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Research article

Comparing The Effectiveness of 10-Minute Dynamic Stretching, Vibration Rolling, and Climbing-Specific Warm-Ups on Exercise Performances in Rock Climbers

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Abstract
The rise of sport climbing as a popular Olympic sport has underscored the need for optimal warm-up regimes, especially for rock climbers. This randomized, counterbalanced crossover study investigated the effects of dynamic stretching warm-up (DW) with Thera-Band, vibration rolling warm-up (VR), and climbing-specific warm-up (CW) on the flexibility, muscle strength, and dynamic stability of upper limbs in 22 recreational rock climbers without musculoskeletal diseases. Participants underwent each warm-up method in a randomized order. Each warm-up session lasted 10 minutes. Flexibility was measured with a goniometer, muscle strength was measured with a hand-held dynamometer, and dynamic stability was measured with an Upper Quarter Y-balance test. The findings revealed that all three warm-up methods significantly enhanced range of motion (ROM) of shoulder flexion, internal rotation, external rotation, overhead flexibility, and dynamic stability ($p < 0.05$). Moreover, VR was notably more effective than DW and CW in augmenting shoulder flexion flexibility and external rotation. All warm-ups increased the maximal muscle strength of the elbow flexors and shoulder extensors, but did not in finger flexors. CW demonstrated superior change improvements in the maximal muscle strength of the shoulder external rotators compared to DW ($p = 0.04$). This study highlights our design, recommending all three warm-ups to enhance flexibility, muscle strength, and dynamic stability of the upper limbs. Specifically, VR is the most effective for improving flexibility, while CW provides superior gains in shoulder external rotator strength. These insights can help climbers and coaches develop targeted warm-up strategies to optimize performance.

Key words: Sports climbing, warm-up, foam rolling, exercise performance, muscle strength.

Introduction

Rock climbing, also recognized as sport climbing, was officially included in the Summer Olympics by the International Olympic Committee in 2020 and 2024. The popularity of climbing was also on the rise. This sport provided access to indoor climbing facilities and comprised three competitive disciplines: bouldering, lead climbing, and speed climbing. Bouldering involved climbing on rock or artificial walls without ropes and harnesses, demanding exceptional physical fitness. It requires strength from upper and lower body muscles, endurance, flexibility, and coordination, and significantly emphasized the combination of skills and strategic thinking (Muller et al., 2022). A bouldering route comprised predefined holds that climbers used to reach a specific target hold. In addition, injuries in climbing predominantly occurred in the upper limbs, mainly affecting the fingers and shoulders (Jones et al., 2008; Lum and Park, 2019; Woollings et al., 2015). A weak musculoskeletal system or inadequate body control and balance, particularly among novices, increased the risk of injuries during climbing activities and falls (Schöffl and Lutter, 2017). Notably, over half of all climbing injuries happened in indoor bouldering facilities. The most common types of injuries recorded included acute tendon strain (65.7%), tendonitis (63.0%), acute muscle strain (54.8%), sprains (47.4%), and fractures (32.4%), with tendon strain being the most frequently occurring injury (McDonald et al., 2017).

Rock climbing required rigorous physical preparation to reduce the risk of injuries and enhance performance. Warming up before engaging in sports was essential. It improved ROM, exercise performance and prevented injuries (Yu et al., 2024; McCrary et al., 2015). Analyses of climbing performance indicated that elite climbers possessed superior functional flexibility in the hips and shoulders compared to intermediate climbers and non-climbers, with shoulder external rotation particularly crucial for climbing efficiency (Torres et al., 2023).

Dynamic stretching (DS) was a preferred warm-up technique that involved gradual, sport-specific movements to increase muscle reach and speed (Behm and Chaouachi, 2011; Yu et al., 2024). Research showed DS immediately improved flexibility, strength, agility, and performance metrics like sprinting and jumping (Behm and Chaouachi, 2011; Behara and Jacobson, 2017). The mechanisms of DS included increased muscle temperature, improved nerve conduction, elevated metabolic rates, and reduced stiffness (Behm et al., 2023; Yu et al., 2024). However, its effectiveness for rock climbers remained inconclusive.

Foam rolling (FR) was proposed as an alternative warm-up method (Warneke et al., 2023). The benefits of FR included enhancing soft-tissue compliance for extended muscle length and boosting blood flow and circulation within the soft tissues during the rolling process. Research evidence demonstrated that FR had immediate and long-term positive effects on the ROM in various muscle groups and joints among healthy individuals. (Glanzel et

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al., 2023; Warneke et al., 2024; Wilke et al., 2020; Yu et al., 2024). Furthermore, vibrating rolling (VR) merged the use of a foam roller with vibration technology; the roller acted specifically on targeted muscle groups. Adding mechanical oscillations increased the recruitment of motor units (Cochrane, 2011). Consequently, VR integrated the benefits of FR with vibrational stimuli, providing advantages such as enhanced muscle tissue compliance, improved circulation, reduced fatigue, and increased pain tolerance (Alonso-Calvete et al., 2022; Lee et al., 2018; Lin et al., 2020; Nakamura et al., 2023; Park et al., 2021; Romero-Moraleda et al., 2019).

