the ST only.
- Maximal voluntary isometric contraction peak torque is reduced after prolonged (2 min) static stretching but not after a similar duration of vibration foam rolling.

AUTHOR BIOGRAPHY

Marina Maren REINER
Employment
Institute of Human Movement Science, Sport and Health, University of Graz
Degree
MSc
Research interests
Training science, biomechanics, muscle-tendon unit.
E-mail: marina.reiner@uni-graz.at

Markus TILP
Employment
Institute of Human Movement Science, Sport and Health, University of Graz
Degree
Professor
Research interests
Biomechanics, training science, muscle-tendon-unit, sports game analysis.
E-mail: markus.tilp@uni-graz.at

Gaël GUILHEM
Employment
Laboratory Sport, Expertise and Performance, French Institute of Sport (INSEP), Paris, France
Degree
PhD
Research interests
Biomechanics and neuromuscular physiology
E-mail: gael.guilhem@insep.fr

Antonio MORALES-ARTACHO
Employment
Laboratory Sport, Expertise and Performance, French Institute of Sport (INSEP), Paris, France
Degree
PhD
Research interests
Exercise physiology
E-mail: antonio.morales@insep.fr

Andreas KONRAD
Employment
Institute of Human Movement Science, Sport and Health, University of Graz
Degree
PhD
Research interests
Biomechanics, muscle performance, training science, muscle-tendon-unit, soccer science.
E-mail: andreas.konrad@uni-graz.at

✉ **Dr. Andreas Konrad**
Institute of Human Movement Science, Sport and Health, University of Graz, Mozartgasse 14, A-8010 Graz, Austria