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Acute Effects of Vibration Foam Rolling Warm-Up on Jump and Flexibility Asymmetry, Agility and Frequency Speed of Kick Test Performance in Taekwondo Athletes

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Abstract: The effect of asymmetry on flexibility and jump in taekwondo athletes and the influence of vibration foam rolling on asymmetry and frequency speed of kick test has not been examined. This study examined the effects of three warm-up protocols on subsequent sports performance in elite male taekwondo athletes. Fifteen elite male taekwondo athletes (20.63 ± 1.18 years) completed three warm-up protocols in a randomized order: general warm-up [GW], GW with vibration foam rolling [GW + VR], and GW with double VR for the weaker leg [GW + double VR]), was delivered before the subsequent tests: flexibility, single-leg countermovement jump (CMJ), 505 agility, hexagon test, and multiple frequency speed of kick tests (FSKTs). Relative to GW, the GW + VR significantly improved the hexagon test (GW + VR = 11.60 ± 1.01 s; GW = 12.80 ± 1.58 s). In addition, the GW + VR and GW + double VR yielded greater kick numbers in FSKT 5 (GW + VR = 21.13 ± 1.96 reps; GW + double VR = 20.93 ± 1.67 reps; GW = 19.27 ± 1.62 reps) and a higher kick decrement index (GW + VR = 5.45 ± 2.57%; GW + double VR = 5.88 ± 3.22%; GW = 9.54 ± 5.00%). However, the GW + VR and GW + double VR did not significantly improve the flexibility and CMJ asymmetry performance. The GW + VR is more beneficial for warming up than the GW is among male collegiate taekwondo athletes.

Keywords: power; preconditioning; fatigue; asymmetry

1. Introduction

Excelling in taekwondo largely depends on leg strength, agility, flexibility, and anaerobic alactic power [1,2], since taekwondo games often involve the use of kick techniques to attack and defend (at least 90%) as well as the ability to make quick turns and apply quick footwork [3]. However, taekwondo athletes often perform kick training by alternating between dominant and non-dominant legs. Moreover, players tend to frequently rely on their dominant leg for kicking, which may cause between-limb muscle performance asymmetries. Therefore, the foot-tapping ability of the dominant leg often tends to be better than that of the non-dominant leg in child taekwondo athletes [4]. Similarly, Guan et al. showed that in elite male child taekwondo athletes, the dominant and nondominant leg asymmetry was 8.20% during a unilateral countermovement jump height, 6.64% during a horizontal hop distance, 5.78% during a triple hop distance, and 9.97% during a posterolateral dynamic balance reach distance [5]. Furthermore, Ball et al. conducted a study on four elite adult taekwondo athletes from the Australian National Olympic team; before a nine-week training intervention, countermovement jump height of the right leg (0.30 ± 0.03 m) was more favorable than that of the left leg (0.26 ± 0.06 m) of the athletes. After sessions 5–7 of the training, the athletes had between-limb asymmetry in power, e.g., the single-leg jump for the right leg being 0.05 m higher than that of the left leg. Additionally, the difference in the allometric scaling of peak power output between the right and left legs was 14% (e.g., in session 8, the value for the left leg was higher than that for the right leg) [6].

Muscle function of lower limbs is related to kicking ability [7]. Between-limb asymmetries in functional performance are associated with a reduced kicking ability and high risk of injury [6,8–10]. For example, football players often use their dominant foot to kick the ball and their nondominant foot to support their body, which results in differences in the kick force, performance, and accuracy [11]. Strength training or other strategies can help reduce between-limb muscle function asymmetry, which may improve athletic performance and reduce injury risk [10,12].

Regular warm-up exercises before a competition or training session can be particularly beneficial for enhancing subsequent sports performance [13–15]. A typical warm-up exercise may include some aerobic work (e.g., jogging and running), stretching exercises (e.g., static, dynamic, or both), and sport-specific activities (e.g., jumps and half-squats) [14]. Elastic band exercises are commonly used in warm-up activities before taekwondo likely induced post-activation potentiation (PAP) and enhanced kicking performance [15]. A recent study [16] also reported superior effects of using elastic band exercises than traditional warm-up on judo sport-specific performance. Stretching exercises not only enhances flexibility but also helps prevent sports injury [17]. However, controversial findings have also been reported [18]. For example, static stretching, proprioceptive neuromuscular facilitation, and ballistic stretching have been reported to negatively affect sprint performance in taekwondo athletes [18].

Vibration foam rolling (VR) combines a foam roller (FR) with continuous vibration can stimulate proprioceptors such as the muscle spindles and Golgi tendon organs [19,20]. The vibration therapy can increase muscle compliance [21], intramuscular temperature [22], blood flow [23], and enhance more motor units [24]. Importantly, the VR has become increasingly popular and has been used as a component in warm-up exercises. Several studies have demonstrated immediate improvement in athletic performance after VR alone and after VR combined with other warm-up modalities [25–29]. For example, Chen et al. [28] compared general running warm-up (GW) and dynamic stretching (DS) combined with VR (four sets of 30 s on quadriceps and hamstring muscles), the DS + VR protocol resulted in significantly greater knee flexion flexibility, lower hamstring muscle stiffness, and greater knee flexor muscle endurance [28]. In addition, Hsu et al. [26] revealed that the DS + static stretching (SS), DS + FR, and DS + VR significantly improved flexibility, power, and ball speed. However, only DS + FR, and DS + VR significantly improved agility in table tennis players. Moreover, Lee et al. [29] showed different findings: the VR significantly increased the knee extension and flexion flexibility, quadriceps muscle strength, and dynamic balance, the FR detrimental effects on knee joint proprioception. Furthermore, the VR was significantly more effective than SS in increasing quadriceps muscle strength and balance. However, Lin et al. [27]. revealed that the DS alone and DS followed by VR could improve knee flexibility, countermovement jump height, and agility. However, to our knowledge, few studies have examined the effects of dynamic stretching alone and in combination with VR and with a greater volume of VR for the weaker leg on leg muscle function, kick frequency and speed, and kick fatigue index in taekwondo athletes.

