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ORIGINAL RESEARCH

The acute effect of foam roller application on eccentric knee flexor strength in rugby sevens players: a randomised crossover trial

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Abstract

Background: Hamstring injuries account for approximately one in six injuries for rugby players. Contributing factors include poor eccentric strength and reduced range of motion (ROM) at the hip and knee joints. Beyond specific training methods, foam rolling is employed extensively to enhance ROM, joint mobility, general performance, and other outcomes pre- and post-physical exercise. The study aimed to investigate the acute effect of foam roller application on eccentric knee flexor strength, hip, and knee ROM in rugby sevens players. **Methods**: A total of 23 rugby sevens players (age: 24.16 $\pm$ 2.15 years, height: 177.0 $\pm$ 5.89 cm, body mass: 64.57 $\pm$ 6.65 kg) underwent two conditions in a randomised crossover experiment. The experimental condition included Foam Roller (FR) exercises (3 sets, 30 seconds each with 10-second recovery intervals) on the gastrocnemius and hamstring muscles of both limbs. The non-foam rolling (NFR) condition involved resting on the mat for the same time period as the foam rolling session. Maximal eccentric strength (MES), average eccentric strength (of three repetitions) (AES), active straight leg raise (ASLR), and active knee extension (AKE) tests were performed on both limbs pre- and post- each condition. **Results**: The present study revealed that FR improved MES and AES (~1.4–1.7%, $p < 0.001$), ASLR (~9–10%, $p < 0.001$), and AKE (~8–10%, $p < 0.001$) compared to the NFR condition. **Conclusions**: These findings confirm that FR is a viable strategy to improve eccentric knee flexor strength, hip, and knee ROM before other activities. Such applications may be useful in improving performance and reducing injury risk for athletes.

Keywords

Hamstring; Myofascial release; Flexibility; Athletes; Humans

1. Introduction

In rugby, hamstring injuries account for up to 15% of all injuries [1], while acute hamstring strains have the highest recurrence rate among muscle-related injuries. At the elite rugby level, hamstring strains rank second to concussion for match-related injuries [2, 3]. Whilst these injuries are multifactorial, common themes include poor or reduced flexibility and eccentric strength of the knee flexor musculature [1]. A variety of interventions have been trialled in an attempt to prevent these injuries. These include strengthening exercises to address muscular weakness, assessment of anterior and posterior strength ratios (quadriceps:hamstrings), eccentric hamstring strength, and flexibility of the corresponding muscle groups. In the existing body of scholarly literature, there is limited evidence demonstrating that increased flexibility may reduce the risk of hamstring injuries. A recent study conducted in a sample of American football players substantiates the aforementioned observations. According to this study, lower hamstring flexibility, a reduced hamstring/quadriceps strength ratio (H/Q), and a lower overall joint laxity score have been identified as risk factors for hamstring injuries. Also, it has been suggested that increasing muscle flexibility and avoiding lower H/Q ratios may confer advantages in preventing hamstring strain injuries in this athletic population [4]. Eccentric hamstring strength can be easily assessed using the Nordic hamstring exercise [5], and the repeated use of this exercise as part of a training program has been shown to decrease the incidence and severity of hamstring injuries in rugby players [1, 6].

In contemporary practice, foam rollers (FR) are used as a method of self-myofascial release (SMR) to improve joint flexibility and range of motion (ROM) [7]. SMR uses FR to reduce or limit functional losses by dispersing the facial adhesions (trigger points) through external pressure [8–10]. Although therapists have traditionally performed myofascial release manually, SMR has gained escalating recognition within musculoskeletal therapy and exercise science [7]. SMR can also provide similar mechanical pressure without the need for a clinician and reduces, if not removes, the cost of ongoing manual treatment of this type [10]. Thus, SMR allows athletes to perform self-administered treatment more frequently and is effective in the long term for improving joint mobility, reducing muscle pain, and preventing movement restriction [7, 9, 10].

Acute bouts of FR, however, tend to show inconsistent effects on joint ROM, strength, and power when compared to other therapies (*i.e.*, stretching). On the one hand, for example, in previous studies, joint ROM improved in a general, healthy population [11, 12] and in athletic populations (Division I College American Football Players) following FR [13]. In this athletic population, a single bout of FR improved flexibility but not power or strength of the knee flexors or extensors compared to no treatment [13]. Similarly, another study conducted in healthy individuals noted that FR use resulted in immediate positive increases in hamstring flexibility, as assessed through active knee extension. However, no significant changes were observed in strength parameters despite the observed improvement in flexibility [14]. Conversely, a recent review, which included four studies, conducted by Anderson *et al.* [15] observed that FR showed little improvement in terms of athletic flexibility compared to a dynamic stretching protocol alone. Likewise, a recent study evidenced that a cumulative time of FR amounting to 60 seconds or less, targeting agonist-antagonist muscle pairs, emerged as inadequate for eliciting notable improvements in the flexibility of athletes compared to an inactive control condition [16]. However, FR during a resistance training session may impair the number of repetitions performed when applied to the agonist muscle [17], suggesting that application timing is significantly important. Furthermore, acute SMR using FR has been reported by some authors to improve ROM [11] and may have a positive effect on strength when applied for more than 60 seconds per muscle group prior to a training/testing session [18]. Additionally, Wiewelhove *et al.* [19] performed a meta-analysis of the effect of FR on performance (as a pre-training warm-up strategy) and recovery (post-training). With respect to pre-training FR applications, the authors concluded that FR resulted in small improvements in sprint and flexibility performance while the effects on jump and strength were negligible. However, it is relevant to note that most of the studies cited by Wiewelhove *et al.* [19] evaluated strength through isometric force production. Consequently, it seems that the existing body of scholarly literature is sparse when evaluating eccentric strength performance, which is one of the goals of the present study.