To summarize the abovementioned research, current research primarily examined the benefits of DS, FR, with or without vibration, on lower limb muscles during warm-up. The impact on upper limb warm-ups remained unclear, particularly in rock climbers. One study highlighted that 20-minute warm-up with varying intensities had minimal effect on the balance of indoor male rock climbers (Askari Hosseini et al., 2013). Another study compared the effects of three warm-up methods on upper limb performance in rock climbers, finding that myofascial release, pre-exhaustion exercises, and static stretching did not notably affect muscle strength, endurance, or climbing performance, including that of the finger flexors (Yu et al., 2022). Unlike many developed sports, comparative studies do not advise rock climbers on selecting optimal warm-up methods to improve exercise performance.

Therefore, this study aimed to assess the immediate effects of DW, VR, and climbing-specific warm-up (CW) on recreational rock climbers. We hypothesized that VR would distinctly improve upper limb flexibility, CW would uniquely enhance muscle strength, and all three warm-up methods would significantly increase dynamic stability in the upper limbs, offering practical insights for rock climbers.

Methods

Participants

The study protocol was approved by Kaohsiung Medical University Chung-Ho Memorial Hospital Institutional Review Board (Approval Number: KMUHIRB-E(I)-20200384). Twenty-two recreational rock climbers (11 men and 11 women), aged 20 to 50, with at least six months of indoor bouldering experience and who participated in climbing activities for more than 30 minutes at least twice a week, were recruited. Eligibility criteria excluded individuals with a recent history (within the past six months) of severe upper limb musculoskeletal injuries, neurological injuries, acute injuries (including sprains, strains, and open wounds), cardiopulmonary diseases, or those currently using analgesic medications. Additionally, participants were advised to avoid engaging in strenuous physical activities, including medium-to-high-intensity exercises and resistance training, during the washout period.

Study Procedures

This study employed a randomized, counterbalanced crossover design. Before participation, each subject was thoroughly briefed on the experimental procedures and trained to execute three distinct warm-up methods: DW, VR, and CW. Initially, subjects underwent a pre-test that included anthropometric measurements and movement assessments (i.e., flexibility, maximal muscle strength, Upper Quarter Y-Balance Test (UQYBT). Subsequently, they were randomly assigned one of the warm-up protocols to execute following a 5-minute rest period. Upon completion of the warm-up, post-test evaluations were conducted in the same sequence as the pre-test, except that anthropometric measurements were omitted. Since participants were required to undergo all three warm-up methods, the study was structured over three separate days of testing, with a 48-hour rest period between the different warm-up interventions (Lin et al., 2020).

Warm-up Protocols

The three warm-up regimes were assigned randomly, with each session standardized to 10 minutes. Before initiating each warm-up, researchers provided participants with verbal explanations and instructions alongside demonstrations of each warm-up technique to ensure proper execution. To ensure accuracy, participants were supervised by a licensed physical therapist during each session.

DW exercises

The DW incorporated the use of a Thera-Band. The resistance provided by Thera-Bands varies with the degree of elongation, with a fully stretched band producing approximately 7 kg of resistance. The regimen consisted of eight specific movements (Figure 1), including shoulder flexion and abduction, shoulder extension, elbow flexion and wrist flexion, scapular retraction, shoulder external rotation, shoulder internal rotation, wrist extension, and finger extension. These exercises aimed to prepare the musculoskeletal system for physical exertion and were performed under the guidance of trained professionals to ensure safety and effectiveness.

Exercises were executed bilaterally, with most movements synchronized to a metronome to maintain consistency in timing. Each exercise was performed for 30 seconds, followed by a 10-second rest period before transitioning to the next over a total duration of 10 minutes. Participants maintained consistent and appropriate tension on the Thera-Band throughout the exercises, with continuous oversight and possible adjustments by a professional physical therapist to ensure correct execution.

VR exercises

The study utilized the TRIGGER POINT Grid Vibe vibrating roller, measuring 30 x 8.9 cm^2 and weighing 0.45kg, with a vibration frequency of 33Hz, as the specified equipment for the warm-up protocol. Participants were thoroughly instructed by certified physical therapists before commencing the routines. The protocol involved six distinct movements (Figure 2), executed on each side separately. Participants used a vibrating roller to massage targeted muscles by applying body weight in a controlled back-and-forth motion, synchronized to a metronome at 40 beats per minute. Each movement lasted 30 seconds, followed by a 10-second rest, with the entire session lasting approximately 10 minutes. Professional physical therapists provided assistance and corrections throughout the process as needed.

