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Research article

Acute Effects of Dynamic Stretching Followed by Vibration Foam Rolling on Sports Performance of Badminton Athletes

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Abstract

Dynamic stretching (DS) is performed to increase sports performance and is also used primarily for transiently increasing range of motion (ROM). Recently, vibration foam rolling (VFR) has emerged. Its underlying concept is that it combines foam rolling techniques with local vibration to improve ROM and muscular activation concurrently. This crossover study investigated the effects of DS or DS + VFR) during warm-ups on flexibility, muscle stiffness, power, and agility of the lower limbs in badminton athletes. Forty badminton players performed DS or DS + VFR as warm-up exercises on two occasions in a randomized order. The target muscle groups were the bilateral shoulder, anterior and posterior thigh, posterior calf, and lower back. Main outcome measures: The primary outcome was knee range of motion (ROM), and the secondary outcomes were muscle stiffness, lower limb power (countermovement jump [CMJ]), and agility. Results indicated that the protocols improved performance. DS increased knee flexion ROM (% change = 1.92, ES = 0.3, $p = 0.033$), CMJ height (% change = 5.04, ES = 0.2, $p = 0.004$), and agility (% change = -4.97, ES = 0.4, $p < 0.001$) but increased quadriceps muscle stiffness (% change = 3.74, ES = 0.3, $p = 0.001$) and increased gastrocnemius muscle stiffness (% change = 10.39, ES = 0.5, $p = 0.001$). DS + VFR increased knee extension ROM (% change =2.87, ES = 0.4, $p = 0.003$), reduced quadriceps muscle stiffness (% change = -2.79, ES = 0.3, $p = 0.017$), CMJ height (% change = 2.41, ES = 0.1, $p = 0.037$), and agility (% change = -4.74, ES = 0.2, $p < 0.001$). DS + VFR was not significantly superior to DS, except for muscle stiffness reduction. Taken together, we suggest that practitioners consider DS as a first line of warm-up exercise to increase ROM, CMJ height, and agility in athletes. Moreover, the addition of VFR to DS results in a large reduction of muscle stiffness, potentially reducing the risk of sports injury. Athletes, coaches and athletic professionals may consider them when selecting effective warm-up practices to augment athletic performance.

Key words: Warm up exercise, foam rolling, athletic performance, sports, vibration therapy

Introduction

Badminton is a popular sport and one of the fastest racquet sports (Lees, 2003). The lunge step is one of the most frequently performed movements in badminton, accounting for approximately 15% of the total movements in a game (Kuntze et al., 2010; Mei et al., 2017). Performing a good lunge step is usually associated with high flexibility. In addition, badminton players must react by moving rapidly with powerful jumps and agile footwork throughout a game. Players must repeat actions quickly with high speed and intensity. Therefore, players need excellent joint range of motion (ROM), power, and agility (Tiwari et al., 2011; Wong et al., 2019).

Warm-up exercise is critical prior to participation in sports. It improves performance and may avoid injury (Woods et al., 2007). Muscle strain injuries usually occur during movements that involve rapid acceleration/deceleration and sprinting (Opar et al., 2012). Dynamic stretching (DS) is the most commonly suggested warm-up protocol (Turki et al., 2019). The DS technique involves a stretch to lengthen the muscle, and it is performed by moving parts of the body and gradually increasing reach and speed of movement (Behm and Chaouachi, 2011). It often mimics movement patterns performed during subsequent exercise. DS provides a more sport-specific warm-up exercise, and as a precursor, it increases body temperature, improves nerve conduction, and increases sports performance (i.e., jump height, sprint speed, and agility) (Chaouachi et al., 2010; Opplert and Babault, 2018; Perrier et al., 2011). However, reports regarding the effect of DS on muscle stiffness are conflicting, indicating that DS may cause increased or reduced muscle stiffness (Chen et al., 2018; Iwata et al., 2019; Pamboris et al., 2018).