Thus, this study aimed to assess the pre-exercise acute effect of an FR-based intervention on eccentric knee flexor strength, hip, and knee joint ROM. The findings of this study are likely to hold relevance for rugby sevens (a modified form of rugby union played with only seven players on the field per team and matches comprising two seven-minute halves) players and other sporting disciplines where high eccentric load hamstring actions occur and injury risk to this muscle group is prevalent. Based on previous research that analyzed flexibility and ROM [11, 14, 15, 19] in rugby sevens players, the study hypothesized that FR use immediately before testing will significantly increase hip and knee ROM in players employing FR compared to those who do not utilize FR. The study also investigated any improvements in eccentric knee flexor strength resulting from FR application (pre-exercise).

2. Materials and methods

2.1 Participants

In this study, 23 male rugby sevens athletes (mean $\pm$ standard deviation: age: 24.16 $\pm$ 2.15 years, height: 177.0 $\pm$ 5.89 cm, body mass: 64.57 $\pm$ 6.65 kg, body mass index: 22.98 $\pm$ 2.31 kg/m^2, and body fat percentage: 13.8 $\pm$ 4.1%) from a Turkish team with an average experience of three years playing at the national level were recruited from 06 April to 30 April 2021. The inclusion criteria for the study were: (i) competitive status (exercise $>$ six hours/week with an emphasis on improving performance and participating in official competition events, *i.e.*, high school or college athletes) [20], (ii) no lower extremity injury in the previous six months, (iii) having regularly completed strength exercises in the previous three months, (iv) at least two years of athletic history, and (v) not using any dietary or physiological ergogenic substances. Subjects were excluded if any of the following medical conditions were evident: epilepsy, diabetes, neurological disorders, lower extremity disability, open wound, surgical lower extremity disability, or any other health issue that could prevent them from participating in the study protocols. Athletes were instructed not to engage in strenuous physical activity for 24 hours prior to the testing sessions and not to consume foods or drinks containing caffeine or similar stimulants for the same period.

The study was conducted according to the Declaration of Helsinki guidelines and was approved by the Ethical Committee for Scientific Research of Trakya University Faculty of Medicine. Informed written consent was obtained from all participants who agreed to participate in this study and met the inclusion criteria.

2.2 Study design

All participants' anthropometric measurements (height, body mass, and body fat percentage) were performed as depicted in Fig. 1. The athletes participated in a single familiarisation session one week prior to starting the test protocols to understand the ROM, FR exercise, and eccentric knee strength measurement techniques (Fig. 1). To avoid potential physiological and neuro-physiological effects and fatigue during physical activity, participants completed both test protocols at the same time of day (10:00–12:00 AM). A randomized crossover study design was employed. Participants were randomly allocated to the FR or non-FR (NFR) conditions and completed each protocol, with a 1-week washout phase between each protocol. Block randomisation was utilized to prevent any learning effect between occasions [21]. This involved randomly assigning 12 participants to commence with the FR protocol and the remaining 11 participants to start with the NFR protocol. The study protocol included tests that measured the eccentric knee flexor strength, hip, and knee ROM prior to and one minute following the FR and NFR protocols [22, 23].

