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ORIGINAL ARTICLE

Tissue flossing of the thigh increases isometric strength acutely but has no effects on flexibility or jump height

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Abstract
The purpose of this study was to investigate the effects of a single floss band treatment of the thigh on hip and knee range of motion (ROM), knee extensor passive resistive torque (PRT), knee extensor maximum voluntary contraction (MVC) torque, and countermovement jump (CMJ) height.

Sixteen healthy male volunteers were tested before and after both the flossing treatment and the control condition, in random order. For the flossing treatment, the floss band was wound around both thighs for 120 s, and the subject was then asked to perform 20 squats. During the control treatment, only the 20 squats were performed. Before and after the treatments, knee and hip ROM were assessed using a Thomas test with 3D motion caption. The PRT and MVC of the knee extensors were measured with a dynamometer, and the electromyographic (EMG) signal was collected from the vastus lateralis. CMJs were performed on a force plate.

Compared to the control condition, the flossing treatment showed a positive effect on the MVC of the knee extensors ($P = 0.01$); however, no effects on hip ROM ($P = 0.58$), knee ROM ($P = 0.37$), CMJ height ($P = 0.75$), or PRT ($P = 0.22$) were observed. Correlation analyses revealed that the increase in MVC was not significantly related to changes in the tension of the muscle-tendon unit ($r_P = -0.13$; $P = 0.64$) or vastus lateralis EMG ($r_S = 0.44$; $P = 0.10$). Since the increase in MVC cannot be explained by changes of the mechanical (PRT) or neuromuscular (EMG) properties, we speculate that an enhancement of growth hormone and norepinephrine levels following the compression release is instead responsible for the increase in MVC.

Keywords: *Occlusion, blood flow restriction, voodoo band*

Highlights

- Knee extensor maximum voluntary contraction (MVC) torque was increased following a 120 s flossing treatment of the thighs.
- Hip range of motion or countermovement jump performance was unchanged.
- Since the increase in MVC cannot be explained by changes of the mechanical (passive resistive torques) or neuromuscular (Electromyography) properties, we speculate that an enhancement of growth hormone and norepinephrine levels following the compression release is instead responsible for the increase in MVC.

Introduction

A flossing treatment consists of wrapping a latex rubber band around the target tissue (muscle or joint) for about 1–3 min (Driller & Overmayer, 2017). Subsequently, the joints from the flossed region are moved to end-range positions (i.e. ankle flossing: maximum dorsiflexion and plantar flexion). In the last few years, this treatment has become more and more popular among both athletes and therapists. Users claim several beneficial effects for this practice, including increased range of motion (ROM) and strength, as well as accelerated recovery after exercise and injuries. To test these claims, a few studies have investigated the acute effects of flossing on ROM,

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sprinting, and jump performance. Although some of these studies reported an increase of ROM following a single flossing treatment (Driller & Overmayer, 2017; Driller, Mackay, Mills, & Tavares, 2017; Pakarklis & Šiupšinskas, 2018; Vogrin et al., 2020), other studies reported no changes (Hodeaux, 2017; Plocker, Wahlquist, & Dittrich, 2015). One possible explanation for the different results might be that those studies that reported changes in ROM flossed the lower limb (ankle joint), while the others flossed the upper limb (shoulder joint (Plocker et al., 2015) or the elbow joint (Hodeaux, 2017)). Changes in ankle ROM following flossing cannot be explained by changes in the muscular stiffness (Vogrin et al., 2020), suggesting acute neurological changes, reduction of fascia stiffness (Mills, Mayo, Tavares, & Driller, 2020; Schleip & Müller, 2013), or changes in other connective tissues (i.e. tendon, ligaments), which so far, however, have not been measured.

Furthermore, an acute bout of ankle flossing seems to have beneficial effects on strength and springiness (Driller et al., 2017; Driller & Overmayer, 2017; Mills et al., 2020), while flossing of the upper body does not produce any such effect (Plocker et al., 2015). However, the underlying mechanism of how flossing potentially increases strength and/or springiness is not yet clear. Therefore, it is of great importance for sports practitioners to investigate a possible neuromuscular or mechanical explanation for such an increase in strength.

Although there is some evidence for the effects of joint flossing on joint function (e.g. an increase in ROM), no study to date has investigated the effects of flossing on the soft tissue only (without wrapping the joint). Flossing of the thigh has become very common in sports practice, and Starrett and Cordoza (2015) suggested that this method could improve the function of the knee and hip joints. However, there is a lack of scientific study to prove these assumptions. Therefore, we wanted to be the first to investigate the effects of flossing on hip and knee ROM and muscle performance (maximum voluntary contraction (MVC) and countermovement jump (CMJ) height) of the thigh muscles (soft tissue only) with the use of an extra-long floss band (to cover the whole thigh). Since it is not yet clear which mechanism can explain possible changes in the muscle-tendon function following a flossing treatment, this study is the first to identify potential mechanical (passive resistive torque (PRT)) and neuromuscular (electromyographic (EMG)) explanations behind the possible changes in muscle-tendon function (ROM, MVC, and CMJ).