Vibration foam rolling (VFR) combines a foam roller with vibration; the roller serves as a foam rolling tool that targets a particular muscle group. It has been suggested as an alternative warm-up method (Lee et al., 2018; Lyu et al., 2020). Beneficial outcomes of VFR include remobilizing soft-tissue compliance to enable longer muscle length and increasing blood flow and circulation to soft tissues conducting rolling on the soft tissue (MacDonald et al., 2013). Concurrently, the additional transmission of mechanical oscillations to the target muscle may increase the number of motor units recruited (Cochrane, 2011). However, few studies have investigated the effectiveness of VFR, particularly for athletic performance. Thus far, studies have focused on ROM (Cheatham et al., 2019; Garcia-Gutierrez et al., 2018; Lee et al., 2018; Lim et al., 2019; Lim and Park, 2019; Lyu et al., 2020), pressure pain threshold (Cheatham et al., 2019; Romero-Moraleda et al., 2019), electromyography activity (Lim et al., 2019), isokinetic muscle strength (Lee et al., 2018; Lyu et al., 2020), perceived joint stability (De Benito et al., 2019), dynamic balance (Lee et al., 2018), and vertical jump (Lim and Park,

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2019). However, these studies have focused on the knee or ankle musculatures rather than combined effects on the whole body—specifically, when the technique targets upper and lower extremities and the lower back. Furthermore, the aforementioned VFR studies were conducted in healthy participants or participants involved in recreational activities rather than in athletes. Scientific evidence is inadequate; little is known about sports performance following the use of VFR as a warm-up regime.

The most beneficial warm-up protocol remains uncertain, particularly for combination warm-up exercises. Moreover, no study has examined the effects of DS combined with VFR on badminton athletes. Studying the effects of combination warm-ups on sports performance can provide evidence that can help athletes, coaches, and clinical professionals to decide whether to add the VFR protocol to DS. Accordingly, this study compared the acute effects of DS as well as DS followed by VFR during warm-up on flexibility, muscle stiffness, power, and agility in young adults. The primary outcome was knee ROM. The secondary outcomes were muscle stiffness, countermovement jump (CMJ), and agility. We hypothesized that DS as warm-up exercise can not only increase ROM, CMJ height, and agility, but increase muscle stiffness. In addition, VFR can offset muscle stiffness.

Methods

Participants

The study protocol was approved by the Yuan's General Hospital Institutional Review Board (Approval Number: 20180209B) and Human Research Ethics Committee in the spirit of the Helsinki Declaration. Participants were informed of the benefits and risks of the study, and they signed an informed consent form before participating. Totally, 40 college badminton players (25 male and 15 female students) participated in two trials: (1) DS and (2) DS followed by VFR (Figure 1). Characteristics of participants are presented in Table 1. The inclusion criteria were as follows: membership in a school badminton team, 20–30 years of age, and no incidence of musculoskeletal disorder in the preceding 6 months. The exclusion criteria were as follows: musculoskeletal disease or neurological impairment, cardiovascular or respiratory disease, irradiation pain/radiation pain transferred to the lower extremities, previous surgery, and taking medication (e.g., anti-inflammatory or muscle relaxants) during the preceding 6 months.

Study procedures

This study was a crossover study with a within-subject design. Tests were performed in an indoor badminton gym at National Sun Yat-sen University. Each participant did the exercises at approximately the same time of day (18:00–20:00). Before the assessment session, participants performed a familiarization session, in which they were instructed by a certified physiotherapist on how to perform DS and VFR exercise regimes. During this orientation, participants were familiarized with the procedures and practiced with the assessment tools and equipment. Participants were asked to maintain normal training programs but to avoid vigorous exercise at least 24 hours before the tests. Each participant performed the two protocols on separate occasions in a randomized order, with an interval of 48 hours (Su et al., 2017). Participants were individually guided by a certified physical therapist for performing both DS and VFR. The target muscle groups were the bilateral shoulder, anterior thigh, posterior thigh, posterior calf, and lower back. Participants performed the pretests in the following order: muscle stiffness, flexibility, CMJ, and agility tests. After completion of pretests, participants did the warm-up exercise (DS or DS + VFR) in a counterbalanced order. Posttest measurements were conducted in the same order as pretest measurements.