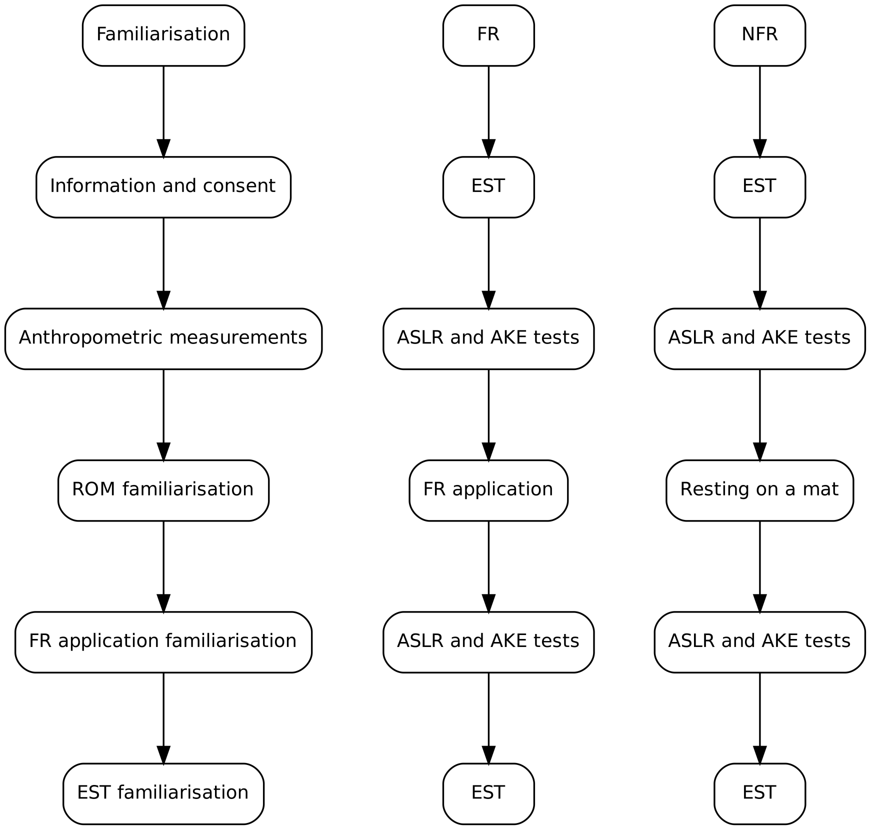

FIGURE 1. Flow diagram of experimental procedures. FR, Foam Roller; NFR, No Foam Rolling; ASLR, Active Straight Leg Raise; AKE, Active Knee Extension; ROM, Range of Motion; EST, Eccentric Strength Test.

2.3 Experimental protocol

Athletes performed a general warm-up on a vertical bike (Monark Peak Bike, Sweden) for 5 minutes at 74 watts (1.5 kg, 50 rpm) prior to each condition. Following the general warm-up protocol, athletes performed three trials of the eccentric knee flexor test at ~60% of perceived maximum intensity before the maximum eccentric knee flexor strength test. Following a 1-minute rest period, the test with one set of three maximum repetitions was performed. The amount of rest between repetitions was two minutes [5]. Following the completion of the knee flexor strength test, athletes were granted a 3-minute rest period. Subsequently, the athletes were asked to lie supine on a mat for the active straight leg raise test (ASLR; hip ROM), wherein they raised the dominant and non-dominant legs upward without bending the knee, and measurements were taken with a manual goniometer. The full protocol for this test has been described previously [24]. Following a 1-minute rest period, athletes were instructed to lie supine on a mat for the active knee extension (AKE) test, wherein they placed the ipsilateral hip and knee in 90° flexion with the ischial tuberosity on the floor. The researcher verbally instructed the athlete not to lift their thighs from the floor and to continue the pelvic tilt until the end of the test. From the starting position, the athlete was informed to extend the ipsilateral knee. The knee was extended, stretching the hamstring muscles until myoclonus occurred, and the athlete was informed to bend the knee until the myoclonus stopped slightly. The knee flexion angle was recorded at this position.

2.4 Foam roller condition

Participants utilized an FR cylinder (height: 33 cm, diameter: 14 cm; TriggerPoint, USA). On the FR day, following the eccentric knee flexor test, the ASLR test and AKE test were completed, and the athletes commenced the FR-based intervention. These exercises were performed for 30 seconds with a 10-second rest interval for three sets, on the gastrocnemius and hamstring muscles on both sides of the body, separately in a random order. During the application, the metronome was set to 40 beats per minute. Thus, the participants were advised to apply an application rate of ten rolls per 30 seconds while targeting the area with maximum tolerable pressure using their body weight while the hamstrings were in a relaxed position [16].

Gastrocnemius: The athlete sat on the exercise mat with the FR underneath the lower leg. The FR was placed at the midpoint between the knee and ankle joints. Hands were used to provide support on the sides to lift the hips. The FR was rolled slowly towards the centre of the ankle and returned to the starting point. The researcher verbally instructed the breathing and speed of the exercise execution.

Hamstring: The athlete sat on an exercise mat with the FR immediately underneath the back of the thigh. The FR was placed in the centre of the hip and knee joints. Hands were used to raise the hips from the ground on the sides. The FR was slowly rolled towards the top of the knee joint and returned to the starting point. The researcher verbally instructed the breathing and speed of the exercise [25].

One minute following exercise completion, the ASLR and

AKE tests were performed on the dominant and non-dominant extremities, and values were recorded. Following a 1-minute rest period, the athletes performed the eccentric knee flexor test for one set of three maximum repetitions. The maximum and average torque and imbalance values were recorded following test completion.

2.5 Assessments

2.5.1 Anthropometric measurements

The athletes' body mass was measured using a Seca scale (Seca 714, Hamburg, Germany) stadiometer, and body fat percentage was analyzed using the bio-impedance method with an Inbody (Inbody 520, InBody USA, Cerritos, CA, USA) bio-impedance measurement device. All anthropometric measurements were taken in an anatomical posture, wearing competition swimwear, and barefoot. Participants were asked not to consume foods or drinks other than water for at least 4 hours prior to the measurements. During the measurements, participants were instructed to step onto the device's metal surface with bare feet, hold onto the device's metal handles with both hands, and maintain a parallel arm position.