The current study evaluated the acute effects of DS + VR warm-up protocols and double VR for the weaker leg on jump height, change of direction speed, flexibility, and outcomes in the hexagon test and frequency speed of kick test performance of taekwondo athletes. Because of the potential effects of DS + VR on enhancing athletic ability, we expected better performance in athletes following this warm-up protocol than following the traditional taekwondo warm-up protocol. The results of the current study may help athletic, coaches or trainers select more beneficial warm-up protocols to reduce the risk of sports injury (e.g., bilateral asymmetry) and potentially to improve taekwondo athletic performance

2. Materials and Methods

2.1. Participants

Fifteen healthy, elite male taekwondo athletes (mean $\pm$ SD: age = 20.63 $\pm$ 1.18 years; height: 173.85 $\pm$ 4.19 cm; body mass = 69.45 $\pm$ 11.12 kg; training experience: 9.79 $\pm$ 2.77 year) volunteered to participate in this study. On average, they trained 3–4 h (including resting periods) a day five times a week. All the participants were black belt holders and were categorized in National Division I. Exclusion criteria were a lower-extremity injury in the last year, lower back pain, and cardiovascular diseases. Each participant provided informed consent before participating in the study. All participants refrained from vigorous physical activities and training at least 3 days before experiment visit days. On all experimental visit days, they were not allowed to consume any food or supplements that contained alcohol or caffeine. All the experimental procedures in this study were in accordance with the Declaration of Helsinki and were approved by the Institutional Review Board of Jen-Ai Hospital (approval number: IRB-108-61).

2.2. Warm-Up Protocol

During the first visit, the participants familiarized themselves with the measurement tests, taekwondo warm-up, and VR protocols. Each participant performed three warm-up protocols every 7 days in random order: a general taekwondo warm-up (GW), GW combined with VR (GW + VR), and GW combined with double VR for the weaker leg (GW + double VR). Participants were required to perform a single-leg countermovement jump; a greater jump height indicated a stronger leg, and a smaller jump height indicated a weaker leg [12]. After each warm-up protocol, the participants performed the following sport-specific tests: quadriceps and hamstring flexibility test, the countermovement jump, hexagon test, 505 agility test, and multiple frequency speed of kick tests.

2.3. General Taekwondo Warm-Up (GW)

In this protocol, after a 5 min jogging exercise, the participants were instructed to perform 5 min dynamic stretches of all joints, with a 5 min rest interval in a sitting position (see Romaratezabala et al. for details of the exercises [30]).

2.4. GW Combined with VR (GW + VR)

In this protocol, after a 5 min jogging exercise, the participants performed GW, followed by three sets of VR for exercising the quadriceps and hamstrings of each leg (Figure 1). The intensity of the vibration foam roller (Vyper 2.0, Hyperice, Irvine, CA, USA) can be set to between 48, 60, and 72 Hz at three different levels. The vibration foam roller was operated at a vibration frequency of 48 Hz. The VR exercise involved lying on the floor and actively rolling the roller back and forth on target muscle groups. Each set of VR was performed for 30 s at a rate of 30 rolls per minute (1 s up, 1 s down) with the help of a metronome [28]. The pressure pain intensity was instructed to maintain at 4–5 on a 10 mm visual analogue scale (VAS), based on each participant's verbal feedback.

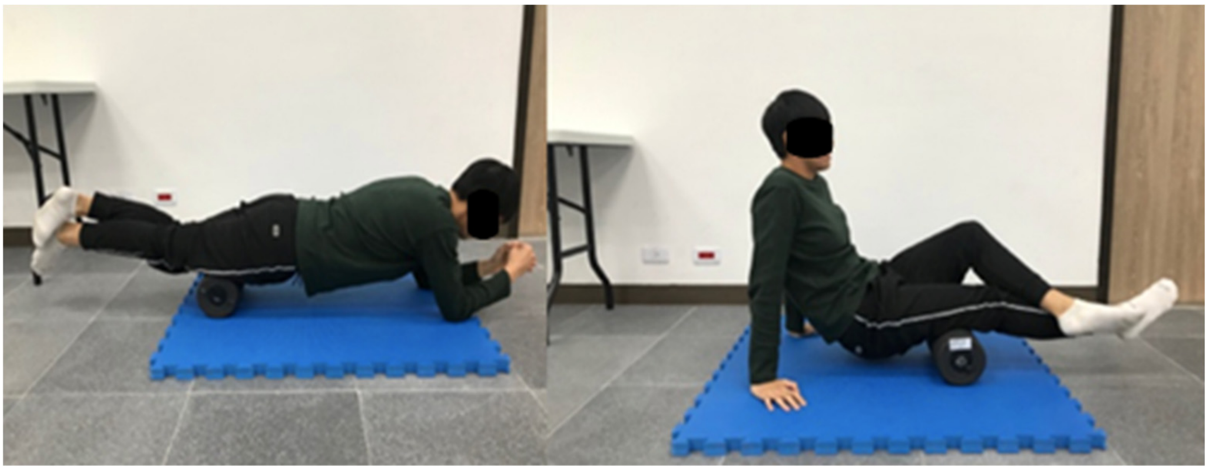

Figure 1. Vibration rolling protocols. (**left**): quadriceps; (**right**): hamstrings.

2.5. GW Combined with Double VR (GW + Double VR)

The exercise protocols were the same as those of the GW + VR intervention, except that the participants performed six sets of VR for the weaker leg.

2.6. Measurement of Dependent Variables

The measurement tests were always conducted in the following order: flexibility test, countermovement jump, hexagon test, 505 agility test, and multiple frequency speed of kick tests.

2.7. Quadriceps Flexibility

This test was conducted based on active knee flexion. In this test, the participants lay prone on a padded plinth while maintaining a neutral hip position, and they were required to actively pull their heel as close as possible to their buttocks [31]. Subsequently, the angle between the thigh and the lower leg was measured using a plastic goniometer. The average measurement value of three trials was recorded for data analysis. This test has an intraclass correlation coefficient (ICC) of 0.91, indicating high test–retest reliability [32].

2.8. Modified Back-Saver Sit-And-Reach Test

This test was developed to assess hamstring and lower back flexibility [33]. The participants performed a single-leg sit-and-reach procedure on a bench on which a meter rule was placed. The untested leg was placed on the floor with the knee at approximately 90°. The participants aligned the heel of their tested leg with the 50 cm mark on the meter rule. Then, the participants were instructed to perform a maximum anterior flexion of the hip joints and trunk slowly to reach forward as far as possible while keeping the knees and arms extended and keeping the hands on top of each other (tips of the middle fingers even) [33]. The value is recorded to the nearest centimeter. Each flexibility test was conducted three times for each leg, and the average value was used for data analysis.