Table 1. **Characteristics of participants Values are mean (standard deviation)**

	Total (n = 40)	Male (n = 25)	Female (n = 15)
Age (year)	21.4 (1.5)	21.2 (1.5)	21.6 (1.6)
Height (m)	1.70 (0.10)	1.74 (0.07)	1.62 (0.07)
Body weight (kg)	64.8 (10.6)	69.5 (9.8)	56.8 (6.2)
BMI (kg/m^2)	22.4 (2.5)	22.8 (2.7)	21.8 (1.9)
Badminton experience (y)	7.1 (3.4)	7.1 (3.3)	7.1 (3.8)

Outcome measures

Before data collection, examiners were well-trained in conducting the flexibility, muscle stiffness, CMJ, and agility tests.

Primary outcome

The primary outcome was knee ROM. The knee flexion ROM of participants was measured using Ely's test, which is also used for testing quadriceps femoris muscle flexibility. This test was shown to have an intraclass correlation coefficient (ICC) of 0.91, which represents high reliability (Piva et al., 2006). With participants in the prone position, the examiner aligned the plastic goniometer with the axis of the knee joint; the stationary arm represents the greater trochanter of the femur, and the passively moving arm represents the lateral malleolus of the ankle. When the hip flexes as the knee is flexed, the pelvis should remain on the floor, and compensation by hyper-lordosis of the lumbar spine is avoided. The outcome measured was rectus femoris tightness by the same researcher, which was used to determine the termination of knee flexion ROM. The researcher subjectively perceived to inability to push the leg farther without any body compensation and measured the ROM. The average measurement of two trials was recorded. In this study, the ICC was 0.821, suggesting high test–retest reliability. In addition, the minimum detectable change (MDC) value was calculated to be 2.2°, corresponding to a standard error of measurement (SEM) of 0.989.

The knee extension ROM of participants was measured using the popliteus angle test, which is also used to measure hamstring flexibility. This test was shown to have an ICC of 0.90, representing high reliability (Youdas et al., 2005). With participants in the supine position, the examiner aligned the plastic goniometer with the axis of the knee joint. The stationary arm represents the vertical ground, and the moving arm represents the lateral malleolus of the ankle. The knee was actively moved upward until the participant felt some tightness but not pain, and the angle between the thigh and calf was measured. The average measurement of two trials was recorded. The ICC was 0.99, suggesting excellent test–retest reliability. The MDC value was calculated to be 2.334°, corresponding to an SEM of 0.842.

Secondary outcomes

Secondary outcomes included muscle stiffness test, CMJ test, and agility test.

Regarding muscle stiffness test, we used a handheld myometer (Myoton® PRO; Myoton AS, Tallinn, Estonia) to measure muscle stiffness. The myometer was shown to have high to excellent reliability (Aird et al., 2012). Myometer measurements were taken by holding the device above the skin overlaying the target muscle assessment site. Once the desired position was achieved, mechanical impact (duration: 15 milliseconds; force: 0.4 N) was delivered to the muscle using a mechanical probe, causing the tissue to briefly deform (Pruyn et al., 2016). The target muscle groups included the middle point of the quadriceps and gastrocnemius. Stiffness was calculated as the ratio between the force applied and muscle deformation (Ditroilo et al., 2011). The average measurement of two trials was recorded. The gastrocnemius ICC was 0.910, and the quadriceps ICC was 0.983, suggesting good to excellent test–retest reliability.

Regarding CMJ test, My jump is a software application available on Appstore (Apple Inc., USA), and it is used to measure CMJ height through frame-by-frame analysis. It has excellent reliability (ICC = 0.997) (Balsalobre-Fernández et al., 2015). The in-app settings allow slow-motion playback for easy identification of the video frames in which jump take-off and landing occur (Stanton et al., 2015). Participants made vertical jumps, with feet shoulder-width apart and toes aligned behind a white line. Participants placed their hands on the hips and kept their knees straight during flight while jumping as high as possible. Three jumps were recorded, with a resting period of 1 minute. The highest height was selected for analysis. The ICC was 0.959, suggesting excellent test–retest reliability. Regarding agility test, FITLIGHT TrainerTM (FITLIGHT Sports Corp., Aurora, ON, Canada) was adopted to measure agility (McMillian et al., 2006a). It is a wireless reaction training system consisting of LED-powered lights controlled by a tablet. The lights can be deactivated by touch. During the test, participants used their dominant hand to touch a red light on the floor until the light deactivated. The test area was the size of a badminton half-court, with eight lights placed at corners and half lines (Figure 1). After touching a light, the player returned to the center of the area. Participants extinguished the eight lights in order as quickly as possible. The completion time was recorded. The ICC was 0.969, suggesting excellent test–retest reliability.

