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ORIGINAL ARTICLE

# Optimal warm-up stimuli of muscle activation to enhance short and long-term acute jumping performance

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**Abstract** The aim of this study was to determine the effect of different types of active warm-up stimuli of muscle activation on explosive jumping performance after short (5 min postwarm-up) and long (6 h postwarm-up) recovery periods following warm-up. Twelve trained volleyball players (21-24 years) performed different types of specific warm-up stimuli (WP) after baseline measurements [e.g., countermovement jump (CMJ) without and with extra load and Drop jump (DJ)] on randomized separate occasions: (1) three sets of five jumps with extra load (WP1), (2) two sets of four reps at 80% of 1RM parallel squat ($1RM_{PS}$) and two sets of two reps at 85% of $1RM_{PS}$ (WP2), (3) two sets of four reps at 80% of $1RM_{PS}$ and two sets of two reps at 90% of $1RM_{PS}$ and two sets of one rep at 95% of $1RM_{PS}$ (WP3), (4) three sets of five DJs (WP4), (5) specified warm-up for a volleyball match (WP5), (6) three sets of five reps at 30% $1RM_{PS}$ (WP6), and (7) an experimental condition of no active warm-up. Height in DJ significantly improved ($P < 0.05$) after WP1 (4.18%), WP2 (2.98%), WP3 (5.47%), and WP5 (4.49%). Maximal power output during CMJ with extra load significantly improved ($P < 0.05$) after WP2 (11.39%), WP5 (10.90%), WP3 (9%), and WP1 (2.47%). High-intensity dynamic loading (e.g., 80–95% 1RM), as well as specific volleyball warm-up protocol bring about the greatest effects on subsequent neuromuscular explosive responses. Acute positive effects on jumping performance after warm-up were maintained after long recovery periods (e.g., 6 h following warm-up), particularly when prior high-intensity dynamic actions were performed.

**Keywords** Warm-up · Complex training · Power · Vertical jump

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## Introduction

The muscle power and explosiveness of muscular actions (i.e., the rate at which force can be applied) has been shown as a main factor in performance in most sports (Young 1993; Izquierdo et al. 2002). It is generally assumed that explosive movements such as jumping ability require a proper warm-up to achieve high levels of explosive force production. Recent research provides evidence that prior maximal voluntary isometric contractions (Gullich and Schmidtbleicher 1996) and maximal or high-intensity dynamic exercises (e.g., one repetition to five repetition maximum squats/snatches) (Radcliffe and Radcliffe 1996; Young et al. 1998; Gourgoulis et al. 2003) can enhance the rate of force development, increase jump height during repeated countermovement jumps (CMJ) and drop jumps (DJ) (Gullich and Schmidtbleicher 1996), vertical jump performance (Gourgoulis et al. 2003; Young et al. 1998), and horizontal CMJ (Radcliffe and Radcliffe 1996).

Most studies that have focused on the enhancement of strength-power performance resulting from optimal warm-up protocols to improve jumping performance have involved isometric contractions or a set of repetitions with low (e.g., 30% of 1RM) heavy weight (e.g., one repetition maximum to five repetition maximum) or maximal isometric contractions, but the results are inconsistent. Some studies have shown improvements in jumping performance (e.g., CMJ, DJ, long jump) (Gullich and Schmidtbleicher 1996; Young et al. 1998; Gourgoulis et al. 2003; Radcliffe and Radcliffe 1996) following an acute bout of heavy resistance exercise (e.g., maximal voluntary contractions, half squats with 5RM or with increased resistance protocols from 20 to 90% of 1RM). Other studies, however, have reported no significant improvements to lower and upper body dynamic muscle actions (Gossen and Sale 2000; Jones and Lees 2003; Hrysomallis 2003) following 10-s maximal isometric or a combination of maximal dynamic actions (e.g., half-squats or knee extension exercises). Thus, the optimal warm-up protocol for explosive performance enhancement in a variety of sports for both training and competitions remains unclear.

The discrepancies between these studies may partly result from differences in (1) warm-up protocols (e.g., range of loading intensities and type of muscle contraction), (2) the muscle performance to be enhanced (e.g., jumping, throwing), (3) the latency period between the warm-up protocol and (4) the change in performance and/or the training status and fiber typing of the subjects (Sale 2002). Previous studies found improvements in performance after maximal or near maximal isometric or dynamic warm-up stimuli. To date, however, the effectiveness of a power-specific intensity (e.g., the load that maximizes power during jumping and parallel squat or the optimal jumping drop height) that would be more similar to the conditions of muscular performance required in the actual explosive performance movement, as a means of specific warm-up to enhance jumping performance to a greater extent than maximal isometric/dynamic contractions, has not been examined.