2.9. Countermovement Jump

The test was conducted using a light timing system (Optojump; Microgate, Bolzano, Italy). It has high test–retest reliability (ICC = 0.99) and validity (r = 0.99) [34]. With both hands placed on hips, each participant was required to perform bilateral and single-leg countermovement to a depth that would elicit the greatest jump height. During their time in the air, the participants maintained extension of the hip, knee, and ankle joints. Three trials were performed for this test, with a 1 min rest interval between each trial. The Optojump system measured the flight time (1 kHz sampling rate) and the jump height = 9.81 × (flight time)^2/8. The trial with the highest jump height (cm) was recorded for data analysis [35].

2.10. Hexagon Test

This test is related to measures of speed, power, and agility [36]. The test requires the participants to stand facing forward in the middle of a hexagon measuring 24 in. per side, with each angle being 120°. The participants were required to perform a double-leg hop forward and backward in a clockwise direction over each of the six sides of the hexagon until they had gone around the hexagon three circuits and then returned to the center (18 jumps). The time (seconds) was recorded using a mobile phone by the participants to complete three circuits. Three trials were performed with a 1 min rest interval between each trial. The best time was recorded for data analysis. This test has an ICC of 0.88 [36].

2.11. 505. Agility Tests

This test was conducted using a FITLIGHT TrainerTM (FITLIGHT Sports Corp., Aurora, ON, Canada). This wireless reaction training system comprises several LED-powered lights that are controlled by a computer tablet, with the ability to capture various attributes of athletic performance such as reaction time, speed, agility, and coordination. The participants were required to run forward with maximal effort until they reached the 15 m line, then turn and place one leg on the line, thus completing a 180° turn, and then sprint back a further 5 m [37]. Three trials were performed for this test, with a 1 min rest interval prescribed between each trial. The best time was recorded for data analysis.

2.12. Frequency Speed of Kick Test

This test comprised five sets of frequency speed of kick tests (FSKTs). Each set lasted 10 s, with a 10 s rest interval prescribed between sets. After a sound signal, the participant was required to kick a boxing bag as fast and as hard as possible by applying the roundhouse kick technique and alternating their right and left legs (Figure 2). The performance was determined by the number of kicks in each set and the total number of kicks. To determine the rate of fatigue, a kick decrement index (KDI) was calculated as a percentage for each set. The test has an ICC of 0.85–0.95 [14,38]. Heart rate was recorded with a heart rate monitor (Polar V800, Kempele, Finland). Rating of perceived exertion (RPE) was rated on a Borg scale of 0–10, with 0 indicating no exertion and 10 indicating maximal perceived exertion [39].

Figure 2. Frequency speed of kick test.

2.13. Statistical Analyses

Data are presented as the mean ±SD. After the Shapiro–Wilk test for normality was conducted, dependent variables were analyzed using SPSS statistical software (IBM SPSS Statistics 25.0; IBM, Armonk, NY, USA) by using separate one-way repeated-measures analysis of variance (ANOVA) for each intervention condition [GW vs. GW + VR vs. GW + double VR]. If a significant condition effect was found, post hoc pairwise comparisons with Bonferroni correction were conducted to compare the potential differences between any two conditions. In addition, separate two-way (repetition interval [1 vs. 2 vs. 3 vs. 4 vs. 5] × condition [GW vs. GW + VR vs. GW + double VR]) repeated-measures ANOVA tests were used to analyze the frequency speed of kick performance. Statistical significance was set at $p < 0.05$. For calculations of interlimb asymmetry, the jump height and flexibility on each leg were used by the formula [40]: Interlimb asymmetry (%) = (stronger limb-weaker limb/stronger limb) × 100. The effect size (Cohen's *d*) ($d = M1 - M2/\sigma$ pooled) [41] was calculated to examine the magnitude of the effects between two different warm-up conditions.

3. Results

Table 1 presents the mean and SDs of the quadriceps and hamstring flexibility test, CMJ, hexagon test, and 505 agility test after the three warm-up protocols. The results of one-way ANOVA revealed statistical significance ($F = 3.86$, $p = 0.03$) in the hexagon test outcomes for warm-up protocols. Pairwise comparisons revealed that the outcomes after the GW + VR intervention was more significantly better than those after the GW intervention ($d = 0.90$, $p = 0.04$). However, no significant differences were observed among the three warm-up protocols in terms of quadriceps flexibility in the stronger leg ($F = 0.13$, $p = 0.88$), quadriceps flexibility in the weaker leg ($F = 0.35$, $p = 0.71$), and quadriceps flexibility asymmetry ($F = 0.46$, $p = 0.64$), hamstring flexibility in the stronger leg ($F = 0.08$, $p = 0.93$), hamstring flexibility in the weaker leg ($F = 0.60$, $p = 0.56$), and hamstring flexibility asymmetry ($F = 0.46$, $p = 0.64$), 505 agility test outcome ($F = 1.00$, $p = 0.37$), CMJ outcomes in both legs ($F = 0.50$, $p = 0.61$), CMJ outcomes in the stronger leg ($F = 0.70$, $p = 0.93$), CMJ outcomes in the weaker leg CMJ ($F = 0.28$, $p = 0.80$), and CMJ asymmetry ($F = 0.15$, $p = 0.86$). Although the CMJ asymmetry was lower in the GW + VR (10.88%) and GW + double VR (11.31%) conditions than in the GW condition, no significant differences were observed among the three warm-up protocols.

Table 1. Mean ± SD of quadriceps, hamstring flexibility, CMJ, hexagon, and 505 agility tests after 3 warm-up protocols (GW, GW + VR, and GW + double VR).