DS exercises

The DS protocol comprised eight movements through the active ROM of the trunk and upper and lower extremities, involved moving parts of the body, and gradually increasing reach, speed of movement, or both. The exercises are detailed in Figure 2. They consisted of controlled leg and arm swings to the limits of the participant's ROM. The exercises were performed from one sideline to the opposite sideline of a badminton court and back (total distance: 18 m), with 10-second intervals (Chatzopoulos et al., 2014).

VFR exercises

Participants were individually instructed by a physical therapist to use a vibrating roller (dimensions: 36 × 20 × 15 cm3; weight: 1.8 kg) that included a vibration generating motor (frequency: 28 Hz) enclosed by a polypropylene foam outer shell (Vyper, Hyperice, Irvine, CA, USA) Participants were asked to put as much body mass as was tolerable on the roller. They performed active and smooth rolling back and forth on the target muscle groups (Figure 2). Each muscle group received 20 seconds of vibration. The duration of single roll was 2 seconds. The exercises (except for that for the lower back) were executed on the opposite side (Figure 3).

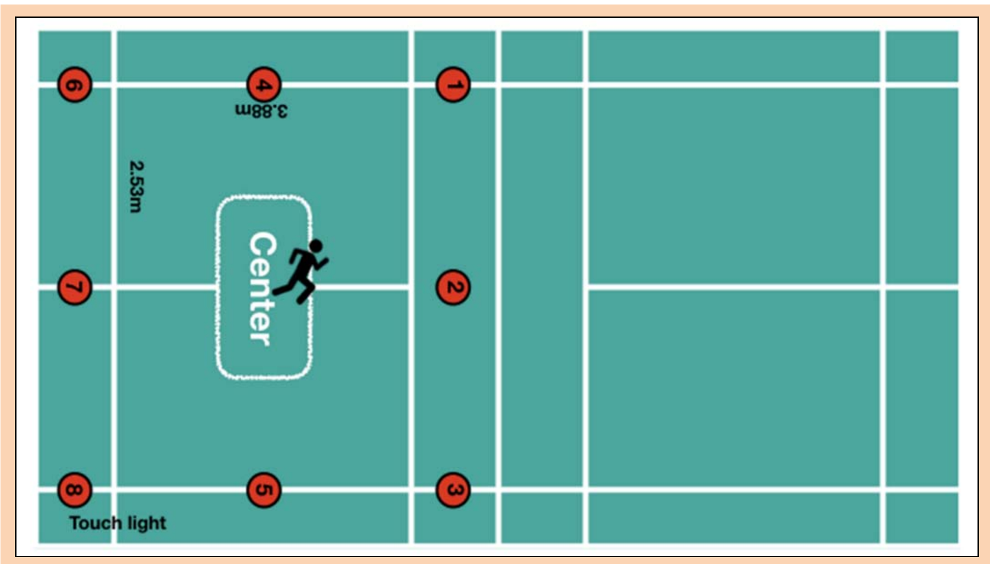
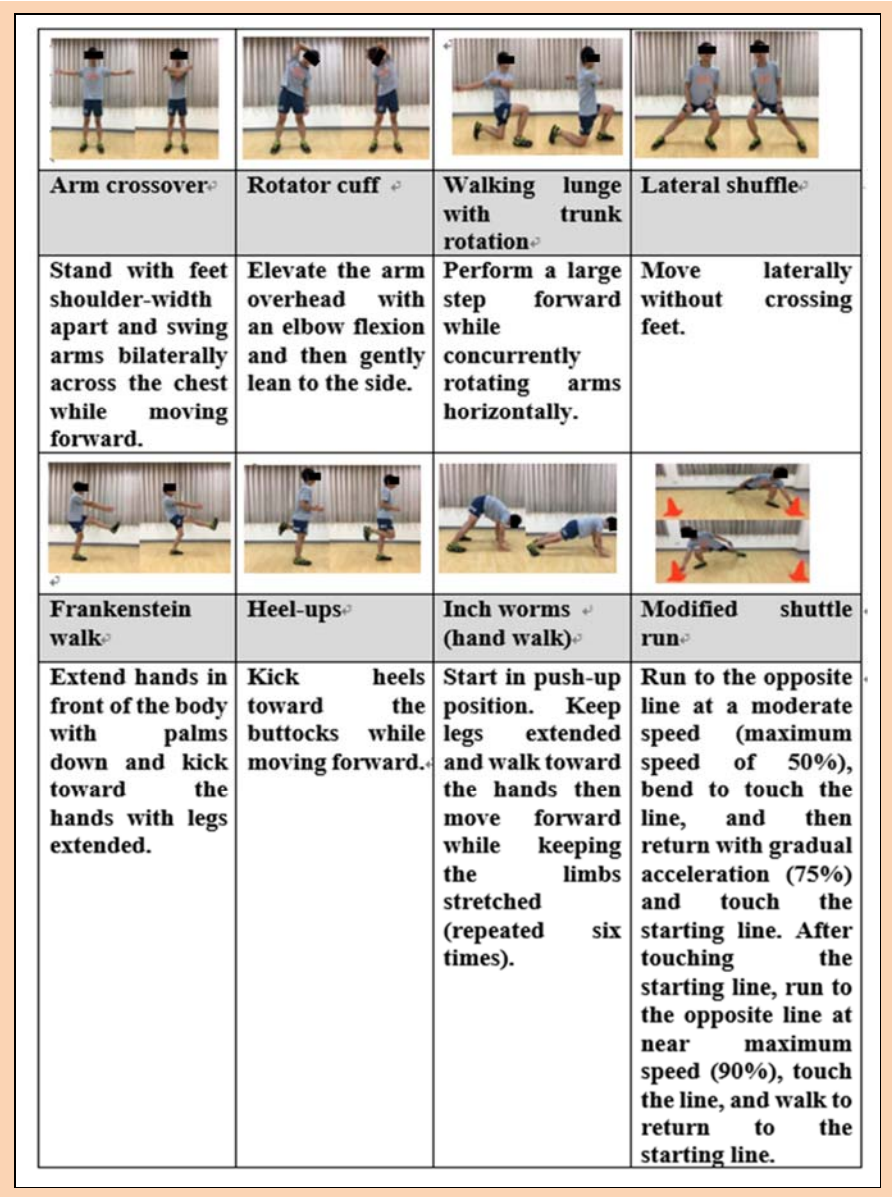