Therefore, the main objective of this study was to analyze the effects of a flossing treatment on ROM, MVC, and jump performance. A second goal was to identify the possible mechanical (PRT) and neuromuscular mechanisms (i.e. changes in EMG) underpinning the expected changes in these parameters. Based on previous studies, we hypothesized an increase in ROM, MVC, and CMJ height. Moreover, we expected that these changes could be explained by neuromuscular (i.e. an increase in EMG activity) and/or mechanical changes (i.e. PRT).

Material and methods

Participants

Sixteen healthy recreational male volunteers (age: 25.69 ± 4.1 years; weight: 76.62 ± 7.66 kg; height: 179.94 ± 6.35 cm) participated in this study. Participants with a history of lower leg injuries, any type of neuromuscular disorder, and elite athletes were excluded from the study. Participants were asked to be in a rested state and to not perform hard workouts in the 72 h before the appointment. According to the study of Mills et al. (2020), who reported small benefits of flossing in CMJ performance and sprint times in 14 participants, we decided to recruit 16 participants for this study. The participants signed a written informed consent form, and ethical approval was obtained by the local ethical commission. The study was performed in accordance with the Declaration of Helsinki.

Experimental design

Participants were asked to visit the laboratory on two separate occasions to complete both test protocols in a randomized order (by picking cards), i.e. control (CON) or tissue flossing (FLOS). The two appointments were separated by 48 h (±1 h). At each session, participants performed a 10-min warm-up on a stationary bike (Monark, Ergomedic 874 E, Sweden) at 60 rev/min (Kay, Husbands-Beasley, & Blazevich, 2015). A modified Thomas test (knee and hip ROM measure) of the right leg was undertaken with a 3D motion capture system before and after the FLOS and CON treatments. The MVC and PRT of the right leg were recorded on a dynamometer before and after the FLOS and CON treatments. CMJ height was also assessed on a force plate before and after the FLOS and CON treatments. Surface EMG was recorded from the vastus lateralis during the MVC and PRT measurements. Tests proceeded in the order and time frame shown in Figure 1.

Measures

Maximum voluntary contraction (MVC). After the standardized warm-up, the MVC tests were

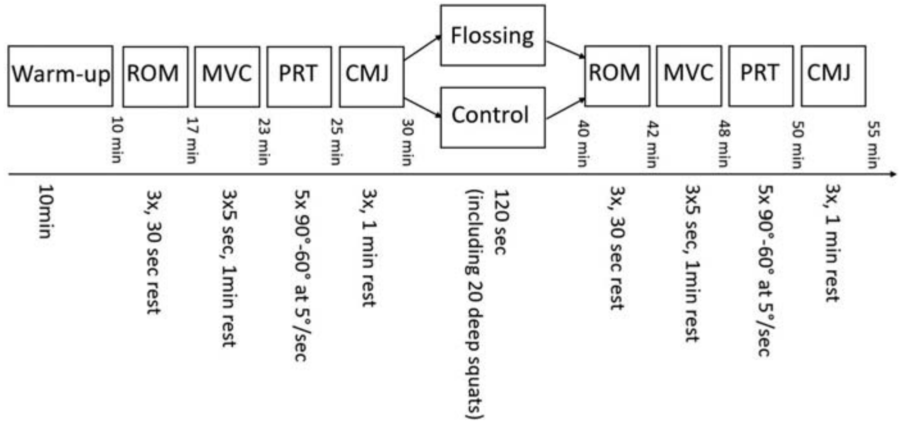

Figure 1. Schematic schedule of the experiment. MVC = maximum voluntary contraction; PRT = passive resistive torque; ROM = range of motion; CMJ = countermovement jump.

performed on an isokinetic dynamometer (CON-TREX® Multijont, Duebendorf, Switzerland). The participant was seated on the dynamometer with both hip and knee angles (test leg only) at 110° (Jakobsen et al., 2012; 180° = anatomical zero; Kaya, Guney-Deniz, Sayaca, Calik, & Doral, 2019). A laser was then used to align the centre of rotation at the dynamometer and the knee joint axis. To ensure the same sitting position during all assessments on the dynamometer, the exact position of the subject during the first MVCs was recorded, and the subject was then placed in the same position in the following measurements. The trunk and test leg were fixed with straps to minimize the possibility of evasive movement. The lever arm was set to about 2 cm above the medial malleolus and the leg was fixed to it (Morales-Artacho, Lacourpaille, & Guilhem, 2017). The participant was asked to cross their arms in front of their chest and perform three isometric MVCs of 5 s, with a 1-min rest in between each attempt (three attempts in total). The participant was instructed to push as hard as possible. The attempt with the highest torque value was taken for further analysis. Calibration and gravity correction were performed following the manufacturer's instructions.