Test	GW	GW + VR	GW + Double VR	*F*-Test *p*-Value
Flexibility				
Quadriceps (degree)				
Stronger leg	127.9 ± 5.3	128.9 ± 5.3	128.7 ± 5.5	0.87
Weaker leg	129.1 ± 4.9	128.7 ± 4.9	130.1 ± 4.6	0.70
Asymmetry (%)	−0.9 ± 3.9	0.1 ± 4.0	−1.2 ± 3.5	0.64
Hamstring (cm)				
Stronger leg	59.8 ± 9.9	60.6 ± 8.4	59.2 ± 9.6	0.92
Weaker leg	57.1 ± 11.1	59.6 ± 8.8	58.8 ± 10.5	0.80
Asymmetry (%)	4.8 ± 10.7	1.4 ± 7.8	0.9 ± 7.8	0.56
Bilateral CMJ (cm)	34.6 ± 4.1	35.1 ± 4.7	36.2 ± 4.4	0.61
Stronger leg	17.2 ± 3.9	17.7 ± 3.4	17.6 ± 3.4	0.92
Weaker leg	14.9 ± 2.7	15.8 ± 3.4	15.6 ± 3.0	0.76
Asymmetry (%)	12.3 ± 7.6	10.9 ± 5.6	11.3 ± 8.1	0.86
Hexagon (s)	12.8 ± 1.6	11.6 ± 1.0 *	11.9 ± 1.1	0.03
505 (s)	2.6 ± 0.2	2.6 ± 0.2	2.5 ± 0.2	0.37

GW: general taekwondo warm-up; GW + VR: GW with vibration foam rolling; GW+ double VR: GW with vibration foam rolling double for weaker leg; S: seconds. *: Statistically significant difference between GW and GW + VR ($p < 0.05$).

For the frequency speed of kick test performance (Table 2), no significant difference was noted in the mean HR ($F = 0.08$, $p = 0.93$), maximal HR ($F = 0.0$, $p = 0.96$), RPE ($F = 0.08$, $p = 0.93$), and overall FSKT ($F = 1.13$, $p = 0.33$) among the three warm-up protocols.

Table 2. Mean and SDs of the frequency speed of kick tests performance.

Variables	GW	GW + VR	GW + Double VR	*F*-Test *p*-Value
		FSKTmult (kicks)		
FSKT1	22.9 ± 1.8	22.7 ± 2.1	22.7 ± 2.0	0.93
FSKT2	21.8 ± 1.9 *	22.6 ± 2.3	22.3 ± 2.2	0.59
FSKT3	20.9 ± 2.3 *	22.0 ± 2.4	21.7 ± 1.9 *	0.41
FSKT4	20.1 ± 1.7 *	21.1 ± 2.1 *	21.1 ± 1.8 *	0.27
FSKT5	19.3 ± 1.6 *	21.1 ± 1.9 *&	20.9 ± 1.7 *&	0.01
FSKT total	105.1 ± 7.7	109.5 ± 9.9	108.7 ± 8.2	0.33
KDI (%)	9.5 ± 5.0	5.5 ± 2.6 &	5.9 ± 3.2 &	0.01
HR mean (beat/min)	158.6 ± 13.5	156.8 ± 13.6	156.9 ± 15.2	0.93
HR max (beats/min)	172.6 ± 11.9	172.3 ± 12.2	173.5 ± 12.9	0.96
RPE	6.8 ± 1.1	6.7 ± 1.6	6.6 ± 1.2	0.93

GW: general taekwondo warm-up; GW + VR: GW with vibration foam rolling; GW+ double VR: GW with vibration foam rolling double for weaker leg. FSKT: frequency speed of kick test; KDI: Kick Decrement Index; HR: heart rate; RPE: rating of perceived exertion. * Statistically significant difference with FSKT1 ($p < 0.05$). &: Statistically significant difference between GW and GW + VR or between GW and GW+ double VR ($p < 0.05$).

The ANOVA results revealed that the KDI (%) was significantly different among the three protocols ($F = 5.42$, $p = 0.008$), with significantly lower KDIs in the GW + VR ($d = 1.00$, $p = 0.01$) and GW + double VR ($d = 0.86$, $p = 0.03$) protocols than in the GW protocol. However, the two-way repeated-measures ANOVA indicated a significant difference in the set interval X protocols interaction ($F = 2.09$, $p = 0.03$) in the frequency speed of kick test performance (Figures 3 and 4). Therefore, follow-up analyses were conducted to examine the changes in kick number during the repetition intervals for each protocol and compare the kick number values among different protocols at each time point. The pairwise comparisons showed that the kick numbers in FSKT 2 ($p = 0.03$), FSKT 3 ($p = 0.006$), FSKT 4 ($p < 0.001$), and FSKT 5 ($p < 0.001$) were significantly lower than that in FSKT 1 for the GW protocol. For the GW + VR protocol, the kick numbers in FSKT 4 ($p = 0.001$) and FSKT 5 ($p = 0.003$) were significantly lower than that in FSKT 1. Moreover, the kick numbers in FSKT 3 ($p = 0.03$), FSKT 4 ($p = 0.002$), and FSKT 5 ($p = 0.006$) were significantly lower than that in FSKT1 for the GW + double VR protocol. Furthermore, the kick number in FSKT 5 was significantly higher in the GW + VR ($d = 1.02$, $p = 0.01$) and GW + double VR ($d = 0.97$, $p = 0.03$) protocols than in the GW protocol.

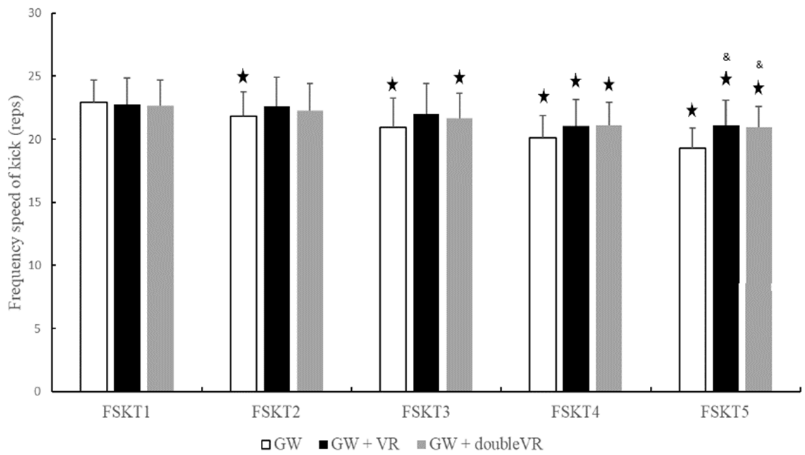

Figure 3. Frequency speed of kick test in different warm up conditions. ⋆ Statistically significant difference with FSKT1 ($p < 0.05$). &: Statistically significant difference between GW and GW + VR or between GW and GW+ double VR ($p < 0.05$).