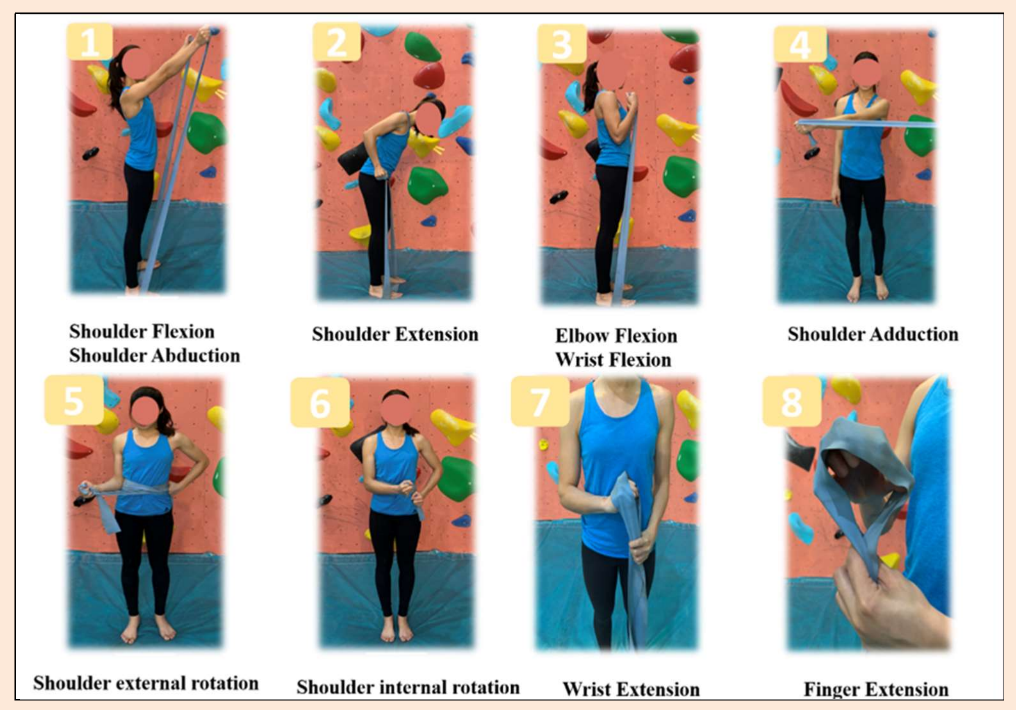

Figure 1. **Dynamic warm-up protocols with Thera-Band.**

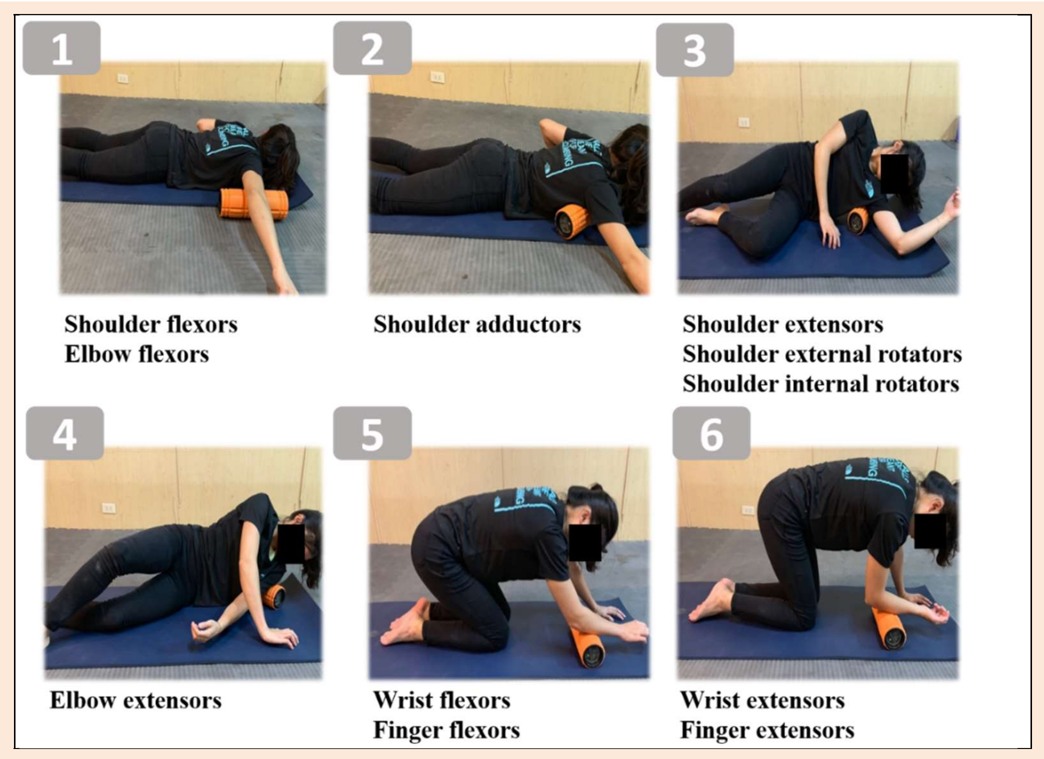

Figure 2. **Vibration rolling protocols.**

CW exercises

The CW conducted at Boulder Space in Sanmin District, Kaohsiung City, consisted of three distinct exercises (Figure 3). Initially, participants engaged in "crossing", traversing a rock climbing wall set at an 85°-90° incline for one minute, followed by a 30-second rest. This cycle was repeated three times for a total of four minutes. Subsequently, participants held onto a 2.5cm finger bar on a wall inclined at 105° for 10 seconds, followed by 30-second breaks, repeating the sequence three times for a total of 1.5 minutes. Finally, climbers tackled specific routes, such as the orange route VB and blue route VO, performing each route three times with brief rests, culminating in five minutes. Participants utilized designated rock blocks for support and strictly adhered to routes indicated by double circles. This regimen was designed to enhance technique, boost endurance, and ensure safety.

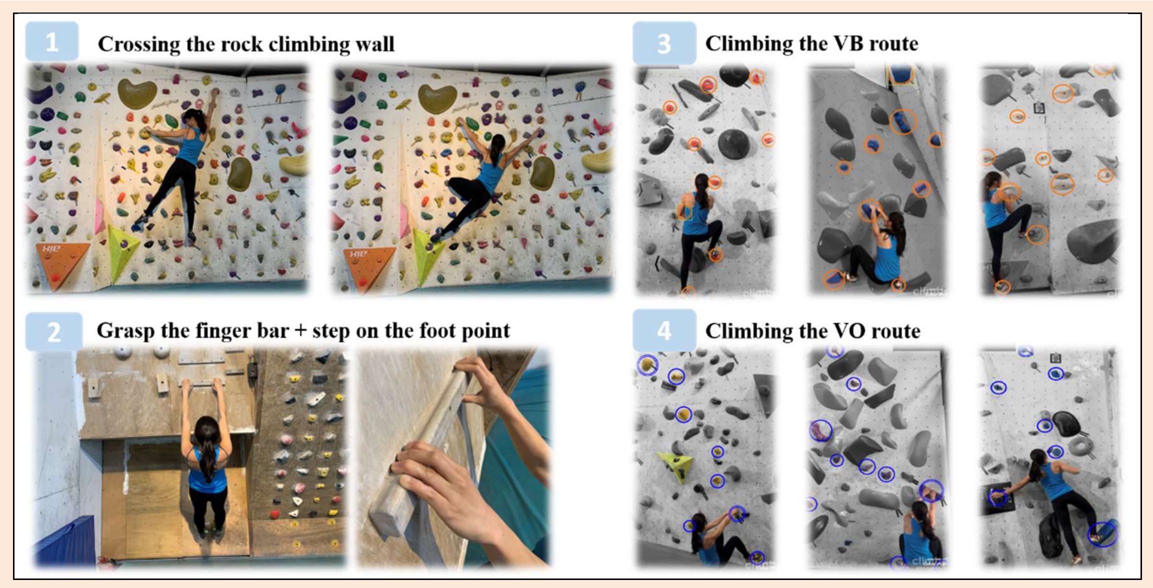

Figure 3. Climbing warm-up protocols.

Outcome measures

Throughout the data collection phase, all assessments were administered by trained professionals.

Anthropometric measurements

The InBody 270 instrument was used to measure the subjects' body composition (weight, body fat mass index, body fat percentage, lean body mass) before the experimental intervention. Arm span was measured as the length of the arms when spread out horizontally to their maximum stretch, with the straight-line distance between the fingertips of the middle fingers of both hands recorded. The ape index was determined