Passive resistive torque (PRT). The PRT test was done in the same sitting position as the MVC measurements. The knee joint was passively moved for five cycles in a continuous motion at an angular velocity of 5°/s from 90° to 60° (180° = anatomical zero). According to previous studies (Kubo, Kanehisa, & Fukunaga, 2002; Mahieu, Cools, De Wilde, Boon, & Witvrouw, 2009), the velocity of the dynamometer was set to 5°/s to exclude any reflexive muscle activity. The participant was asked to relax completely. The cycle with the lowest torque value within the last three cycles at 60° knee angle was taken for further analysis.

Range of motion (ROM). ROM was measured with a 3D motion capture system (Qualisys, Göteborg, Sweden). Reflective markers of 1 cm in diameter were placed according to the Qualisys cast model on the participant's hip (with two extra markers placed on the crista iliaca to ensure a proper measurement in a supine position) and test leg (right leg). Six markers were placed near the pelvis, two on the knee, and six on the lower limb. In addition, clusters of markers (of four markers each) were placed on the shank and on the thigh (see Figure 2). The participant was then asked to perform three modified Thomas tests of the right leg for 5 s each on a medical treatment bed. The participant lay supine, with the iliac crest close to the edge of the bed (Aslan, Buddhadev, Suprak, & San Juan, 2018), hips and knees at 90°, and knees were fixed by hands with extended arms to ensure the same hip angle at the initial position between the measurements and a flat lumbar spine. The legs were completely relaxed. While holding the contralateral leg in position, the test leg was lowered toward the floor and the participant was asked to relax in the end position (see Figure 3). At the pre-tests, marker positions were marked in pencil for the repositioning of the markers after the flossing or control intervention. For the analysis, the mean of the three attempts was calculated.

Countermovement jumps (CMJs). For the dynamic strength measurements, a transportable force plate (Quattro Jump, Kistler GmbH, Winterthur, Switzerland) was used at a 500-Hz recording frequency. The participant was asked to perform three CMJs, with 1-min rest in between. Start and end position was

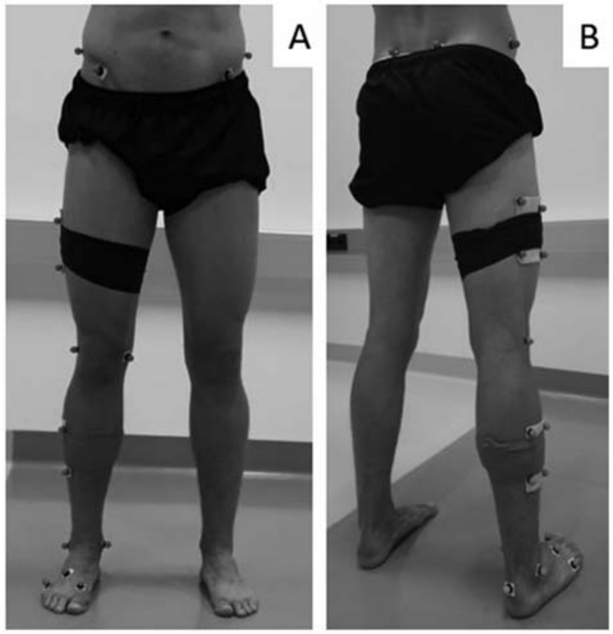

Figure 2. The marker set used for the modified Thomas test in front view (A) and back view (B).

upright, in a hip-wide standing position, with hands placed on the hips (Pedersen, Heitmann, Sagelv, Johansen, & Pettersen, 2019). The hands were not allowed to be moved during the whole measurement, in order not to influence the jump height (Tayech et al., 2020). On command, the participant lowered their center of mass by bending the knees to a self-selected grade, and immediately after reaching the lowest position they jumped vertically as high as possible. The highest jump height was used for the further analysis.

Electromyography (EMG). EMG was recorded during the MVC and PRT measurements at a sampling rate of 2000 Hz with a wireless electromyography system (Myon 320, Myon AG, Zurich, Switzerland). After standard skin preparation, surface electrodes (Blue Sensor N, Ambu A/S, Ballerup, Denmark) were placed on the muscle belly of the vastus lateralis according to SENIAM recommendations (Hermens et al., 1999). The positions of the electrodes were marked to ensure the same placement following the flossing intervention. Data were high-pass filtered (10 Hz, Butterworth filter), and the root-mean-square (RMS) was calculated with a time window of 50 ms. The RMS values from the MVC measurement in the range of ±250 ms around the torque peak were used for the subsequent analysis. For the PRT measurement, a post-hoc analysis was performed to ensure that the participant was relaxed, i.e. did not show EMG activity exceeding 5% of MVC (Gajdosik, Vander Linden, McNair, Williams, & Riggin, 2005; Kato, Kanehisa, Fukunaga, & Kawakami, 2010).