2.5.2 Active straight leg raise (ASLR) test

The ASLR test was performed while lying supine on a mat to determine hip ROM. The hip movement was measured with a manual goniometer placed on the side of the athlete's thigh. The athlete had to lie supine on a mat, extended, and raise the leg upwards without bending the knee while maintaining stability with the non-dominant leg by applying pressure to the floor [26]. In order to enhance statistical precision, the test involved the repetition of measurements three times for each leg. Subsequent to each ASLR test, participants were instructed to adopt a state of relaxation for an approximate duration of 10 seconds [27]. The same procedure was followed when testing the non-dominant leg.

2.5.3 Active knee extension (AKE) test

The AKE test was performed to determine hamstring ROM. During this test, the knee joint extension angle was measured by a manual goniometer placed on the lateral epicondyle of the knee joint. The athlete lay supine on a mat. The ipsilateral hip and knee were flexed to 90°, with the ischial tuberosity resting on the ground. The researcher verbally instructed the athlete not to remove the thigh from the ground and to maintain pelvic tilt during the test. From the starting position, the researcher verbally instructed the athlete to extend the ipsilateral knee. The knee was extended to stretch the hamstring muscles, causing myoclonus. The researcher verbally instructed the athlete to bend the knee slightly until the myoclonus stopped. At this point, the knee flexion angle was recorded [28]. Moreover, each knee underwent two measurements, interspersed with 10-second intervals of rest. The resultant average angle from the AKE test constituted the focal point for subsequent analytical procedures [29, 30]. The same procedure was followed when testing the non-dominant leg.

2.5.4 Eccentric knee flexor strength

The eccentric knee flexor strength test determined maximum force values and asymmetries in athletes. During the NordBoard (Vald Performance, Queensland, Australia) test, athletes were fixed to the sensors passing over the ankle. The athletes placed their arms across their chests and slowly lowered forward. The test was completed using a one-maximum set of three repetitions. Maximum eccentric strength (MES) (*i.e.*, highest values recorded across the set) and average eccentric strength (AES) (*i.e.*, average across the three repetitions) were recorded [5].

2.6 Statistical analysis

The *a priori* sample size for the current study was determined using G*Power Software 3.1.9.7 (University of Dusseldorf, Düsseldorf, NRW, Germany). Considering that previous research [31–34] presented lower sample sizes than the present study, a sensitive, power analysis was performed using F tests based on the study design, which involved repeated measures Analysis of Variance (ANOVA) with within-between interaction analyses. The study involved two conditions and measurements at two time points. The error probability (α) was set at 0.05, the correlation value among repeated measures was set at 0.5, and the nonsphericity correction was set at 1. This resulted in a minimum (critical) effect size (ES) of 0.31.

Data analysis was conducted using SPSS 26.0 (SPSS, Inc., Chicago, IL, USA). Descriptive statistics, including mean and standard deviation, were presented for numerical variables in the tables, and individual responses were shown graphically. The normality of numerical variables was evaluated using the Shapiro-Wilk test. All variables had a normal distribution ($p > 0.05$). The measurements were compared using a two-way (condition $\times$ time) Repeated Measures ANOVA to determine if the pre-test and post-test measurements in the acute FR and NFR conditions differed based on condition and time. In cases of significant differences, *post hoc* comparisons were analyzed using Bonferroni-corrected t-tests. To demonstrate the power of the statistical analysis, ES values using partial Eta squared were utilized (partial eta squared (η^2) indicates the proportion of variance in the dependent variable explained by a specific independent variable). Partial eta squared (${\eta_p}^2$) values less than 0.01, between 0.06 and 0.14, and greater than 0.14 were classified as small, medium, and large ES, respectively [35]. Additionally, Cohen's d ES with 95% confidence intervals (CI) were calculated to define the magnitude of pairwise comparisons. The ES magnitude was defined as follows: $<$0.2 = trivial, 0.2 to 0.6 = small effect, $>$0.6 to 1.2 = moderate effect, $>$1.2 to 2.0 = large effect, and $>$2.0 = very large [36]. The significance level was set at $p < 0.05$ for all statistical analyses.

3. Results

Tables 1 and 2 demonstrate the effects of the FR and NFR conditions on the dominant and non-dominant leg MES, AES, ASLR, and AKE values. Additionally, individual variations for MES, AES, ASLR, and AKE values of both dominant and non-dominant legs pre- and post-FR and NFR conditions are shown in Figs. 2,3.

TABLE 1. The effect of foam roller and non-foam roller conditions on MES, AES, ASLR, and AKE values of the dominant leg.