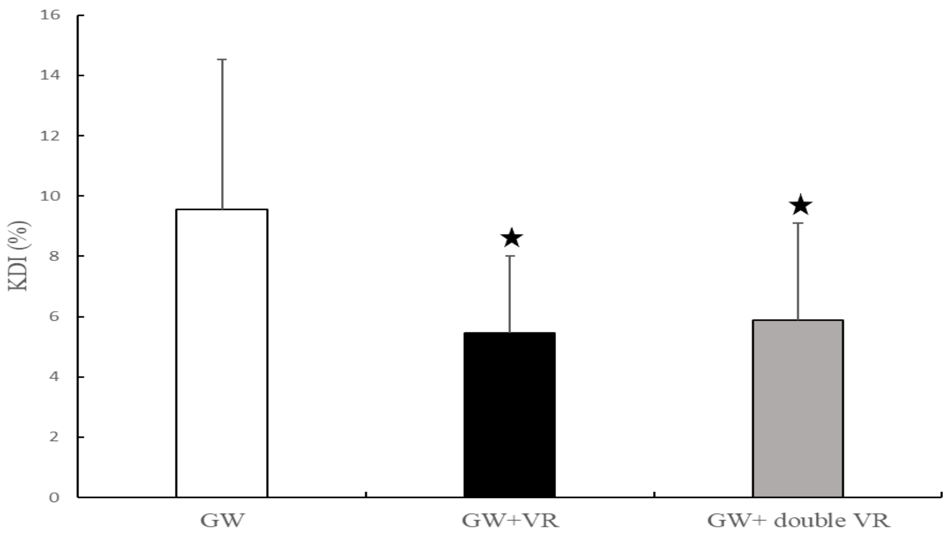

Figure 4. The kick decrement index (%) in different warm up conditions. ⋆: Statistically significant difference between GW and GW + VR or between GW and GW+ double VR ($p < 0.05$).

4. Discussion

To our knowledge, the current study is one of the few to compare the acute effects of different warm-up protocols (GW, GW + VR, and GW + double VR for weaker leg) on flexibility, CMJ, hexagon test performance, 505 agility test performance, and multiple frequency speed of kick performance in elite collegiate male taekwondo athletes. The main findings are as follows: (a) The outcomes in the hexagon test were significantly better after the GW + VR protocol than after the GW warm-up protocol; (b) no differential warm-up effects were observed in terms of flexibility, CMJ, and 505 agility test; (c) the KDI (%) after the GW + VR and GW + double VR protocols was significantly lower than that after the GW warm-up protocol, and (d) the kick numbers in FSKT 5 were significantly higher after the GW + VR and GW + double VR protocols than after the GW warm-up protocol.

No significant differences were noted among the three warm-up protocols in terms of flexibility, CMJ, and 505 agility test outcomes. Similar to our findings, Lin et al. [27] reported that DS followed by VR was not significantly superior to DS in terms of knee flexion range of motion and outcomes in the CMJ and badminton agility test, although two warm-up protocols improved performance. Behara and Jacobson found no significant effect of a warm-up protocol involving a deep tissue roller and DS on vertical jump power, peak, average knee flexion, and extension isometric torque [42]. In addition, Su et al. [25] revealed no significant differences in the effects on isokinetic quadriceps and hamstring muscle strength between the foam rolling and DS protocols.

Su et al. [25] reported that the quadriceps and hamstring flexibility significantly improved after foam rolling compared with static and dynamic stretching. Chen et al. [28] found that relative to the general warm-up protocol comprising running, DS followed by VR significantly increased knee flexion range of motion and reduced hamstring muscle stiffness in handball players with limited hamstring flexibility. The nonsignificant results in the current study may be attributed to the fact that taekwondo athletes already have a high degree of flexibility, and the resulting ceiling effect may have affected the results.

Little is known about the differential effects of different warm-up protocols on lower-limb hexagon test outcomes. Only the GW + VR warm-up protocol yielded a shorter jumping time than did the GW protocol in the current study. However, the hexagon test is a measure of speed, power, and agility [36,43], and the results may indicate lower extremity injury risk [44]. For example, a study revealed that the outcome time in the hexagon test was significantly correlated with 20 m linear sprint time, change of direction (COD), and jump performance in tennis players [36]. Similarly, Tsai and Chen demonstrated that the drop jump height and hip muscle power increased 2 min after foam rolling (each muscle was rolled for 1 min) [45].

Furthermore, the current study demonstrated no differences in the outcomes of the hexagon test between the GW + double VR protocol for the weaker leg and GW protocol. A possible reason for this finding is that foam rolling times greater than 90 s promote knee extension muscular fatigue [46].

To our knowledge, few studies have examined the acute effect of a warm-up protocol on asymmetry. Our results revealed that the GW + VR and GW + double VR protocols did not improve the CMJ asymmetry performance, which is consistent with a study that reported no significant effects of a loaded warm-up protocol on a single leg CMJ asymmetry performance [47]. For example, the previous study reported no significant differences in the change of direction speed, single-leg CMJ, or single-leg CMJ asymmetry performance between the traditional dynamic warm-up protocol (including DS, jogging, step, jump, and corner shadow play drill) and a warm-up protocol with a weight vest (10% body mass vest was worn for the performance jump and corner shadow play drill [47]. In contrast, Mangine et al. revealed that rugby athletes completed three maximal, 40 m sprint trials while being tethered to a robotic resistance device (loaded at 147.1N), which reduced the bilateral asymmetry [48].

Notably, during the multiple FSKTs, participants performing the GW + VR and GW + double VR warm-up protocols were more fatigue-resistant than were those performing the GW warm-up protocol. In addition, the kick number in FSKT 5 was significantly higher after the GW + VR (21.13 $\pm$ 1.96 reps) and GW + double VR (20.93 $\pm$ 1.67 reps) than after the GW (19.27 $\pm$ 1.62 reps) protocol.