Flossing intervention

The latex rubber floss bands (Artzt Vitality Flossband Standard, 5 m × 5.5 cm, Ludwig Artzt GmbH, Dornburg, Germany) were applied by an experienced massage therapist on both thighs, always starting with the left leg to ensure standardized test conditions. During the wrapping procedure, the participant's upper body (head to gluteal fold) was placed supine on a medical bed, and the feet were put on a separate desk next to the end of the bed, with a knee angle of 90°. The starting point for wrapping was 4.5–5 cm from the proximal edge of the patella (in a bent position) until the trochanter major. The floss band was attached from distal to proximal, with an overlap of 50% (Borda & Selhorst, 2017). On the test leg (right leg), the compression of the floss band during the treatment was monitored with an adapted sphygmomanometer, and a mean value of 154.3 ± 13.3 mmgH was recorded. In the control condition, the participant rested for 3 min in the same supine position as already described for the flossing intervention.

In both groups (FLOS and CON), participants were asked to perform 20 hip-wide deep squats (weight-free), in which they were allowed to hold on to a door frame to support balance (see Figure 4). Each squat lasted 6 s (3 s to get into the squat position and 3 s to get back to upright standing), resulting in a total intervention time of 120 s.

After finishing the squats with the floss band applied, the participant was asked to lie down

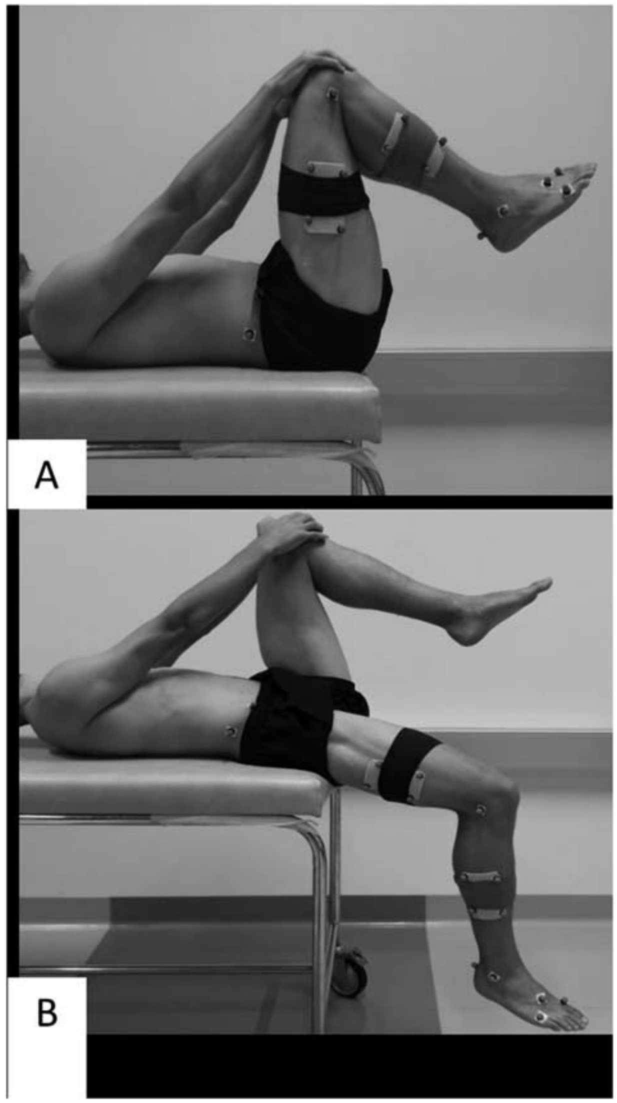

Figure 3. The modified Thomas test in the starting position (A) and in the stretching position (B).

again, and the two examiners unwrapped both legs (this procedure took about 15 s). After both treatments, the participant was asked to walk around the laboratory for 1 min, and after exactly 5 min from the end of the FLOS or CON treatment, the ROM was assessed.

Statistical analyses

SPSS (version 25.0, SPSS Inc., Chicago, Illinois) was used for all the statistical analyses. The variables tested were ROM, PRT, MVC, RMS EMG, and CMJ height. To determine the inter-day reliability of all the parameters, intraclass correlation coefficients (ICC, 2-way mixed-effect model, absolute agreement definition) were used. The standard error of the mean was calculated as the standard deviation multiplied by the square root of one minus the ICC. A Shapiro–Wilk test was used to verify the normal distribution of all the variables. If the data were normally distributed, we performed a two-way repeated-measures ANOVA (factors: time (pre vs. post) and intervention (flossing vs. control)). Otherwise, we performed a Friedman test to test the effects of the flossing and control protocols. If the interaction effect (time × intervention) of ANOVA with repeated measures or the Friedman test was significant, we performed a paired t-test or a Wilcoxon test to test for differences. To test the relationships between changes in MVC and changes in RMS EMG and respective PRT, a Pearson's or Spearman's correlation analysis was applied for normally