Figure 1. Experimental court for the badminton agility test. The numbers ① to ⑧ represent light placement.



Arm crossover	Rotator cuff	Walking lunge with trunk rotation	Lateral shuffle
Stand with feet shoulder-width apart and swing arms bilaterally across the chest while moving forward.	Elevate the arm overhead with an elbow flexion and then gently lean to the side.	Perform a large step forward while concurrently rotating arms horizontally.	Move laterally without crossing feet.
Frankenstein walk	Heel-ups	Inch worms (hand walk)	Modified shuttle run
Extend hands in front of the body with palms down and kick toward the hands with legs extended.	Kick heels toward the buttocks while moving forward.	Start in push-up position. Keep legs extended and walk toward the hands then move forward while keeping the limbs stretched (repeated six times).	Run to the opposite line at a moderate speed (maximum speed of 50%), bend to touch the line, and then return with gradual acceleration (75%) and touch the starting line. After touching the starting line, run to the opposite line at near maximum speed (90%), touch the line, and walk to return to the starting line.

Figure 2. **Dynamic stretching protocols.**

Statistical Analyses

An a priori sample size calculation based on anticipated differences in knee extension ROM as the primary outcome was conducted using an anticipated difference of 4° with a standard deviation of 6° between pretest and postintervention in the DS + VFR group. The calculation, with an alpha level of 0.01 and a desired statistical power of 80%, was conducted using G*Power (Faul et al., 2007). The minimum sample size was 30. To increase statistical power, we enrolled 40 participants.