Dependent Variables	Condition	Pre-test Mean ± SD	Post-test Mean ± SD	% Δ Pre–Post, Cohen's *d* (95% CI)	Main Effect: Time			Main Effect: Condition			Interaction: Condition × time		
					F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
MES (N)													
	FR	460.52 ± 43.41	468.0 ± 44.16	+1.62*, 3.05 (2.06 to 4.03)	64.540	<0.001*	0.595	0.167	0.685	0.004	40.449	<0.001*	0.479
	NFR	458.69 ± 40.74	459.56 ± 42.17	+0.18, 0.20 (−0.21 to 0.61)									
AES (N)													
	FR	432.08 ± 40.53	438.26 ± 40.62	+1.43*, 2.37 (1.55 to 3.16)	0.921	0.342	0.021	0.470	0.496	0.011	27.947	<0.001*	0.388
	NFR	431.65 ± 38.04	422.73 ± 39.74	−2.06*, 0.66 (0.20 to 1.11)									
ASLR (°)													
	FR	75.47 ± 6.07	82.78 ± 6.56	+9.68*, 1.89 (1.19 to 2.57)	5.267	0.027*	0.107	14.358	<0.001*	0.246	111.457	<0.001*	0.717
	NFR	74.60 ± 6.51	69.91 ± 6.60	−6.28*, 1.21 (0.66 to 1.75)									
AKE (°)													
	FR	55.52 ± 7.07	61.34 ± 7.07	+10.48*, 2.29 (1.50 to 3.08)	3.153	0.083	0.067	4.730	0.035*	0.097	198.434	<0.001*	0.819
	NFR	55.91 ± 7.73	51.39 ± 8.29	−8.08*, 1.84 (1.16 to 2.51)									

FR, Foam Roller; NFR, Non-foam roller; MES, Maximum eccentric strength; AES, Average eccentric strength; ASLR, Active Straight Leg Raise; AKE, Active Knee Extension; SD, standard deviation; CI, confidence intervals; Δ, percent change (−decrease, +increase); η_p^2*, partial eta squared (effect size); N, Newton; °, degree; *significant differences (*$p \leq 0.05$*).*

TABLE 2. The effect of foam roller and non-foam roller conditions on the non-dominant leg's MES, AES, ASLR, and AKE values.

Dependent Variables	Condition	Pre-test Mean ± SD	Post-test Mean ± SD	% Δ Pre–Post, Cohen's *d* (95% CI)	Main Effect: Time			Main Effect: Condition			Interaction: Condition × time		
					F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
MES (N)													
	FR	457.56 ± 41.29	465.69 ± 40.02	+1.77*, 1.61 (0.98 to 2.23)	19.931	<0.001*	0.312	0.308	0.582	0.007	47.528	<0.001*	0.519
	NFR	455.86 ± 40.06	454.13 ± 40.91	−0.37, 0.37 (−0.05 to 0.79)									
AES (N)													
	FR	430.86 ± 39.62	438.17 ± 38.23	+1.69*, 1.21 (0.66 to 1.75)	0.534	0.393	0.009	0.604	0.441	0.014	17.596	<0.001*	0.286
	NFR	430.56 ± 40.47	420.69 ± 39.25	−2.29*, 0.52 (0.08 to 0.96)									
ASLR (°)													
	FR	75.69 ± 6.71	82.69 ± 7.08	+9.24*, 2.12 (1.37 to 2.86)	5.031	0.030*	0.103	13.851	0.001*	0.239	108.738	<0.001*	0.712
	NFR	74.43 ± 6.29	69.91 ± 6.54	−6.07*, 1.08 (0.56 to 1.59)									
AKE (°)													
	FR	55.60 ± 7.47	60.00 ± 8.10	+7.91*, 0.82 (0.34 to 1.29)	0.045	0.833	0.045	3.827	0.057	0.080	48.217	<0.001*	0.523
	NFR	55.65 ± 7.14	51.52 ± 7.65	−7.42*, 1.63 (0.99 to 2.25)									

FR, Foam Roller; NFR, Non-foam roller; MES, Maximum eccentric strength; AES, Average eccentric strength; ASLR, Active Straight Leg Raise; AKE, Active Knee Extension; SD, standard deviation; CI, confidence intervals; Δ, percent change (−decrease, +increase); η_p^2*, partial eta squared (effect size); N, newton; °, degree, *significant differences (*$p \leq 0.05$*).*