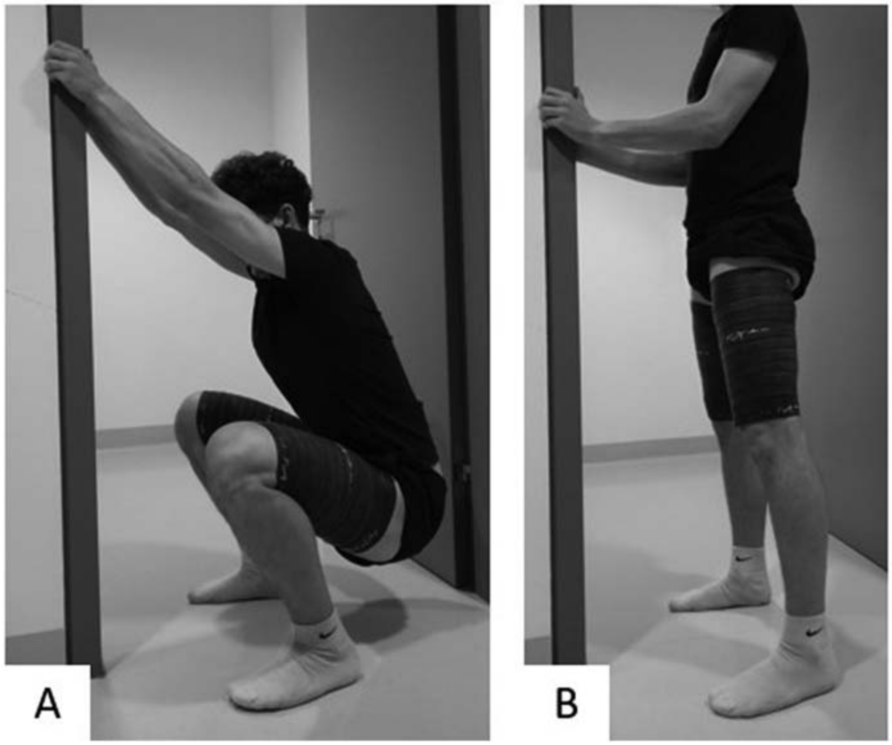

Figure 4. The floss band was placed on both thigh and the participants were asked to perform an unloaded deep squat (as deep as possible) (A) back to an upright standing position with the hips and knees fully extended (B).

and not normally distributed data, respectively, and the r_P or ρ correlation coefficients are reported, respectively. To confirm similar baseline characteristics in all the parameters, a paired t-test or a Wilcoxon test was used. The effect sizes *d* (for the t-test) and *r* (for the Wilcoxon test) were established following the suggestions of Cohen (1988). Thus, the effect size *d* was defined as 0.2, 0.5, and 0.8 for a small, medium, and large effect, respectively. Moreover, the effect size *r* was defined as <0.3, 0.3–0.5, and >0.5 for a small, medium, and large effect, respectively. The alpha level was set to 0.05.

Results

The pairwise comparison of the baseline values (pre-flossing/pre-control) showed no significant difference for knee ROM ($P = 0.75$), hip ROM ($P = 0.65$), PRT ($P = 0.09$), MVC ($P = 0.12$), CMJ ($P = 0.67$), and RMS EMG ($P = 0.75$).

Range of motion (ROM)

For the hip ROM and knee ROM, the ICC (95% confidence interval (CI)), standard error of

Table I. Mean (CI 95%). Results for the parameter ROM (range of motion) of the knee and hip (assessed with a Thomas test), PRT (passive resistive torque), MVC (maximum voluntary contraction torque), RMS EMG (root-mean-square electromyogram), and CMJ (countermovement jump height), before (PRE) and after (POST) the flossing treatment (left side of the table) and the control treatment (right side of the table).

	Flossing				Controls			
	PRE		POST		PRE		POST	
ROM knee(°)	58.00	(51.61 – 65.19)	59.79	(53.62 – 66.96)	57.30	(51.98 – 64.00)	57.08	(50.83 – 64.91)
ROM hip (°)	5.25	(−0.87 – 10.32)	5.62	(−0.11 – 10.89)	4.72	(−0.76 – 9.66)	4.47	(−1.11 – 9.78)
PRT (Nm)	17.93	(16.98 – 18.86)	17.71	(16.81 – 18.73)	17.41	(16.50 – 18.33)	17.64	(16.69 – 18.58)
MVC (Nm)	293.10	(267.16 – 317.83)	309.56	(282.18 – 335.76)*	302.44	(276.83 – 329.29)	299.76	(276.96 – 324.84)
RMS EMG (mV)	0.09	(0.08 –0.12)	0.10	(0.08 – 0.12)	0.10	(0.08 – 0.12)	0.10	(0.08 – 0.12)
CMJ (cm)	49.53	(46.90 – 51.57)	48.84	(46.52 – 50.52)	49.19	(46.62 – 51.31)	48.51	(45.98 – 50.63)

Mean ±. SD. * = significant difference comparing the pre- and post-measurements within the condition (flossing/control).

measurement, and minimum detectable change were 0.89 (0.69–0.99), 0.96 (0.88–0.99), 4.26°, 2.17°, 11.81°, and 6.00°, respectively. The two-way repeated-measures ANOVA test for hip ROM showed no interaction effect ($P = 0.58$; $F = 0.32$; $df = 15$; $\eta^2 = 0.02$), no time effect ($P = 0.93$; $F = 0.008$; $df = 15$; $\eta^2 = 0.001$), and no group effect ($P = 0.37$; $F = 0.86$; $df = 15$; $\eta^2 = 0.05$). Moreover, the ANOVA test for knee ROM showed no interaction effect ($P = 0.37$; $F = 0.87$; $df = 15$; $\eta^2 = 0.06$), no time effect ($P = 0.53$; $F = 0.42$; $df = 15$; $\eta^2 = 0.03$), and no group effect ($P = 0.27$; $F = 1.32$; $df = 15$; $\eta^2 = 0.08$) (see Table I).