Statistical analyses were performed using SPSS version 20.0 (Chicago, IL, USA). Data are expressed as mean and standard deviation and tested for normality (Shapiro–Wilk's test, $p > 0.05$), and homogeneity of variance was confirmed using Levene's test. If results of the Mauchly's sphericity test indicated the sphericity assumption was violated, the Greenhouse–Geisser adjustment was adopted to correct the degrees of freedom. A 2 (condition: DS vs. DS + VFR) × 2 (time: pretest vs. posttest) repeated measures analysis of variance was conducted to test the effects of different conditions on dependent variables. If a significant group × time interaction was identified, follow-up analysis was conducted using a t test to determine the effect. Paired t tests within each group were conducted to determine significant main effects of the intervention. Furthermore, changes in values from pretest to posttest were calculated and analyzed using a paired t test. The effect size (Cohen's d) was calculated to show the magnitude of the effects ($d = M1 - M2 / \sigma pooled$) for each group. Significance level (α) was set at 0.05.

To confirm that ROM measurement was greater than measurement error, the MDC value was calculated as follows: SEM was initially calculated using the formula $SEM = SD \times \sqrt{(1-ICC)}$, where SD is the standard deviation of scores from the first test, and ICC is the test–retest ICC. Subsequently, MDC was calculated using the following formula: $1.96 \times \sqrt{2} \times SEM$ (Chen et al., 2019).

Quadriceps	**Maintain a prone position on the elbows with the right knee bending and with the roller under the anterior thigh; roll from the groin to the top of the knee back and forth for 20 seconds and then change to the other side.**	
Hamstrings	**The roller is under the right posterior thigh and the left leg supports with the foot on the ground. Roll from near the gluteal line down to the knee back and forth for 20 seconds and then change to the other side.**	
Calf	**The roller is under the posterior right lower leg near the knee with the left leg crossed onto the right. Roll a round trip of the calf for 20 seconds and then change to the other side.**	
Rotator cuff	**Roll the roller from the outside of the shoulder to the upper rear arm back and forth for 20 seconds and then change to the other side.**	
Lower back	**After bending the knees in the supine position, roll the roller in a round trip as far as the lower back and roll back and forth for 20 seconds.**	

Figure 3. Vibration rolling protocols.

Table 2. Outcomes for dynamic stretching with or without vibration foam rolling

Parameters		DS						DS + VFR					
		Pre	Post	Change	% Change	Effect size	p	Pre	Post	Change	% Change	Effect size	p
Knee ROM	Flexion (degrees)	124.1 (7.2)	126.4 (7.4)*	2.38 (6.8)	1.92	0.3	0.033	122.8 (8.1)	123.2 (10.3)	0.4 (6.9)	0.33	0.1	0.692
	Extension (degrees)	143.0 (10.7)	146.8 (12.5)*	3.74 (9.7)	2.62	0.3	0.019	142.7 (9.4)	146.8 (10.5)*	4.1 (8.0)	2.87	0.4	0.003
Muscle stiffness	Quadriceps	258.9 (27.6)	268.5 (33.7)*	9.7 (16.5)	3.74	0.3	0.001	265.6 (23.7)	258.2 (32.1)*	-7.4 (18.7)†	-2.79	0.3	0.017
	Gastrocnemius	329.3 (61.7)	363.5 (70.2)*	34.2 (59.2)	10.39	0.5	0.001	314.6 (39.8)	314.6 (33.9)	0.1 (36.8)†	0.03	0	0.993
CMJ	Height (cm)	37.7 (9.5)	39.6 (10.5)*	1.9 (3.9)	5.04	0.2	0.004	37.4 (9.3)	38.2 (9.6)*	0.9 (2.5)	2.41	0.1	0.037
Agility	Total time (s)	18.1 (1.7)	17.3 (1.9)*	-0.9 (1.0)	-4.97	0.4	<0.001	19.0 (1.8)	18.7 (0.6)*	-0.9 (0.7)	-4.74	0.2	<0.001

* Significant difference ($p < 0.05$) compared with the pretest results. †Significant difference ($p < 0.05$) compared with DS.

Results

All outcomes are displayed in Table 2.

Knee ROM outcomes

For the knee flexion ROM, condition × time interactions (p = 0.25) were not significant. However, significant main effects were observed for condition (p = 0.002) and time (p = 0.051). Compared with the pretest results, according to the post hoc test results, significant improvement in Ely's test was found in the DS group (% change = 1.92, ES = 0.3, p = 0.033), but no significant improvement was identified in the DS+VFR group (% change = 0.33, ES = 0.1, p = 0.629).