by the difference between height and arm span (Saul et al., 2019). The value obtained by subtracting the height from the arm span was recorded as either positive or negative. For example, a positive value indicated that the height was greater than the arm span, while a negative value indicated the reverse.

Flexibility

Functional shoulder mobility was hypothesized to play a role in effective climbing (Torres et al., 2023). Flexibility was tested using a joint angle goniometer to measure the ROM. There were four items in total: shoulder flexion, shoulder external rotation, shoulder internal rotation, and overall shoulder ROM measurement. All measurements were conducted on the dominant side, with each test performed twice, and the larger value recorded.

Shoulder flexion test

Subjects were instructed to lie on their back with the shoulder joint placed at the edge of the bed in a neutral position. The goniometer's axis was positioned on the greater tuberosity of the humerus, with the fixed arm aligned with the thoracic cavity's midline and the moving arm aligned with the lateral humerus. Subjects actively lifted their arms from their thighs toward their ears while maintaining a pain-free movement. In this study, ICC score was excellent test–retest reliability (shoulder flexion: 0.998).

Shoulder external rotation test

For the external rotation test, subjects lay on their back with their shoulder and elbow bent at 90 degrees. The goniometer axis was placed on the olecranon process, with the fixed arm vertical to the ground and the moving arm aligned with the humerus. Subjects rotated their forearm backward painlessly. In this study, ICC score was excellent test–retest reliability (shoulder external rotation: 0.998).