Passive resistive torque (PRT)

For the PRT, the ICC (95% CI), standard error of measurement, and minimum detectable change were 0.90 (0.70–0.96), 0.63, and 1.74 Nm, respectively. The two-way repeated-measures ANOVA test for hip ROM showed no interaction effect ($P = 0.22$; $F = 1.64$; $df = 15$; $\eta^2 = 0.09$), no time effect ($P = 0.97$; $F = 0.001$; $df = 15$; $\eta^2 = 0.000$), and no group effect ($P = 0.18$; $F = 1.95$; $df = 15$; $\eta^2 = 0.11$) (see Table 1).

Maximum voluntary contraction (MVC)

For the MVC, the ICC (95% CI), standard error of measurement, and minimum detectable change were 0.95 (0.85–0.98), 12.01, and 33.30 Nm, respectively. The ANOVA test for MVC revealed a significant interaction effect ($P = 0.003$; $F = 12.1$; $df = 15$; $\eta^2 = 0.45$), but no time effect ($P = 0.11$; $F = 2.86$; $df = 15$; $\eta^2 = 0.16$) or group effect ($P = 0.96$; $F = 0.003$; $df = 15$; $\eta^2 = 0.000$) (see Table 1). The pairwise comparison showed a significant increase following the flossing treatment (+5.62%; P=0.01) (with a medium to large magnitude ($d = 0.77$)), but not following the control condition (−0.01%; P=0.55) (with a small magnitude ($d = 0.15$)) (see Figure 5).

Countermovement jump (CMJ)

For the CMJ, the ICC (95% CI), standard error of measurement, and minimum detectable change were 0.97 (0.91–0.99), 0.89, and 2.45 cm, respectively. The Friedman test for CMJ showed no significant difference ($P = 0.75$; $\chi^2 = 1.19$) (see Table 1).

Electromyography (EMG)

For the RMS EMG, the ICC (95% CI), standard error of measurement, and minimum detectable change were 0.90 (0.71–0.97), 0.01, and 0.04 mV, respectively. The two-way repeated-measures ANOVA test for RMS EMG (during MVC) showed no interaction effect ($P = 0.44$; $F = 0.64$; $df = 15$; $\eta^2 = 0.04$), no time effect ($P = 0.81$; $F = 0.06$; $df = 15$; $\eta^2 = 0.004$), and no group effect ($P = 0.86$; $F = 0.03$; $df = 15$; $\eta^2 = 0.002$) (see Table 1).

Correlation analyses

There was no significant correlation between the changes in MVC and the changes in RMS EMG in both the flossing treatment ($\rho = 0.44$; P=0.10) and the control group ($r_P = -0.14$; P=0.59). Furthermore, no significant correlation was found between the changes in MVC and the changes in PRT in both the flossing treatment (r_P−0.13;P=0.64) and the control group (r_P−0.27;P=0.32).

Discussion

This study was the first to investigate the effects of a combined tissue flossing and end-range movement (squats) treatment of the thigh on ROM, MVC, and CMJ height. A specific novelty was the investigation of possible mechanical (PRT) and/or neuromuscular mechanisms (EMG) underlying the possible changes in the muscle-tendon function.

We found that ROM did not change after the flossing treatment, which is in accordance with the findings of a number of previous studies (Hodeaux, 2017; Plocker et al., 2015), but not all (Driller et al., 2017; Driller & Overmayer, 2017; Pakarklis & Šiupšinskas, 2018; Vogrin et al., 2020). Meanwhile, no changes in ROM were detected in the joints of the upper body, but there is evidence that flossing of the ankle joint increases ROM in recreational athletes (Driller et al., 2017; Driller & Overmayer, 2017). Since we also tested the leg muscles, we were expecting an increase in ROM. However, the Thomas test did not show a change in either the knee or the hip ROM. One possible explanation for these contradictory results when compared to the studies which were dealing with flossing of the ankle joints (Driller et al., 2017; Driller & Overmayer, 2017; Pakarklis & Šiupšinskas, 2018; Vogrin et al., 2020) might be that our participants received a flossing treatment of the soft tissue only, rather than also the joint. Since we flossed our participants from 4.5 to 5 cm of the proximal edge of the patella to the trochanter major, neither the bony structures of the hip joint nor the knee joint were flossed. The lack of compression of the connective tissue and ligaments close to the joints (as in studies dealing with the ankle joint, e.g. Driller & Overmayer, 2017)