Relevant research reporting findings similar to ours is limited. Santos et al. studied the effects of four warm-up conditions (half-squat, jumps, half-squat + jumps, and control [5 min jogging and 3 min rest]) on taekwondo athletes and reported no differences between their effects on CMJ, but the kick performance in the half-squat + jumps protocol with a 10 min rest (kicks 23 $\pm$ 5 reps) was superior to that in the controls (kicks 19 $\pm$ 3 reps) [14]. The improvement in the kick performance may be because warm-up protocols increase muscle activity and blood flow. For example, Aandahl et al. [15] revealed that kicking with elastic resistance during a warm-up had a positive effect on kicking velocity and increased rectus femoris muscle activity. Another study reported significant increases in rectus femoris, vastus lateralis, and vastus medialis muscle activity after a VR (32 Hz, 5 min) intervention targeting the hamstring [24]. Moreover, DS or VR exercises increase muscle temperature and blood circulation [49–51], which may improve sports performance [28].

Regarding the effects of different warm-up protocols on fatigue, a related study revealed that the DS + VR protocol yielded greater hamstring muscle endurance than did general running warm-up and DS protocols [28]. In addition, a single bout of FR for 30 s significantly restored the loss of maximal isometric voluntary force of the knee extensors compared with no treatment [52]. Although Healey et al. revealed no significant differences between the foam rolling and control (planking intervention) protocols in terms of isometric squat force, pro agility, and vertical jump, they reported significantly less fatigue among participants after foam rolling than after the control protocol [53]. In contrast, another study reported higher muscular fatigue after a foam rolling intervention (more than 90 s) than after the control protocol [46].

Furthermore, in the present study, both the GW + VR and GW + double VR warm-up protocols were more effective than the GW was in improving kick performance. This finding may be explained by the use of trunk stabilization exercises (e.g., plank exercise), which involve isometric contraction and activate the rectus abdominus and external oblique abdominis muscles [54]. For example, to perform exercises targeting the quadriceps, the participants were required to be in a prone position with the foam roller under their thighs, and their forearms were on the ground in a planking position. Therefore, these protocols may increase trunk muscle strength and coordination, thus improving explosive leg movements (e.g., rebound jump reactive strength index) [55] and resulting in immediate improvements in dynamic balance in male soccer players [56].

This study has some limitations. First, the participants were healthy male elite college taekwondo athletes with high flexibility. Results may differ for other athletic populations or for individuals with limited flexibility. Second, the participants performed the VR protocol on the quadriceps and hamstring muscles; therefore, the VR results may differ for other muscle groups (e.g., quadriceps, hamstrings, adductors, calf muscles, and the ili-otibial tract).

5. Conclusions

The results demonstrated that although the effect of the GW + VR and GW + double VR protocols for the weaker leg on flexibility, CMJ, and 505 agility did not differ from that of the GW protocol, superior effects of GW + VR were found in the hexagon test. In addition, the GW + VR and GW + double VR protocols for the weaker leg increased the number of kicks and enhanced fatigue resistance compared with the GW protocol, which may improve taekwondo kick performance and reduce the risk of injury in the lower extremities.

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References

1. Heller, J.; Peric, T.; Dlouha, R.; Kohlikova, E.; Melichna, J.; Novakova, H. Physiological profiles of male and female taekwon-do (ITF) black belts. *J. Sports Sci.* **1998**, *16*, 243–249. [CrossRef] [PubMed]
2. Markovic, G.; Misigoj-Durakovic, M.; Trninic, S. Fitness profile of elite Croatian female taekwondo athletes. *Coll. Antropol.* **2005**, *29*, 93–99.
3. Yoon, S.D.; Sung, D.H.; Park, G.D. The effect of active core exercise on fitness and foot pressure in Taekwondo club students. *J. Phys. Ther. Sci.* **2015**, *27*, 509–511. [CrossRef]
4. Čular, D.; Miletić, Đ.; Miletić, A. Influence of dominant and non-dominant body side on specific performance in taekwondo. *Kinesiology* **2010**, *42*, 184–193.
5. Guan, Y.; Bredin, S.; Jiang, Q.; Taunton, J.; Li, Y.; Wu, N.; Wu, L.; Warburton, D. The effect of fatigue on asymmetry between lower limbs in functional performances in elite child taekwondo athletes. *J. Ortho. Surg. Res.* **2021**, *16*, 33. [CrossRef] [PubMed]
6. Ball, N.; Nolan, E.; Wheeler, K. Anthropometrical, physiological, and tracked power profiles of elite taekwondo athletes 9 weeks before the Olympic competition phase. *J. Strength Cond. Res.* **2011**, *25*, 2752–2763. [CrossRef] [PubMed]
7. Norjali Wazir, M.R.W.; Van Hiel, M.; Mostaert, M.; Deconinck, F.J.A.; Pion, J.; Lenoir, M. Identification of elite performance characteristics in a small sample of taekwondo athletes. *PLoS ONE* **2019**, *14*, e0217358. [CrossRef]
8. Eagle, S.R.; Kessels, M.; Johnson, C.D.; Nijst, B.; Lovalekar, M.; Krajewski, K.; Flanagan, S.D.; Nindl, B.C.; Connaboy, C. Bilateral Strength Asymmetries and Unilateral Strength Imbalance: Predicting Ankle Injury When Considered with Higher Body Mass in US Special Forces(a). *J. Athl. Train.* **2019**, *54*, 497–504. [CrossRef]
9. Son, M.; Youm, C.; Woo, J.; Lee, M.; Kim, Y.; Kim, J. Postural stability for taekwondo athletes with repetitive ankle sprains during a single-leg stance. *J. Phys. Ther. Sci.* **2018**, *30*, 405–410. [CrossRef]