For the knee extension ROM test, the condition × time interaction (p = 0.88) and main effect of condition (p = 0.89) were not significant. However, a significant main effect of time (p < 0.001) was observed, indicating a difference between pre- and posttest knee extension ROM. Compared with the pretest results, according to the post hoc test results, both the DS group (% change = 2.62, ES = 0.3, p = 0.019) and DS + VFR group (% change = 2.87, ES

= 0.3, p = 0.003) exhibited significant improvement in the popliteus angle test.

Muscle stiffness outcomes

For quadriceps muscle stiffness, the condition × time interaction was significant. The DS group demonstrated significantly increased stiffness compared with the DS + VFR group (p < 0.001). We further analyzed the simple main effect. Compared with the pretest results, the DS group exhibited a significant increase in quadriceps stiffness (% change = 3.74, ES = 0.3, p = 0.001), but the DS + VFR group showed decreased stiffness (% change = -2.79, ES = 0.3, p = 0.017).

For gastrocnemius stiffness, the condition × time interaction was significant. The DS group demonstrated significantly increased stiffness compared with the DS + VFR group (p = 0.001). We analyzed the simple main effect. Compared with the pretest results, according to the post hoc test results, the DS group exhibited a significant increase in gastrocnemius stiffness (% change = 10.39, ES = 0.5, p = 0.001), but the DS + VFR group did not (% change = 0.03, ES = 0, p = 0.993).

CMJ outcomes

For the CMJ test, the condition × time interaction (p = 0.192) and the main effect of condition (p = 0.089) were not significant. However, the main effect of time was significant (p < 0.001). Compared with the pretest results, according to the post hoc test results, participants exhibited significant improvement in CMJ height after the DS (% change = 5.04, ES = 0.2, p = 0.004) and DS + VFR (% change = 2.41, ES = 0.1, p = 0.037) interventions.

Agility outcomes

For the agility test, the condition × time interaction in total time (p = 0.625) was not significant. However, the main effect of the condition (p < 0.001) and the time effect were significant (p < 0.001). Compared with the pretest results, according to the post hoc test results, participants exhibited significant improvement in agility after the DS (% change = -4.97, ES = 0.4, p < 0.001) and DS + VFR (% change = -4.74, ES = 0.2, p < 0.001) interventions.

Discussion

This is the first study to investigate the acute effects of DS + VFR as a whole-body warm-up protocol including the upper and lower limbs and trunk muscles in badminton athletes. Most research on VFR has focused on single joints of the body, such as the knee (Cheatham et al., 2019; De Benito et al., 2019; Lee et al., 2018; Lim et al., 2019; Lim and Park, 2019; Romero-Moraleda et al., 2019) or ankle (Garcia-Gutierrez et al., 2018; Lyu et al., 2020). The findings indicated that DS with or without VFR significantly increased knee ROM, CMJ height, and agility; however, DS increased thigh and calf muscle stiffness. DS followed by VFR did not have synergistic effects.

DS integrates controlled movement through the active ROM of a joint and includes change-of-direction movements. The current results for DS confirmed positive effects, consistent with previous findings regarding flexibility (Paradisis et al., 2014; Ryan et al., 2014a; Su et al., 2017), jump height (Fletcher, 2010; Ryan et al., 2014a; Turki et al., 2011), and agility (Chaouachi et al., 2010; McMillian et al., 2006b). The improved sports performance may be because DS increases muscle temperature or causes rearrangement/slipping of collagen fibers to regain flexibility (Herda et al., 2013; Nordez et al., 2009). In addition, DS provides a preload stimulus before an actual activity as post-activation potentiation. This generates increased phosphorylation of myosin light chains and motor neuron excitability (Hodgson et al., 2005); thus, athletic performance can be augmented.