Shoulder internal rotation test

The subject was instructed to lie on his back, and the shoulder and elbow joint were bent at 90 degrees, respectively, and the axis of the goniometer was placed on the olecranon process, the fixed arm was vertical to the ground, and the moving arm was at the parallel to the lateral midline of the humerus, and the distal end could be aligned with the ulnar styloid process. The subject was asked to actively rotate the forearm forward and close to the bed surface without pain. In this study, ICC score was excellent test–retest reliability (shoulder internal rotation: 0.91).

Overhead shoulder flexibility test

Subjects stood while holding a pole with palms downward, lifting it overhead and back to the lower back without bending the elbows or moving the pelvis. This movement was repeated five times, and the minimum distance between the hands was recorded. In this study, ICC score was excellent test–retest reliability (overhead shoulder flexibility: 0.968).

Maximum muscle strength

Maximum muscle strength was measured with a handheld device (MicroFET3). Measurements were taken on the dominant side, with two trials separated by a 30-second rest, and the larger value was recorded. A professional physical therapist supervised the tests.

Shoulder extensors test

Subjects were instructed to stand with their upper body against the wall, keeping their arm at the side of the body and the elbow flexed at approximately 90 degrees. The researcher placed the measuring instrument on the wall at the same height as the subject's elbow. The subjects then positioned their elbow on the instrument and exerted maximum force actively. In this study, ICC score was excellent test–retest reliability (shoulder extensors: 0.989).

Shoulder external rotators test

Subjects were instructed to lie down with their shoulder and elbow flexed at approximately 90 degrees. The researcher placed the measuring instrument on the back of the subject's wrist. The subjects then actively rotated their shoulder back to exert maximum force. In this study, ICC score was excellent test–retest reliability (shoulder external rotators: 0.98).

Elbow flexors test

Subjects were instructed to stand with their dominant arm close to the side of the body and the elbow flexed at approximately 90 degrees. The researcher placed the measuring instrument on the lower edge of the table at the same height as the subject's wrist. The subjects then positioned their wrists on the instrument and exerted maximum force vertically upwards as much as possible. In this study, ICC score was excellent test–retest reliability (elbow flexors: 0.989).

Finger flexors test

Subjects were instructed to stand with their dominant arm close to the side of the body and the elbow flexed at approximately 90 degrees. The subjects held the measuring instrument in their palm and applied maximum force vertically with their fingers on the instrument. In this study, ICC score was excellent test–retest reliability (Finger flexors: 0.976).

Upper Quarter Y-Balance Test (UQYBT)

The UQYBT assessed upper limb dynamic stability with high reliability (Gorman et al., 2012). Cramer et al. further reported inter-rater ICC scores exceeding 0.98 for the QUYBT, demonstrating its reliability as a cost-effective tool for assessing upper quarter physical performance measures (Cramer et al., 2017). Measurements of upper limb length were standardized, and barefoot subjects supported the YBT instrument with one hand while extending the other in three directions (Medial, Superolateral, and Inferolateral). Each extension required a controlled stop without exerting force on the ground. Each direction was tested twice, and average distances were normalized against limb length.

Statistical analyses

An a priori sample size calculation was estimated based on the expected difference between the pre-test and post-test estimates of the muscle strength among the three conditions, using G*Power (Faul et al., 2007) to estimate (power = 0.8) and the calculated sample size is at least 20 people. To increase statistical power, we enrolled 22 participants.

All data were displayed as means ± standard deviations. Statistical analyses were performed using the SPSS software version 20.0 (IBM, Chicago, IL, USA). Data was examined for normality using a Shapiro-Wilks test. Statistical differences were considered significant at $P < 0.05$. If the results of Mauchly’s sphericity test indicated that the sphericity assumption was violated, the Greenhouse–Geisser adjustment was used to correct the degrees of freedom. Three conditions of factors (DW, VR, CW) X 2 time factors (pre-test, post-test) calculate the two-way repeated analysis of variance (ANOVA) to determine the significance of any between conditions and between-time differences for the dependent variables. Moreover, Bonferroni post hoc tests were performed to control type I error because multiple comparison methods were employed.

The difference in change (Δ) was from pre-test to post-test measurements within each condition and was compared using a 1-way repeated-measures ANOVA. The change between pre-test and post-test was compared using a paired t-test. The effect size (ES) was calculated to show the magnitude of the effects (Cohen d) for each condition. Effect sizes were identified as trivial (< 0.2), small (0.2 – 0.4), moderate (0.5 - 0.8), or large (> 0.8). The significance level (α level) was set at 0.05.

Results

A total of 22 subjects (11 men and 11 women) completed the study, and their data were analyzed in present Table 1.

Table 1. Characteristics of participants.