10. Ryu, S.; Lee, T.K. Biomechanical Parameters that May Influence Lower Limb Injury during Landing in Taekwondo. *Medicina* **2021**, *57*, 373. [CrossRef]
11. Chew-Bullock, T.S.; Anderson, D.I.; Hamel, K.A.; Gorelick, M.L.; Wallace, S.A.; Sidaway, B. Kicking performance in relation to balance ability over the support leg. *Hum. Mov. Sci.* **2012**, *31*, 1615–1623. [CrossRef]
12. Gonzalo-Skok, O.; Moreno-Azze, A.; Arjol-Serrano, J.L.; Tous-Fajardo, J.; Bishop, C. A Comparison of 3 Different Unilateral Strength Training Strategies to Enhance Jumping Performance and Decrease Interlimb Asymmetries in Soccer Players. *Int. J. Sports Physiol. Perform.* **2019**, *14*, 1256–1264. [CrossRef] [PubMed]
13. Bishop, D. Warm up I: Potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med.* **2003**, *33*, 439–454. [CrossRef]
14. Santos, J.F.; Valenzuela, T.H.; Franchini, E. Can different conditioning activities and rest intervals affect the acute performance of taekwondo turning kick? *J. Strength Cond. Res.* **2015**, *29*, 1640–1647. [CrossRef]
15. Aandahl, H.S.; Von Heimburg, E.; Van den Tillaar, R. Effect of Postactivation Potentiation Induced by Elastic Resistance on Kinematics and Performance in a Roundhouse Kick of Trained Martial Arts Practitioners. *J. Strength Cond. Res.* **2018**, *32*, 990–996. [CrossRef] [PubMed]
16. Lum, D. Effects of Various Warm-Up Protocol on Special Judo Fitness Test Performance. *J. Strength Cond. Res.* **2019**, *33*, 459–465. [CrossRef]
17. Chen, C.H.; Nosaka, K.; Chen, H.L.; Lin, M.J.; Tseng, K.W.; Chen, T.C. Effects of flexibility training on eccentric exercise-induced muscle damage. *Med. Sci. Sports Exerc.* **2011**, *43*, 491–500. [CrossRef]
18. Alemdaroglu, U.; Koklu, Y.; Koz, M. The acute effect of different stretching methods on sprint performance in taekwondo practitioners. *J. Sports Med. Phys. Fit.* **2017**, *57*, 1104–1110.
19. Fallon, J.B.; Macefield, V.G. Vibration sensitivity of human muscle spindles and Golgi tendon organs. *Muscle Nerve* **2007**, *36*, 21–29. [CrossRef]
20. Roll, J.P.; Vedel, J.P.; Ribot, E. Alteration of proprioceptive messages induced by tendon vibration in man: A microneurographic study. *Exp. Brain Res.* **1989**, *76*, 213–222. [CrossRef]
21. Reiner, M.M.; Glashuttner, C.; Bernsteiner, D.; Tilp, M.; Guilhem, G.; Morales-Artacho, A.; Konrad, A. A comparison of foam rolling and vibration foam rolling on the quadriceps muscle function and mechanical properties. *Eur. J. Appl. Physiol.* **2021**, *121*, 1461–1471. [CrossRef]
22. Kerschan-Schindl, K.; Grampp, S.; Henk, C.; Resch, H.; Preisinger, E.; Fialka-Moser, V.; Imhof, H. Whole-body vibration exercise leads to alterations in muscle blood volume. *Clin. Physiol.* **2001**, *21*, 377–382. [CrossRef] [PubMed]
23. Lai, Y.-H.; Wang, A.-Y.; Yang, C.-C.; Guo, L.-Y. The Recovery Benefit on Skin Blood Flow Using Vibrating Foam Rollers for Postexercise Muscle Fatigue in Runners. *Int. J. Environ. Res. Public Health* **2020**, *17*, 9118. [CrossRef]
24. Lim, J.H.; Park, C.B.; Kim, B.G. The effects of vibration foam roller applied to hamstring on the quadriceps electromyography activity and hamstring flexibility. *J. Exerc. Rehabil.* **2019**, *15*, 560–565. [CrossRef] [PubMed]
25. Su, H.; Chang, N.J.; Wu, W.L.; Guo, L.Y.; Chu, I.H. Acute Effects of Foam Rolling, Static Stretching, and Dynamic Stretching During Warm-ups on Muscular Flexibility and Strength in Young Adults. *J. Sport Rehabil.* **2017**, *26*, 469–477. [CrossRef] [PubMed]
26. Hsu, F.Y.; Tsai, K.L.; Lee, C.L.; Chang, W.D.; Chang, N.J. Effects of Dynamic Stretching Combined With Static Stretching, Foam Rolling, or Vibration Rolling as a Warm-Up Exercise on Athletic Performance in Elite Table Tennis Players. *J. Sport Rehabil.* **2020**, *30*, 1–8. [CrossRef]
27. Lin, W.C.; Lee, C.L.; Chang, N.J. Acute Effects of Dynamic Stretching Followed by Vibration Foam Rolling on Sports Performance of Badminton Athletes. *J. Sports Sci. Med.* **2020**, *19*, 420–428.
28. Chen, C.H.; Chiu, C.H.; Tseng, W.C.; Wu, C.Y.; Su, H.H.; Chang, C.K.; Ye, X. Acute Effects of Combining Dynamic Stretching and Vibration Foam Rolling Warm-up on Lower-Limb Muscle Performance and Functions in Female Handball Players. *J. Strength Cond. Res.* **2021**. Publish Ahead of Print. [CrossRef]
29. Lee, C.L.; Chu, I.H.; Lyu, B.J.; Chang, W.D.; Chang, N.J. Comparison of vibration rolling, nonvibration rolling, and static stretching as a warm-up exercise on flexibility, joint proprioception, muscle strength, and balance in young adults. *J. Sports Sci.* **2018**, *36*, 2575–2582. [CrossRef]
30. Romaratezabala, E.; Nakamura, F.Y.; Castillo, D.; Gorostegi-Anduaga, I.; Yanci, J. Influence of warm-up duration on physical performance and psychological perceptions in handball players. *Res. Sports Med.* **2018**, *26*, 230–243. [CrossRef] [PubMed]
31. Aguilar, A.J.; DiStefano, L.J.; Brown, C.N.; Herman, D.C.; Guskiewicz, K.M.; Padua, D.A. A dynamic warm-up model increases quadriceps strength and hamstring flexibility. *J. Strength Cond. Res.* **2012**, *26*, 1130–1141. [CrossRef]
32. Piva, S.R.; Fitzgerald, K.; Irrgang, J.J.; Jones, S.; Hando, B.R.; Browder, D.A.; Childs, J.D. Reliability of measures of impairments associated with patellofemoral pain syndrome. *BMC Musculoskelet. Disord.* **2006**, *7*, 33. [CrossRef]
33. Hui, S.S.; Yuen, P.Y. Validity of the modified back-saver sit-and-reach test: A comparison with other protocols. *Med. Sci. Sports Exerc.* **2000**, *32*, 1655–1659. [CrossRef]
34. Glatthorn, J.F.; Gouge, S.; Nussbaumer, S.; Stauffacher, S.; Impellizzeri, F.M.; Maffiuletti, N.A. Validity and reliability of Optojump photoelectric cells for estimating vertical jump height. *J. Strength Cond. Res.* **2011**, *25*, 556–560. [CrossRef]
35. Keane, K.M.; Salicki, R.; Goodall, S.; Thomas, K.; Howatson, G. Muscle Damage Response in Female Collegiate Athletes After Repeated Sprint Activity. *J. Strength Cond. Res.* **2015**, *29*, 2802–2807. [CrossRef]