A strategy to optimize warm-up is also related to the recovery period between the end of the conditioning activity and the beginning of the performance (Bishop 2003; Sale 2002). Some evidence indicates that active warm-up of moderate intensity (e.g., 3–5 min of moderate-intensity jogging) (Goodwin 2002) or one that includes half-squats with gradually increased intensity (Gourgoulis et al. 2003; Young et al. 1998) significantly improve short-term vertical jump performance (e.g., after <5 min). When longer recovery periods are used (e.g., 5–20 min), it appears that active warm-up has also the potential to improve performance, mainly related to the same temperature-related mechanisms thought to improve short-term performance (i.e., decreased stiffness and an improved force–velocity relationship) (Binkhorst et al. 1977; Febbrario et al. 1996; Ranatunga et al. 1987; Bishop 2003). Despite the importance of warm-up for improving vertical jumping performance before nearly every athletic event or work out session, only a limited number of studies have attempted to optimize changes in jumping ability following warm up.

Finally, since high-intensity training sessions are often repeated twice a day in modern strength training, information about the time-course of acute active warm up-related performance increases could be useful from a scientific and practical point of view (e.g., optimize the effectiveness of warm-up in the morning to play an official match in the afternoon and/or optimize the use of exercise that involves heavy loads in the morning and an exercise set that emphasizes speed or power such as plyometric exercise in the afternoon).

The purpose of this study was to examine the effect of different types of active warm-up stimuli of muscle activation (e.g., experimental condition of no active warm-up verses different loaded concentric and jumping actions), as a means of specific warm-up to enhance height during vertical CMJ, height during CMJ with extra load (e.g., percentage of 1RM) that maximize power output and optimal DJ height that maximizes power output (e.g., minimal contact time and higher flying time) after short (5 min postwarm-up) and long (6 h postwarm-up) recovery periods following different stimuli of active warm-up.

## Methods

### Experimental design and approach to the problem

This study was designed to determine the effect of different types of active warm-up procedures: (1) experimental condition of no active warm-up (e.g., control) versus (2) different loaded concentric and jumping actions, as a means of specific active warm-up to enhance explosive jumping performance after short (5 min postwarm-up) and long (6 h postwarm-up) recovery periods following warm-up. The study had a randomized, balanced, test-retest design in which subjects were assessed in a series of exercise measures under seven experimental conditions on non-consecutive days. The design allowed for comparison (e.g., baseline measurements, post-5-min warm-up, and post-6-h warm-up) of the effectiveness on explosive jumping performance of several warm-up techniques, including parallel squat with different loaded concentric conditions and jumping actions.

### Subjects

This study involved a group of 12 trained males between the ages of 21 and 26 with 2–4 years of resistance training experience and 6 years of volleyball training experience (Table 1). All the subjects were competitive male Spanish first division volleyball players from the same club. Exclusion

**Table 1** Initial characteristics of the experimental group (mean ± SD)

| Age (years) | Height (cm) | Body mass (kg) | Body fat (%) | Experience (years) |
|---|---|---|---|---|
| 22.83 ± 2.65 | 183.71 ± 4.11 | 76.91 ± 8.03 | 8.25 ± 2.33 | 6.58 ± 1.83 |

criteria included any lower extremity reconstructive surgery in the past 2 years or unresolved musculoskeletal disorders that prohibited the subjects from participating in sports. Subjects were not taking (and had not previously taken) anabolic steroids, growth hormones or performance-enhancing drugs of any kind. However, individuals were not eliminated if they were taking vitamins, minerals, or related natural supplements (other than creatine monohydrate). All the subjects were carefully informed about the experimental procedures and about the possible risks and benefits associated with participation in the study and they voluntarily signed an informed consent document before any of the testing. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the responsible department; it was performed in April and May at the end of the competitive season. During the 7 months preceding the beginning of the study the subjects had trained four times a week on average and had participated in competition at a national level every weekend.

### Experimental protocol

The study consisted of a 4-week testing period. During this time subjects were required to report to the laboratory on ten separate occasions. The testing time was constant throughout the study. During the first week subjects visited the laboratory on three different days (Monday–Wednesday–Friday) as part of a regular testing program. During the first day session each subject was tested for one concentric repetition maximum (1RM) from parallel-squat ($1RM_{PS}$) position. After 1RM testing, the load that maximizes power output during parallel squat was examined by using the added relative loads of 50, 75, 100, 125, 150% of body weight, respectively. During the second testing day, the load that maximizes power output during jump squat was examined by using the added relative loads of BW − 20 kg, BW − 10 kg, BW − 5 kg, BW, BW + 5 kg, and BW + 10 kg, respectively. The third day session involved a maximal CMJ test and the examination of the optimal starting vertical height that maximizes power output during a DJ (e.g., from 20, 40, and 60 cm drop heights). The testing days were interspersed with a minimum of 48-h rest periods to limit the effects of fatigue on subsequent tests.