	Total	Male	Female
Subject (n)	22	11	11
Age (years)	31.1(8.4)	30.8(8.0)	31.4(9.2)
Climbing experience (yrs)	4.2(6.9)	5.6(9.2)	2.8(3.3)
Climbing grade (IRCRA Reporting)	V3	V3	V2
Body height (cm)	168.0(7.1)	173.5(4.5)	162.5(4.3)
Body weight (kg)	56.7(10.5)	62.2(12.3)	51.2(3.8)
Body mass index(kg/m^2)	20.5(1.9)	21.6(1.6)	19.4(1.5)
Lean body mass (kg)	50.1(8.8)	57.8(4.6)	42.3(2.9)
Body fat percentage (%)	14.1(4.8)	10.9(3.6)	17.3(3.5)
Arm length (cm)	168.0(11.3)	177.1(7.8)	158.9(5.1)
Ape index (ratio)	-0.9(5.0)	1.8(5.5)	-3.7(2.2)

Primary outcomes

For the shoulder flexion test, there was no significant effect in the condition factor ($F = 0.60$, $p = 0.55$); however, the significant time factor ($F = 76.53$, $p = 0.01$) and the time factor x condition factor ($F = 5.97$, $p = 0.01$) were noted. In post hoc testing, compared with the pre-test, there were significant improvements in the DW ($p = 0.01$, ES = 0.31), VR ($p = 0.01$, ES = 0.52), and CW ($p = 0.01$, ES = 0.31). In addition, the VR had a significantly positive change difference compared to the DW ($p = 0.049$) and CW ($p = 0.01$) (Table 2).

For the shoulder external rotation test, there was no significant effect in the condition factor ($F = 0.03$, $p = 0.97$); however, the time factor ($F = 46.29$, $p = 0.01$) and the time factor x condition factor ($F = 3.77$, $p = 0.03$) were noted. In post hoc testing, compared with the pre-test, there were significant improvements in the DW ($p = 0.01$, ES = 0.19), VR ($p = 0.01$, ES = 0.36), and CW ($p = 0.01$, ES = 0.21). In addition, the VR had a significantly positive change difference compared to the DW ($p = 0.02$) and CW ($p = 0.01$) (Table 2).

Table 2. Pre-and-post-test descriptive results in upper limb flexibility.

Warm-up#	DW				VR				CW			
	Flexion	ER	IR	OHF	Flexion	ER	IR	OHF	Flexion	ER	IR	OHF
Pre	170.64 (13.16)	88.91 (10.30)	51.18 (8.61)	99.77 (11.37)	167.64 (11.44)	86.27 (10.62)	51.36 (8.67)	100.55 (11.54)	172.55 (11.40)	88.64 (9.94)	51.55 (7.88)	97.52 (10.79)
Post*	178.91 (12.12)	92.64 (9.02)	53.36 (7.52)	96.05 (13.52)	181.27 (11.14)	94.82 (11.56)	56.73 (9.91)	94.70 (12.08)	179.45 (9.94)	93.27 (11.93)	54.55 (7.76)	94.14 (11.94)
Change	8.27 (7.54)	3.73 (5.14)	2.18 (6.73)	-3.73 (5.16)	13.64[a,b] (8.52)	8.55[a,b] (5.66)	5.36 (8.40)	-5.84 (4.46)	6.91 (6.58)	4.64 (7.96)	3.00 (6.95)	-3.39 (4.40)
Effect size	0.31	0.19	0.13	-0.15	0.52	0.36	0.28	-0.24	0.31	0.21	0.19	-0.15

DW, Dynamic Warm-up; VR, Vibrating Rollers; CW, Climbing Warm-up. ER = Shoulder External Rotation, IR = Shoulder Internal Rotation, OHF = Overhead Shoulder Flexibility. Data were represented as mean (SD). * Indicated a significant difference in the time factor. # Indicated a significant interaction effect in shoulder flexion and ER. [a] Significant difference ($p < 0.05$) compared with DW. [b] Significant difference ($p < 0.05$) compared with CW.

Table 3. Pre-and-post-test descriptive results in maximum upper limb muscle strength.

Warm-up#	DW				VR				CW			
	EF	FF	SE	SER	EF	FF	SE	SER	EF	FF	SE	SER
Pre	25.84 (8.52)	19.90 (5.99)	20.63 (4.93)	15.42 (3.49)	26.65 (7.73)	20.50 (6.21)	20.20 (4.98)	14.58 (2.65)	24.43 (7.50)	20.05 (6.25)	19.25 (3.95)	14.72 (3.60)
Post*	25.54 (7.60)	20.55 (6.18)	20.67 (4.85)	14.76 (3.12)	25.19 (8.30)	20.97 (7.05)	20.71 (5.09)	14.64 (2.75)	25.98 (8.97)	20.57 (6.40)	20.82 (4.95)	15.44 (4.10)
Change	-0.30 (3.06)	0.65 (2.78)	0.04 (2.31)	-0.65 (1.86)	-0.45 (3.04)	0.48 (3.06)	0.50 (2.90)	0.06 (1.64)	1.55 (3.21)	0.52 (2.92)	1.57 (3.22)	0.71[a] (2.02)
Effect size	-0.02	0.05	0.00	-0.10	-0.03	0.04	0.05	0.01	0.09	0.04	0.17	0.09

DW, Dynamic Warm-up; VR, Vibrating Rollers; CW, Climbing Warm-up. EF = Elbow Flexors, FF = Finger Flexors, SE = Shoulder Extensors, SER = Shoulder External Rotators. Data were represented as mean (SD). * Indicated a significant difference in the time factor, except FF. # Indicated a significant interaction effect in shoulder SER.[a] Significant difference ($p < 0.05$) compared with DW.