36. Hernández-Davó, J.L.; Loturco, I.; Pereira, L.A.; Cesari, R.; Pratdesaba, J.; Madruga-Parera, M.; Sanz-Rivas, D.; Fernández-Fernández, J. Relationship between Sprint, Change of Direction, Jump, and Hexagon Test Performance in Young Tennis Players. *J. Sports Sci. Med.* **2021**, *20*, 197–203. [CrossRef]
37. Nimphius, S.; Callaghan, S.J.; Spiteri, T.; Lockie, R.G. Change of Direction Deficit: A More Isolated Measure of Change of Direction Performance Than Total 505 Time. *J. Strength Cond. Res.* **2016**, *30*, 3024–3032. [CrossRef]
38. Santos, J.; Franchini, E. Frequency Speed of Kick Test Performance Comparison Between Female Taekwondo Athletes of Different Competitive Levels. *J. Strength Cond. Res.* **2018**, *32*, 2934–2938. [CrossRef]
39. Noble, B.J.; Borg, G.A.; Jacobs, I.; Ceci, R.; Kaiser, P. A category-ratio perceived exertion scale: Relationship to blood and muscle lactates and heart rate. *Med. Sci. Sports Exerc.* **1983**, *15*, 523–528. [CrossRef]
40. Impellizzeri, F.M.; Rampinini, E.; Maffiuletti, N.; Marcora, S.M. A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Med. Sci. Sports Exerc.* **2007**, *39*, 2044–2050. [CrossRef]
41. Cohen, J. A power primer. *Psychol. Bull.* **1992**, *112*, 155–159. [CrossRef]
42. Behara, B.; Jacobson, B.H. Acute Effects of Deep Tissue Foam Rolling and Dynamic Stretching on Muscular Strength, Power, and Flexibility in Division I Linemen. *J. Strength Cond. Res.* **2017**, *31*, 888–892. [CrossRef]
43. Beekhuizen, K.S.; Davis, M.D.; Kolber, M.J.; Cheng, M.S. Test-retest reliability and minimal detectable change of the hexagon agility test. *J. Strength Cond. Res.* **2009**, *23*, 2167–2171. [CrossRef]
44. Lyle, M.A.; Valero-Cuevas, F.J.; Gregor, R.J.; Powers, C.M. Lower extremity dexterity is associated with agility in adolescent soccer athletes. *Scand. J. Med. Sci. Sports* **2015**, *25*, 81–88. [CrossRef]
45. Tsai, W.C.; Chen, Z.R. The Acute Effect of Foam Rolling and Vibration Foam Rolling on Drop Jump Performance. *Int. J. Environ. Res. Public Health* **2021**, *18*, 3489. [CrossRef]
46. Monteiro, E.R.; Neto, V.G. Effect of Different Foam Rolling Volumes on Knee Extension Fatigue. *Int. J. Sports Phys. Ther.* **2016**, *11*, 1076–1081.
47. Yeung, W.-C.; Bishop, C.; Turner, A.; Maloney, S. Does a Loaded Warm-Up Influence Jump Asymmetry and Badminton-Specific Change of Direction Performance? *Int. J. Sports Physiol. Perform.* **2020**, *16*, 578–584. [CrossRef]
48. Mangine, G.; McNabb, J.; Feito, Y.; VanDusseldorp, T.; Hester, G. Increased Resisted Sprinting Load Decreases Bilateral Asymmetry in Sprinting Kinetics Among Rugby Players. *J. Strength Cond. Res.* **2020**. Publish Ahead of Print. [CrossRef]
49. Cheatham, S.W.; Kolber, M.J.; Cain, M.; Lee, M. The Effects of Self-Myofascial Release Using a Foam Roll or Roller Massager on Joint Range of Motion, Muscle Recovery, and Performance: A Systematic Review. *Int. J. Sports Phys. Ther.* **2015**, *10*, 827–838.
50. Games, K.E.; Sefton, J.M.; Wilson, A.E. Whole-body vibration and blood flow and muscle oxygenation: A meta-analysis. *J. Athl. Train.* **2015**, *50*, 542–549. [CrossRef]
51. Behm, D.G.; Wilke, J. Do Self-Myofascial Release Devices Release Myofascia? Rolling Mechanisms: A Narrative Review. *Sports Med.* **2019**, *49*, 1173–1181. [CrossRef]
52. Fleckenstein, J.; Wilke, J.; Vogt, L.; Banzer, W. Preventive and Regenerative Foam Rolling are Equally Effective in Reducing Fatigue-Related Impairments of Muscle Function following Exercise. *J. Sports Sci. Med.* **2017**, *16*, 474–479.
53. Healey, K.C.; Hatfield, D.L.; Blanpied, P.; Dorfman, L.R.; Riebe, D. The effects of myofascial release with foam rolling on performance. *J. Strength Cond. Res.* **2014**, *28*, 61–68. [CrossRef]
54. Ekstrom, R.A.; Donatelli, R.A.; Carp, K.C. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *J. Orthop. Sports Phys. Ther.* **2007**, *37*, 754–762. [CrossRef]
55. Imai, A.; Kaneoka, K.; Okubo, Y.; Shiraki, H. Immediate Effects of Different Trunk Exercise Programs on Jump Performance. *Int. J. Sports Med.* **2016**, *37*, 197–201. [CrossRef]
56. Imai, A.; Kaneoka, K.; Okubo, Y.; Shiraki, H. Comparison of the immediate effect of different types of trunk exercise on the star excursion balance test in male adolescent soccer players. *Int. J. Sports Phys. Ther.* **2014**, *9*, 428–435.