An unanticipated finding was that the effects of DS + VFR were not superior to those of DS alone on flexibility, lower limb power, or agility in the athletes. Possible reasons are as follows: (1) optimal protocols for VFR (i.e., frequency, duration, vibration setting, and target muscles) have not been established; (2) the selection of participants (students, recreationally active adults, and athletes) differed among studies; and (3) outcomes of laboratory measures (i.e., isokinetic dynamometer) may differ from those of practical field tests. In the present study in badminton athletes, for the practical use of VFR, we selected the following protocol: 28 Hz, 20 seconds × 1 set on the bilateral rotator cuff, quadriceps, hamstrings, posterior gastrocnemius, and lower back muscles). Moreover, we used field assessments for power and agility. In a laboratory assessment, Lyu et al. indicated that the use of VFR (28 Hz, 30 seconds × 3 sets on bilateral gastrocnemius muscles) in recreationally active adults significantly improved ankle plantar flexor peak torque (Lyu et al., 2020). Lee et al. determined that the use of VFR (28 Hz, 30 seconds × 3 sets on bilateral quadriceps and hamstring muscles) significantly increased quadriceps isokinetic muscle strength (Lee et al., 2018). However, García-Gutiérrez et al. demonstrated that use of VFR (49 Hz, 20 seconds × 3 sets on bilateral gastrocnemius muscles) in undergraduate students did not significantly increase ankle muscle maximal voluntary isometric contraction. Sağiroğlui et al. found no significant difference in jump height after the use of VFR (38 Hz, 30 seconds × 2 sets on hamstrings, quadriceps, gluteals, and gastrocnemius) in well-trained male soccer players. Lim et al. indicated that the use of VFR (38 Hz, 60 seconds × 5 sets on bilateral hamstrings) in college students caused no significant improvement in vertical jump (Lim and Park, 2019). Future studies should investigate optimal warm-up protocols for different populations and validate whether the beneficial effects identified in laboratory assessments can be translated to field applications.

Muscle stiffness is one of the main components of athletic performance (Miyamoto et al., 2017). Research has indicated that performing DS protocols after repeated muscle contractions may impair performance due to muscle fatigue (Costa et al., 2014; Ryan et al., 2014b) and may cause increased muscle stiffness (Pamboris et al., 2018). Adenosine triphosphate (ATP) loss may be a reason for increased muscle stiffness (Spudich, 2001), because ATP is required to detach myosin from actin during muscle contraction cycles. With ATP loss during repeated exercise, this detachment ability declines, and the two proteins remain connected (Spudich, 2001). However, in this study, DS followed by VFR significantly decreased muscle stiffness, potentially reducing the risk of sports injury (e.g., muscle strain). We speculate that the following mechanism underlies the reduced muscle stiffness after VFR: rollers may modulate myofascial tone through changes in thixotropic properties, blood flow, and fascial hydration, affecting tissue stiffness (Behm and Wilke, 2019). In addition to these effects, the transmission of additional mechanical oscillations to the target muscles affects several physiological systems, such as joint mechanoreceptors (e.g., the Golgi tendon organ) (Lee et al., 2018; Moezy et al., 2008). Some limitations of the study warrant mention. First, only DS and combined DS and VFR warm-ups were conducted and compared and not static stretching or VFR alone. Different combinations may have other effects. Second, whether VFR prior to DS is more effective must be verified in the future. Third, the density of outer foam layers of rollers can differ and may affect outcomes (Cheatham and Stull, 2019).

Conclusion

The findings suggest that DS with or without additional VFR as a warm-up protocol significantly improves ROM, CMJ height, and agility. In addition, VFR considerately offset muscle stiffness compared with DS alone. Therefore, we suggest that practitioners consider DS as a first line of warm-up exercise to increase ROM, CMJ height, and agility in badminton athletes. Moreover, the addition of VFR to DS results in a large reduction of muscle stiffness, which may be advantageous for improving exercise performance and reducing the risk of injury. The findings may also be useful in athletic practice settings. Athletes, coaches and athletic professionals may consider them when selecting effective warm-up practices to augment athletic performance.

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Key points

- Dynamic stretching (DS) with or without vibration foam rolling (VFR) significantly increased knee range of motion, jump height, and agility
- However, DS increased thigh and calf muscle stiffness.
- DS followed by VFR significantly decreased muscle stiffness, potentially reducing the risk of sports injury.

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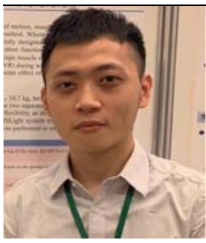

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