The seven warm-up conditions were performed during the second, third, and fourth weeks. The first warm-up stimulus was executed in the second week on Monday at 10:00 a.m. Before testing the effects of an active warm-up protocol on jumping performance, subjects carried out a standardized warm-up consisting of 10 min submaximal running at 9 km h$^{-1}$ followed by light stretching, half-squat with low loads (two sets of ten repetitions at 50% of body mass) and submaximal familiarization trials with the assessment exercises. Following the standardized warm-up, subjects were seated for 15 min to avoid possible residual acute positive effects from a prior exercise stimulus. After that time, subjects performed the baseline measures of explosive exercise performance under the experimental condition of no prior active warm-up sequence (prewarm-up), as follows: CMJ + loaded CMJ with the percentage of subject's weight (e.g., percentage of body mass) that maximize their power output and DJ from the optimal height that maximizes their power output. The rest period between jumps was 60 s. After baseline measurements of explosive jumping performance were made under the experimental condition of no active warm-up (e.g., control), subjects performed one of the seven different types of warm-up procedures (e.g., including different loaded concentric, and jumping actions) for jumping performance enhancement. After the active warm-up protocol (postwarm-up), the subjects performed a similar sequence of explosive exercise tests as those performed during the prewarm-up in a test-retest fashion, at 5 min (Post-5-min warm-up) and 6 h after the active warm-up protocol (post-6-h warm-up). The same protocol was used for each stimulus during the second, third, and fourth weeks.

All the subjects underwent the same treatment during the experimental period. Their daily schedules were quite similar, and every test was at 10:00 a.m. and 4:00 p.m. Consideration was given to the rest interval between stimuli, with each stimulus being carried out every 72 h. The subjects were instructed to avoid any strenuous physical activity during the experiment and to maintain their dietary habits for the whole duration of the study. Body weight and body fat estimates from the measurements of seven skinfold thickness (Jackson and Pollock 1978) were made at the beginning of the first testing session. The subjects were carefully familiarized with the testing protocol as they had been previously tested on several occasions during the season, with the same testing procedures for control training purposes. In addition, several warm-up muscle actions were recorded prior to the maximal and explosive test actions.

The test-retest reliability coefficients for the day-to day reproducibility of the testing procedure variables used in this study were greater than 0.91 and the coefficients of variation (CV) ranged from 1.1 to 2.3%.

## Performance testing

### *Vertical height and maximal muscle power output during jumping*

A CMJ was used to maximize stretch–shortening cycle activity and to assess explosive strength of the lower extremity muscles. The CMJ test was performed using an electronic contact mat system (Globus Tester, Codogne, Italy). Jump height was determined using an acknowledged flight-time calculation (Bosco et al. 1983). During the CMJ, the subject was instructed to rest his hands on his hips while performing a downward movement, followed by a maximum effort vertical jump. All the subjects were instructed to land in an upright position and to bend the knees on landing. The best of four trials was recorded for further analyses.

The load that maximizes power output during jump squat was also examined by using the added relative loads of BW − 20 kg, BW − 10 kg, BW − 5 kg BW, BW + 5 kg, and BW + 10 kg, respectively. Jump squat power testing was assessed using a squatting apparatus (Smith machine) in which the barbell was attached at both ends, with linear bearings on two vertical bars allowing only vertical movements, and using an electronic contact mat system (Globus Tester) to determine the flight time of the jump. Average mechanical power of each jump for each loading condition was calculated from the flight phase time (Bosco et al. 1983). The optimal loading condition for maximal power output during jumping (optimal loaded CMJ) was thereafter assigned as one of the warm-up stimuli for jumping performance enhancement. Adequate recovery was allowed between all trials (2–3 min). In all these neuromuscular performance tests strong verbal encouragement was given to all subjects to motivate them to perform each test action as maximally and rapidly as possible.

### *Optimal drop jump height (DJ)*

The optimal vertical starting height that maximizes power output during DJ was examined from a 20, 40, and 60-cm-high platform, using an electronic contact mat system (Globus Tester). Height and power were determined using an acknowledged flight-time/contact-time calculation (Bosco et al. 1983). The subjects were instructed to place their hands on their hips and step off the platform with the leading leg straight to avoid any initial upward propulsion, ensuring a starting drop height of 20, 40, and 60 cm. They were instructed to jump for maximal height and minimum contact time. The subjects were again instructed to leave the platform with knees and ankles fully extended and to land in a similarly extended position to ensure the validity of the test. The best jump height attained with contact of less than 250 ms was recorded. Three repetitions were executed from each height with 60 s rest between trials. The best of three trials from each height was recorded and assigned as a warm-up condition for jumping performance enhancement.