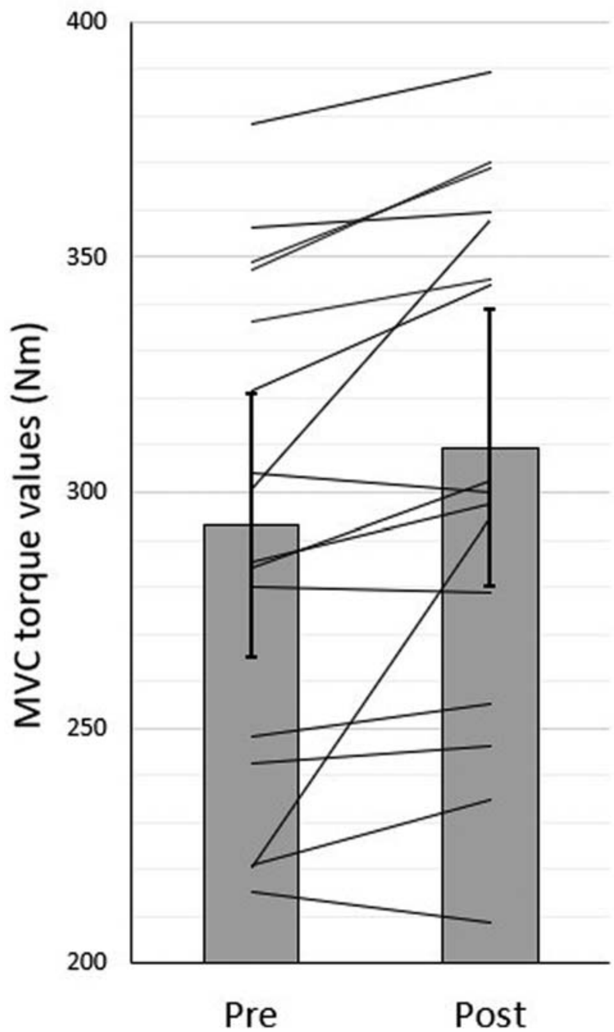

Figure 5. Pre and post values of individual participants (lines) including the mean value of all participants with a confidence interval of 95%.

might have prevented the expected increase in ROM. A second explanation for us not finding an increase in ROM could be ascribed to the bandage pressure we adopted. Indeed, in this study, this was lower (154.3 ± 13.3 mmHg) than the bandage pressure applied in those previous studies in which compression pressure was also measured (e.g. 182 ± 38 mmHg in Driller & Overmayer, 2017). However, to date, it is not clear whether compression pressure is related to changes in muscle performance parameters (e.g. CMJ), as already suggested by Mills et al. (2020).

The lack of changes in ROM in the present study goes along with the lack of changes in PRT (at the same angle pre- and post-intervention) which have sometimes (Kay et al., 2015; Konrad, Stafilidis, & Tilp, 2017) but not always been detected (Magnusson et al., 1996) following a single static stretching exercise. While an increase in ROM corresponding to a decrease in PRT (at the same angle pre- and post-stretch) has been associated with a decrease in muscle stiffness (Kay et al., 2015; Konrad et al., 2017) or tendon stiffness (Kato et al., 2010) following a single static stretch (Kay et al., 2015; Konrad et al., 2017), an increase in ROM and no change in PRT (at the same angle pre- and post-stretch) is commonly associated with an altered perception of stretch and pain (Magnusson et al., 1996). Although Vogrin et al. (2020) showed an increase in ROM of the ankle joint following a flossing treatment, they could not detect any changes of muscle stiffness (measured by tensiomyography) in the gastrocnemius medialis. However, the PRT of the ankle joint is affected by several muscles and connective tissues, including tendons, ligaments, and joint capsules. Therefore, it cannot be excluded that tissue changes other than in the gastrocnemius medialis occurred in the study by Vogrin et al. (2020).

With regard to the performance parameters, we found an increase in MVC torque of the leg extensors (with a medium to large magnitude of change (+5.62%, $d = 0.77$)), but no significant change in CMJ height (−1.39%, $r = 0.26$). Although the difference in MVC was significant and meaningful from a sport-specific perspective, the change was below the minimum detectable change and should therefore be interpreted with caution. Follow-up studies are warranted to confirm the present result. However, since the magnitude of change of the MVC showed a medium to large effect ($d = 0.77$) the results of this study will be highly relevant for both athletes and conditioning coaches. Thus, flossing could be implemented in sports where isometric strength is required to enhance the performance (e.g. alpine skiing). However, since leg extensor strength plays an important role in jump performance, this was a surprising result. However, CMJs also involve other muscles (core, gluteal, and calf muscles) which were not included in the flossing treatment. Therefore, it can be assumed that the flossing treatment of the thigh only was not stimulus enough to induce changes in complex movements including several muscle groups, such as CMJs. Furthermore, McLellan, Lovell, and Gass (2011) pointed out that, during a CMJ, the rate of force development has a closer relationship to CMJ jump height than peak torque. The performance in jumps and other explosive movements seems to be primarily caused by the ability to develop force rapidly (RFD), and to a lesser extent by maximal strength (Maffiuletti et al., 2016). Although the flossing intervention had a positive effect on maximum isometric torque production, it might have had less of an effect on the rate of force development, which would explain the lack of increase in CMJ height. However, we did not include a measurement to determine RFD, which we suggest is included in further studies.