For the shoulder internal rotation test, neither the condition factor ($F = 0.52$, $p = 0.60$) nor the time factor x condition factor ($F = 1.27$, $p = 0.29$) had a significant effect. The time factor ($F = 11.69$, $p = 0.01$) showed significant improvement, indicating that all groups improved. In addition, there was no significant change difference among the three conditions (Table 2).

For the overhead shoulder flexibility test, neither the condition factor ($F = 3.06$, $p = 0.06$) nor the time factor x condition factor ($F = 1.77$, $p = 0.18$) had a significant effect. The time factor ($F = 56.00$, $p = 0.01$) showed significant improvement, indicating that all groups improved. In addition, there was no significant change difference among the three conditions. (Table 2).

Secondary outcomes

For elbow flexors maximal strength, neither the condition factor ($F = 0.45$, $p = 0.64$) nor the time factor x condition factor ($F = 2.51$, $p = 0.09$) had a significant effect. The time factor ($F = 0.66$, $p = 0.04$) showed significant improvement, indicating that all groups improved. In addition, there was no considerable change difference among the three conditions (Table 3).

For finger flexors maximal strength, there was no significant effect in time factor ($F = 2.32$, $p = 0.14$), condition factor ($F = 0.45$, $p = 0.64$), and time factor x condition factor ($F = 0.02$, $p = 0.98$). In addition, there was no significant change difference among the three conditions (Table 3).

For shoulder extensors maximal strength, there was no significant effect in condition factor ($F = 1.05$, $p = 0.36$) and time factor x condition factor ($F = 1.47$, $p = 0.24$). Thetime factor ($F = 5.67$, $p = 0.03$) was showed significant improvement, indicating that all groups improved. In addition, there was no considerable change difference among the three conditions. (Table 3).

For shoulder external rotators maximal strength, there was no significant effect in time factor ($F = 0.03$, $p = 0.87$), condition factor ($F = 0.83$, $p = 0.44$), and time factor x condition factor ($F = 3.24$, $p = 0.047$). In post hoc testing, compared with the pre-test, there were significant improvements in the DW ($p = 0.01$, ES = -0.10), VR ($p = 0.01$, ES = 0.01), and CW ($p = 0.01$, ES = 0.09). In addition, CW had a significantly positive change difference compared to the DW ($p = 0.04$) (Table 3).

For upper extremity dynamic stability, there was no significant effect in condition factor ($F = 0.02$, $p = 0.98$) and time factor x condition factor ($F = 1.92$, $p = 0.16$). The time factor ($F = 59.95$, $p = 0.01$) showed significant improvement, indicating that all groups improved. In addition, there was no significant difference between the three conditions. (Table 4).

Table 4. Pre-and-post-test descriptive results in upper limb dynamic stability.

Warm-up	DW	VR	CW
Pre	0.99 (0.06)	0.99 (0.07)	0.98 (0.06)
Post*	1.01 (0.06)	1.01 (0.07)	1.02 (0.06)
Change	0.02 (0.00)	0.02 (0.00)	0.03 (0.01)
Effect size	0.16	0.14	0.32

DW, Dynamic Warm-up; VR, Vibrating Rollers; CW, Climbing Warm-up. Data are represented as mean (SD). *Indicated a significant difference in the time factor ($P < .05$)

Discussion

This study compared the acute effects of three distinct warm-up regimes on upper limb flexibility, maximal muscle strength, and dynamic stability in recreational rock climbers. The key findings are summarized as follows: (1) All warm-ups significantly enhanced the flexibility of the upper limbs, with VR showing greater improvement compared to DW and CW. (2) All warm-ups significantly improved the strength of the elbow flexors and shoulder extensors, but not the finger flexors, with CW showing greater gains in shoulder external rotators strength compared to DW. (3) All three warm-ups notably increased the dynamic stability of the upper limb.