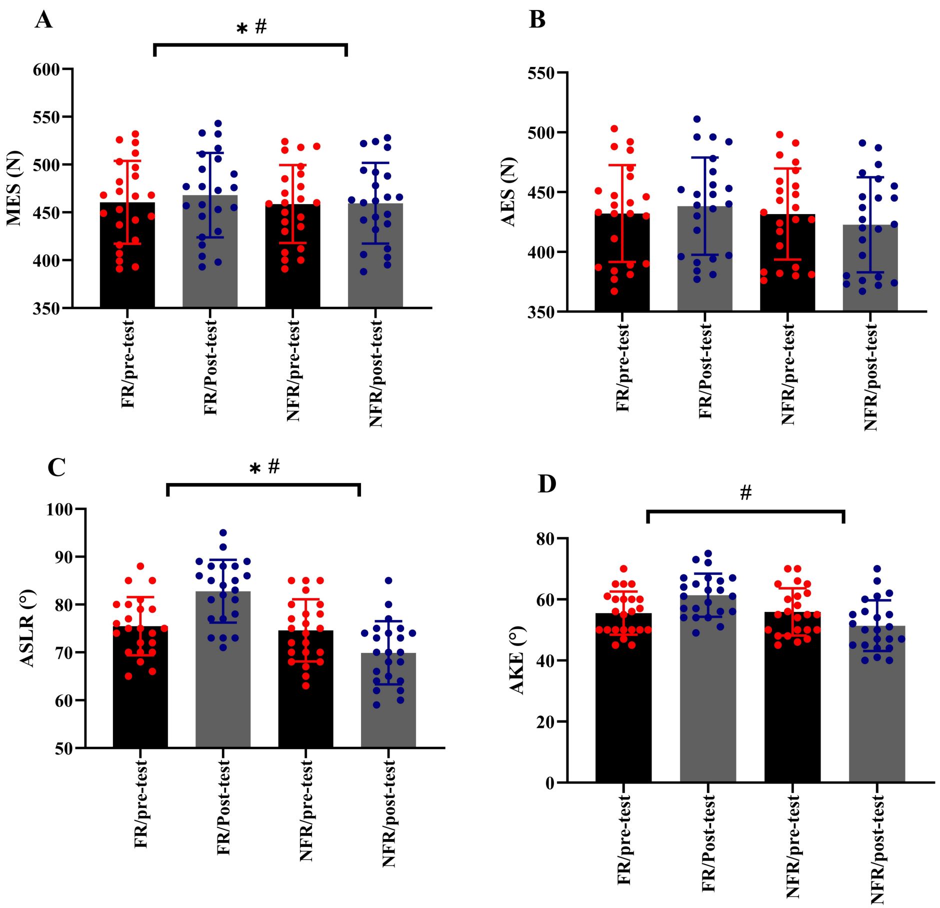

FIGURE 2. Individual changes in muscle strength and flexibility outcomes of the dominant leg before and after acute FR and NFR applications. (A) MES, (B) AES, (C) ASLR, and (D) AKE. *denotes significant differences between pre- and post-test ($p < 0.05$). #denotes significant differences between the conditions (FR versus NFR) ($p < 0.05$). ASLR, Active straight leg raise; AKE, Active Knee Extension; FR, Foam Roller; NFR, Non-foam roller; N, Newton; MES, Maximum eccentric strength; AES, Average eccentric strength.

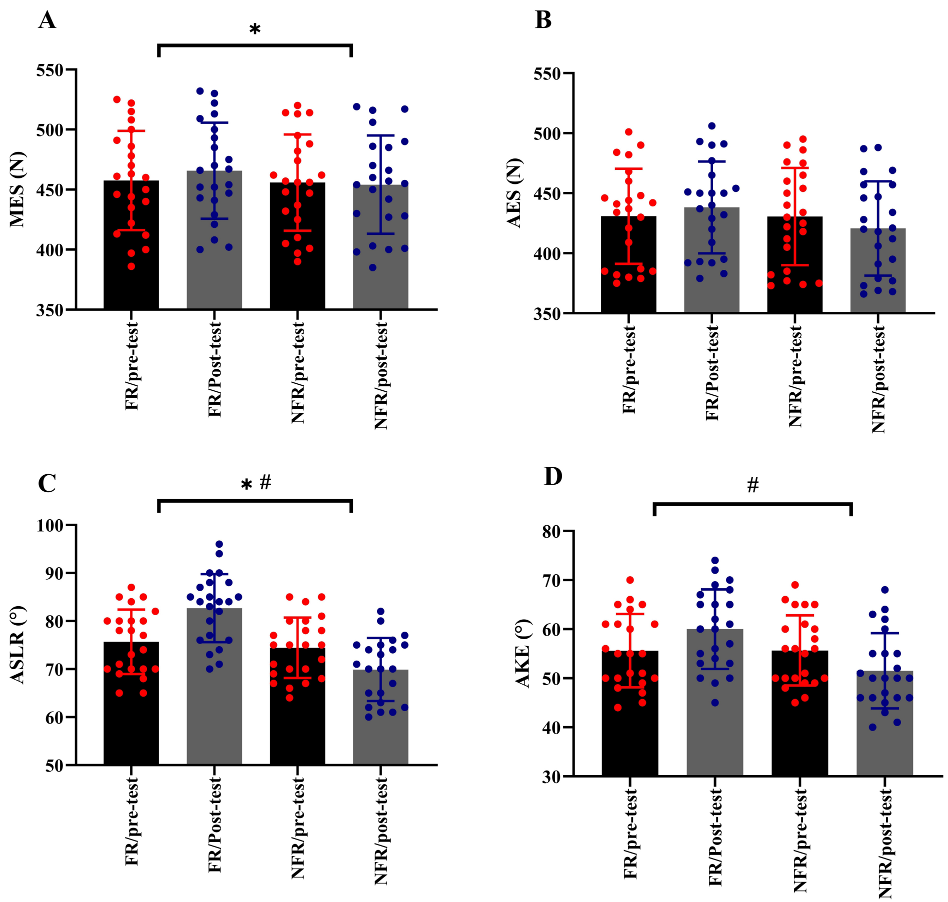

FIGURE 3. Individual changes in muscle strength and flexibility outcomes of the non-dominant leg before and after acute FR and NFR applications. (A) MES, (B) AES, (C) ASLR, and (D) AKE. *denotes significant differences between pre- and post-test ($p < 0.05$). #denotes significant differences between the conditions (FR versus NFR) ($p < 0.05$). ASLR, Active straight leg raise; AKE, Active Knee Extension; FR, Foam Roller; NFR, Non-foam roller; N, Newton; MES, Maximum eccentric strength; AES, Average eccentric strength.