EMG measurements during MVC provided us with the possibility to explore whether the increased value in the leg extension task mirrored a proportional increase in the neural drive to the muscle. Indeed, it is known that EMG amplitude during isometric contractions increases progressively in relation with torque (Coburn, Housh, Cramer, & Weir, 2005).

However, the correlation between changes in MVC (POST–PRE) and changes in vastus lateralis RMS EMG (POST–PRE) was only moderate and non-significant ($r_S 0.44$; $P 0.10$) in the flossing group. This could be attributed to the extent of the MVC increase (about 5.5%), which might have been insufficient to induce an appreciable change in neuromuscular activation properties detectable with surface EMG recordings. Moreover, the electrodes were removed during the flossing treatment (to prevent discomfort and because the pressure could have damaged the electrodes or squeezed the gel outside the adhesive capsule, with related changes in impedance) and were replaced with new ones in the same position. This procedure could have compromised the reproducibility of the electromyographic measurements, which are known to be susceptible to even minimal changes in repositioning (Veiersted, 1991). An alternative explanation for the mechanism underpinning the MVC increase has already been suggested by Driller et al. (2017), who attributed it to a hormonal response related to the flossing. In fact, by adopting different occlusion methods, enhanced growth hormone and sympathetic hormone (norepinephrine) levels after the release of the compression were reported (Takarada et al., 2000), which were assumed to be responsible for the increase in performance in the tested strength tasks (Driller et al., 2017; Morales et al., 2014). Among other responses related to an increase of sympathetic outflow, there is an enhanced facilitation of the short-latency stretch reflex (Hjortskov, Skotte, Hye-Knudsen, & Fallentin, 2005). It has long been known that afferents from muscle spindles contribute in various ways to different voluntary muscle contractions (Burke, Hagbarth, & Skuse, 1978; Macefield, Hagbarth, Gorman, Gandevia, & Burke, 1991; Vallbo, 1974), and thus an increase in Ia afferents might have provoked the observed increase in MVC. It would be interesting to repeat the experiment to test this hypothesis by recording the EMG with tattoo electrodes, which would overcome the limitation of having to remove and replace the electrodes (Ferrari et al., 2018).

A further explanation for the lack of a significant correlation between the changes in MVC and the changes in vastus lateralis RMS EMG might be found in the muscle activity of the other muscles of the leg extensors (e.g. vastus medialis or rectus femoris). It is reasonable that they may have also increased their activation (non-significantly), resulting in a cumulative effect for all the leg extensors, which led to the observed increase in leg extensor MVC. Furthermore, the intervention could have also affected the activation of the knee flexors. Following a similar compression treatment, i.e. foam rolling of the leg extensors, Cavanaugh, Aboodarda, Hodgson, and Behm (2017) observed a decrease of the leg flexor activation, but no change in the leg extensor muscle activation (Cavanaugh et al., 2017). Since the emphasis of the flossing treatment in this study was also on the quadriceps muscles (compressing the quadriceps during squats), a decrease in antagonist activation seems reasonable. However, neither synergistic muscles (vastus medialis or rectus femoris) nor antagonist muscles (hamstrings) were measured in this study, due to the restriction in space on the thigh with the used dynamometer setup, and also because of the time restriction (attaching electrodes to at least six muscles instead of one). However, for future studies of flossing, we strongly recommend monitoring the muscle activity of all the main agonist and antagonist muscles. Furthermore, we suggest the use of tattoo electrodes to speed up the process.

There are some limitations to this study. Firstly, since we had to remove the EMG electrodes during the flossing intervention, this might have had an impact on the reproducibility of the EMG measurements. We recommend that future studies investigating flossing should use tattoo EMG to overcome this limitation (Ferrari et al., 2018). Secondly, only the EMG of one target muscle (vastus lateralis and not vastus medialis and rectus femoris) and no antagonist muscle was recorded. This reduced the opportunities to interpret the neuromuscular findings of this study. Thirdly, no possible change in the hormonal response due to flossing was measured in this study. Nevertheless, this study was the first to investigate the effects of flossing that tried to establish the underlying mechanical or neuromuscular mechanism of changes in ROM, MVC, and/or CMJ. Fourthly, although the difference in MVC was significant and meaningful from a sport-specific perspective, the change was below the minimum detectable change and should therefore be interpreted with caution.

Perspectives

In conclusion, a single flossing treatment of the thigh, including end-range movements (squats), for 120 s did not induce any changes in hip or knee ROM. Although the leg extensor MVC increased, no changes in CMJ height were observed. Changes in vastus lateralis muscle activation (EMG) were only moderately and non-significantly related to the increase in MVC. Since the increase in MVC cannot be explained by changes of the mechanical (PRT) or neuromuscular (EMG) properties, we speculate that an enhancement of growth hormone and norepinephrine levels following the compression release is instead responsible for the increase in MVC.

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