Numerous VR studies have demonstrated significant improvements in ROM of the knee and ankle joints in the lower limbs (Alonso-Calvete et al., 2022; Lee et al., 2018; Lin et al., 2020; Park et al., 2021; Reiner et al., 2021), yet studies focusing on the upper limbs were relatively scarce. Researchers proposed that the vibratory sensation could serve as a stimulus for muscles, potentially inhibiting the Golgi tendon organs, reducing muscle contractions, and facilitating muscle relaxation(Lai et al., 2020). The effects of VR were confirmed to enhance muscle elasticity and joint ROM and alleviate pain(Cheatham et al., 2019; De Benito et al., 2019; Han et al., 2017; Romero-Moraleda et al., 2019), aligning with the hypothesis that VR intervention effectively improves upper limb ROM (i.e., shoulder flexion and external rotation) in the present study.

All warm-ups significantly enhanced the strength of the elbow flexors and shoulder extensors, though not the finger flexors, with CW providing greater improvements in shoulder external rotator strength compared to DW. Previous studies pointed out the critical role of upper limb muscle strength in rock climbing (Giles et al., 2021; Michailov et al., 2009). Rock climbing techniques such as Campus or Figure Four demanded robust strength in the upper limb muscles, particularly the elbow flexors and shoulder extensors (i.e., biceps and latissimus dorsi). Additionally, the importance of digit and elbow flexors for climbing performance was emphasized, noting that fatigue in these muscles could impair climbing capability (Deyhle et al., 2015). Muscle endurance in the fingers was also identified as a pivotal factor for elite climbers. (Saul et al., 2019). However, this study found that significant enhancements were limited to finger flexors strength. This outcome may have been due to participants' varying climbing skills: relatively simple routes might not have provided sufficient warm-up for more skilled climbers, whereas more challenging routes could lead to premature fatigue among less experienced individuals, potentially increasing the risk of sports injuries. Therefore, the immediate effects of post-activation potentiation (PAP) on the upper limb strength through pull-up PAP stimulation may not have occurred. Research into effective PAP protocols, including dosage, timing, and loading, was recommended for pre-competition warm-up strategies for climbers. (Sas-Nowosielski and Kandzia, 2020). Despite ongoing attempts to elucidate the physiological mechanisms underlying PAP through various methodologies (Chiu et al., 2003), this study did not investigate PAP's physiological aspects, suggesting the potential for future research incorporating myoelectric signals to explore neuromuscular physiology.

Regarding upper limb dynamic stability, all three warm-up interventions had significant improvements. Although little research explored warm-up effects on upper limb stability, the use of the UQYBT in this study provided valuable information (Gokalp and Kirmizigil, 2020), such as the ROM and stability of upper limb and shoulder girdle and core stability to achieve the ability that one hand supported stably, the other hand extend as far as possible and keeping body balance (Westrick et al., 2012). While UQYBT was previously confirmed to be accurate and reliable (Gorman et al., 2012), there was still no research to verify the correlation between rock climbing ability and upper limb dynamic stability. Many climbing skills, such as Dyno, Double Dyno, or Gaston, required strong upper limb stability. However, this study showed that all three warm-ups significantly improved upper limb dynamic stability, but further research is needed to explore the connection between stability and climbing ability.

The limitations of this study included investigating the relevant warm-up methods among recreational rock climbers. Thus, no restrictions were imposed on climbing ability during acceptance conditions, potentially leading to variations in ability levels. Notably, boys exhibited a higher average climbing experience compared to girls (Table 1). Regarding the choice of vibration frequency, a frequency of 33Hz was utilized, consistent with prior research indicating that frequencies between 28 Hz and 45 Hz effectively improved various aspects, such as ROM, muscle stiffness, muscle endurance, and specific lower limb sports performance(Chen et al., 2023; Lee et al., 2018). However, limited studies focused on upper limb interventions with vibrating rollers, suggesting the need for further exploration of optimal frequencies for upper limb interventions. Finally, the study focused on single warm-up methods (DW, VR, or CW), highlighting the potential for future research into combinations, such as vibrating rollers paired with climbing-specific warm-ups.

Conclusion

The immediate effects of three 10-minute warm-up protocols -DW, VR, and CW- on recreational rock climbers. All three warm-ups significantly improved upper limb flexibility, with VR showing the greatest enhancement compared to DW and CW. Additionally, all warm-ups increased the maximal muscle strength of the elbow flexors and shoulder extensors, although no significant changes were observed in finger flexors. CW demonstrated superior improvements in the maximal muscle strength of the shoulder external rotators compared to DW. Furthermore, all warm-ups effectively enhanced upper limb stability, emphasizing their value in preparing climbers for performance. These results underline the importance of warm-up strategies and provide a foundation for future research to explore more complex and combined warm-up protocols for climbers.

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Key points

- This was the first study to assess the immediate effects of dynamic stretching warm-up (DW), vibration rolling warm-up (VR), and climbing-specific warm-up (CW) on recreational rock climbers.
- All three warm-ups significantly enhanced the flexibility of the upper limbs, but VR had a significant improvement than DW and CW.
- All three warm-ups significantly enhanced the maximal muscle strength of elbow flexors and shoulder extensors, but did not finger flexors.
- CW showed significant improvements in the maximal muscle strength of the shoulder external.

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