As shown in Table 1, the results of the ANOVA revealed statistically significant condition by time interactions for the dominant leg MES ($p < 0.001$), AES ($p < 0.001$), ASLR ($p < 0.001$), and AKE ($p < 0.001$). The FR condition showed significant improvement pre- to post- for MES ($p < 0.001$), AES ($p < 0.001$), ASLR ($p < 0.001$), and AKE ($p < 0.001$), whilst the NFR condition showed significant decreases for AES ($p = 0.002$), ASLR ($p < 0.001$), and AKE ($p < 0.001$). There was a statistically significant condition effect in ASLR ($F_{(1,44)} = 14.358$, $\eta_p{}^2 = 0.246$, large effect, $p < 0.001$) and AKE variables ($F_{(1,44)} = 4.730$, $\eta_p{}^2 = 0.097$, medium effect, $p = 0.035$). Without distinguishing between pre- and post-test, ASLR ($t = 6.038$, $p < 0.001$, $d = 0.890$ (0.54 to 1.22, 95% CI), moderate effect) and AKE ($t = 4.418$, $p < 0.001$, $d = 0.651$ (0.33 to 0.96), 95% CI, moderate effect) variables were found to be significantly higher in the FR condition compared to the NFR condition. No other significant differences were noted. Fig. 2A–D shows the individual response of each participant for MES, AES, ASLR, and AKE following the FR and NFR conditions in the dominant leg.

As shown in Table 2, the results of the ANOVA revealed a significant condition by time interaction for MES ($F_{(1,44)} = 47.528$, $\eta_p{}^2 = 0.519$, large effect, $p < 0.001$) in the non-dominant leg. Similar outcomes were observed for AES ($F_{(1,44)} = 17.596$, $\eta_p{}^2 = 0.286$, large effect, $p < 0.001$), ASLR ($F_{(1,44)} = 108.738$, $\eta_p{}^2 = 0.712$, large effect, $p < 0.001$), and AKE ($F_{(1,44)} = 48.217$, $\eta_p{}^2 = 0.523$, large effect, $p < 0.001$). The FR condition showed significant improvement pre- to post- for MES ($p < 0.001$), AES ($p < 0.001$), ASLR ($p < 0.001$), and AKE ($p < 0.001$), whilst the NFR condition showed significant decreases for AES ($p = 0.01$), ASLR ($p < 0.001$), and AKE ($p < 0.001$). Regarding the condition effect, significance was only observed for ASLR ($F_{(1,44)} = 13.851$, $\eta_p{}^2 = 0.239$, large effect, $p = 0.001$). Irrespective of pre- and post-test differentiation, the ASLR variable was significantly higher in the FR condition compared to the NFR condition ($t = 6.597$, $p < 0.001$, $d = 0.973$ (0.61 to 1.32, 95% CI), moderate effect). No other noteworthy distinctions between the conditions were identified. Fig. 3A–D shows the individual response of each participant for MES, AES, ASLR, and AKE following the FR and NFR conditions.

4. Discussion

This study investigated the acute effects of FR prior to the assessment of eccentric strength performance of the knee flexors, hip, and knee ROM. Our results demonstrate that a single bout of FR increased the maximum (peak and average) eccentric strength and hip joint mobility (greater flexion) of the dominant and non-dominant legs of rugby sevens players compared to the NFR condition. Although mechanistic contributions to these changes were not explored, the observed performance improvements suggest that FR may be useful prior to strength training to improve in-session strength and mobility or to sports discipline-specific training and competitions. This may also be considered in situations where poor muscle strength and mobility may contribute to the increased possibility of hamstring strain injury.

Eccentric strength of the hamstring muscles has been identified as an important factor in preventing hamstring muscle tears [1]. Given this, it is imperative that practitioners continue to explore methods that improve the strength capacity of this muscle group. The current study data show an acute improvement in eccentric strength of the dominant and non-dominant knee flexors following the completion of SMR using FR (improvement for both limbs; MES (~1.6–1.7%), AES (~1.4–1.7%)). Our results contrast with the earlier systematic review by Wiewelhove *et al.* [19], which reported that the acute use of FR prior to activity or testing resulted in negligible differences in strength performance. Similarly, more recently, Konrad *et al.* [18] reported that an acute bout of FR had no significant effect on strength compared to static or dynamic stretching. However, the same researchers suggest that FR can favour performance improvements for strength when applied for more than 60 seconds. However, only a few studies (~4 studies) included assessed hamstring strength and only seemed to review isometric and isokinetic forms of contraction. The nature of maximal eccentric contractions likely differs from these tasks due to the known differences in motor unit activation and greater engagement of passive structural elements in force production [37]. Furthermore, as the present study employed an inactive NFR condition (resting quietly) and saw the completion of three sets of 30-second FR, the effects of FR on knee flexor strength (MES and AES) may be more pronounced than in the studies by Konrad *et al.* [18] and Wiewelhove *et al.* [19]. Nonetheless, coaches and athletes may wish to consider the inclusion of SMR using FR as part of a warm-up/preparation period in place of rest periods (*i.e.*, whilst waiting in the changing rooms prior to a match or sitting during half-time).

Additionally, whilst the current study reported an acute increase in eccentric knee flexor strength, it is unclear what this could mean for other populations and contexts, such as hamstring injury reduction, which was beyond the scope of this study. Additionally, a recommendation from this study is that acute FR should not be used in isolation, as regular strength training is vital to induce chronic adaptations in strength capacity. However, an acute FR-based intervention may be considered a potential ergogenic "method" used during the pre-training/warm-up period to facilitate training performance. For example, FR prior to posterior chain or lower body compound exercises may allow slightly greater training loads and mechanical strain to be developed in maximal eccentric exercises or other compound movements. Although negligible additional adaptations may be expected in a single session, repeated performance may help facilitate greater neuromuscular improvements via greater force output during training [33]. Indeed, volume-load is considered an important driver of hypertrophic and neuromuscular adaptations [38]. However, the present authors acknowledge that this was not an aim of the current investigation, which should be explored in future prospective studies.

Using rolling-based SMR prior to activity is reported to improve flexibility (+4.0%, $g = 0.34$) [19]. When utilizing a cylindrical foam roller, similar to that used in the present study, a meta-analysis by Wiewelhove *et al.* [19] reported a 5.0% ($g = 0.32$) improvement in ROM. The current findings report that flexibility in the dominant and non-dominant leg of rugby sevens players improved following the use of FR compared to the NFR condition. Specifically, the ASLR of the dominant and non-dominant legs improved by ~9–10%. For AKE, ~8–10% improvements in the dominant and non-dominant limbs were also observed, respectively. In both legs, ROM did not improve following the NFR condition. Some authors suggest that greater stretch tolerance [18] or a decrease in muscle stiffness may contribute to FR-induced improvements in ROM [39]. That being said, decreased muscle stiffness is considered problematic for the rate of force development and overall force production [18, 40], which, in light of the greater eccentric strength capacity observed in the current study, could suggest that decreased tissue stiffness did not occur in this athlete cohort. Whilst encouraging, it is also unclear whether these improvements in ROM persist beyond the immediate testing period. Schleip *et al.* [41] suggest that changes to ROM from the thixotropic effects of FR dissipate within minutes of applying pressure or heat to the targeted muscles. Thus, the results of the current investigation should not be utilised to infer improved ROM beyond the assessment period. Athletes and coaches should ensure that an appropriate flexibility program is included in conjunction with SMR and FR practices for improved ROM and joint flexibility.

This study has several limitations. First, including a passive NFR condition makes it difficult to determine the magnitude of the effect observed with FR compared to other active strategies (*e.g.*, dynamic stretching activities). Nonetheless, the crossover design of the study indicates a benefit of FR to eccentric strength and ROM amongst these rugby sevens players. Second, although performance changes were observed, it is unclear how long such effects may last, as this may have practical implications for timing and use in warm-up or game preparation routines. Third, in our study, the absence of a force plate during the implementation of FR may be considered a limitation. Given the potential impact of participants' body weight on the compressive forces induced by FR [42], incorporating force plates into the FR application would be essential for more accurate measurement of these forces and facilitation of inter-participant comparisons of variations [16]. Lastly, although beyond the scope of this study, the potential physiological and neuromuscular mechanisms that may underpin these acute performance changes were not explored. However, it seems plausible that altered proprio- and pain-perception and improved muscle fibre recruitment via altered muscle and tendinous afferent activity, especially if combined with vibration, may contribute to acute FR-induced changes in the neuromuscular function [14, 23]. Conversely, changes in muscle temperature, which are known to impact muscle force and power output positively [43], are not observed following the 60 seconds of foam rolling [44] and, hence, are unlikely to contribute to the observed performance improvements.

5. Conclusions

The acute application of SMR using FR resulted in an acute increase in the eccentric strength capacity of the knee flexors and improved ROM in a sample of rugby sevens players' dominant and non-dominant legs. The findings of this investigation contribute to the expanding body of evidence to support the application of SMR using FR in athlete warm-up routines (prior to training or match situations). However, the present study did not investigate the duration of these effects or the underlying physiological mechanisms. As such, athletes and coaches should consider the potential additive effects of acute and chronic SMR exposure using FR prior to exercise. Future investigations are warranted to identify the utility of these methods to improve hamstring strength and potentially aid in attenuating hamstring strain injury rates in this population or other similar sporting contexts.

AVAILABILITY OF DATA AND MATERIALS

Data are available for research purposes upon reasonable request to the corresponding author.

AUTHOR CONTRIBUTIONS

İS—designed the research study. İS and HİC—wrote the manuscript. İS, RO and HİC—performed the research. HİC and KÖ—analyzed the data. İS, HİC, KÖ, RO, RM and NLB—critically revised the manuscript and approved the final manuscript for publication. All authors contributed to editorial changes in the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was conducted according to the Declaration of Helsinki guidelines and was approved by the Ethical Committee for Scientific Research of Trakya University Faculty of Medicine (Decision no: 18/20, Date: 06 November 2019). Informed written consent was obtained from all participants who agreed to participate in this study and met the inclusion criteria.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. Rafael Oliveira is serving as one of the Editorial Board members of this journal. We declare that Rafael Oliveira had no involvement in the peer review of this article and has no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to DM.

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