### *Maximal strength and muscle power test during parallel squat*

The half-squat was selected to provide data on maximum strength through the full range of motion of the muscles involved. Maximal strength of the lower extremity muscles was assessed using one repetition concentric maximum (1RM) parallel squat action ($1RM_{PS}$). In the half-squat the shoulders were in contact with a bar and the starting knee angle was 85°. On command, the subjects performed a concentric leg extension (as fast as possible) starting from the flexed position to reach the full extension of 180° against the resistance determined by the weight plates added to both ends of the bar. The trunk was kept as straight as possible. A safety belt was used by all subjects. All the tests were performed in a squatting apparatus (Smith machine). Warm-up consisted of a set of ten repetitions at loads of 40–60% of the perceived maximum. Thereafter, five to six separate single attempts were performed until the subject was unable to extend the legs to the required position (Izquierdo et al. 2002). The last acceptable extension with highest possible load was determined as 1RM. The rest period between actions was always 2 min.

The load that maximizes power output during parallel squat was tested using added relative loads of 50, 75, 100, 125, and 150% of body weight, respectively. In this case, the subjects were instructed to move the loads as fast as possible. Two test actions were recorded with each weight and the best reading (with the highest power) was taken for further analysis. The time for rest between each trial was also 2 min. During the lower extremity test actions, bar displacement, peak, and mean power (Watts) were recorded by linking a rotary encoder to the end part of the bar. The rotary encoder recorded the position and direction of the bar to an accuracy of 0.0003 m. Software (Rotational Globus Real Power) was used to calculate the power output for each repetition of half-squat performed throughout the whole range of motion (Izquierdo et al. 2002). The load condition that maximizes power output served as a warm-up stimulus for jumping performance enhancement (optimal Squat load).

## Warm-up stimuli

After baseline measures (prewarm-up) of explosive jumping performance (e.g., CMJ, optimal loaded CMJ, and optimal DJ) were made under the experimental condition of no active warm-up (e.g., control), subjects performed one of the seven different types of warm-up procedures (e.g., including different loaded concentric, and jumping actions) for jumping performance enhancement on randomized separate occasions. Postwarm-up, the subjects performed a similar sequence of explosive exercise tests as those performed during the prewarm-up in a test-retest fashion, 5 min (Post-5-min warm-up) and 6 h after the active warm-up protocol (Post-6-h warm-up). The same protocol was used for every warm-up protocol during the second, third, and fourth weeks, with at least 72 h of rest between experimental sessions. The optimal individual loading condition for maximal power output during jumping (optimal loaded CMJ) and parallel squat (optimal Squat load), as well as the optimal DJ height, served as a warm-up loading condition for jumping performance enhancement. Active warm-up procedures including low to high-load tasks at different percentages of 1RM (e.g., 30, 80–85, and 80–95% of $1RM_{PS}$) were also examined. In addition, acute positive effects on jumping performance after warm-up that included a specific standard warm-up typically performed by volley-players prior to taking part in a competitive match were also evaluated. As a control session not involving any loading intervention, an experimental condition of no active warm-up was also examined.

Prior to all the stimuli, subjects carried out a standardized warm-up consisting of 5 min submaximal running at 9 km $h^{-1}$ followed by 5 min of light stretching of the lower limb, half-squat with low loads (two sets of five repetitions at 50% of body mass with 2 min of rest between sets). The first stimulus consisted of the implementation of three series of five jumps with the optimal loaded CMJ obtained in the baseline test. The second stimulus consisted of two series of four repetitions to 80% of the $1RM_{PS}$ and two series of three repetitions to 85% of the $1RM_{PS}$. The third stimulus consisted of the implementation of two series of four repetitions to 80% of the $1RM_{PS}$, two series of two repetitions to 90% of the $1RM_{PS}$ and two series of one repetition to 95% of the $1RM_{PS}$. The fourth stimulus consisted of three series of five DJ from the optimal height achieved by each subject. The fifth stimulus involved a specific standard warm-up prior to taking part in a competitive volleyball match, consisting of 5 min submaximal running at 9 km $h^{-1}$, 2 min of several displacements (ahead, backwards, sideways), four different plyometric exercises [Two-foot ankle hops (five hops); Split squat jump (five jumps); Standing jump and reach (five jumps) and Rim jump (ten jumps)] followed by 5 min of light stretching. The sixth stimulus consisted of three series of five repetitions to 30% of the $1RM_{PS}$. The seventh and final stimulus was without any prior loading (in this case the subjects were resting in a seated position or light walking). Prior to performing the postwarm-up jumping exercises 6 h after the active warm-up protocol (Post-6-h warm-up), the subjects carried out a similar standardized warm-up to that performed in the prewarm-up. The time allowed for resting between the series was 1 min for all stimuli. The repetitions were carried out consecutively without any resting periods in between. Table 2 contains a schematic representation of the methodology.

### Statistical analysis

Descriptive statistics (mean ± SD) for the different variables were calculated. To assess the acute positive effects on height and muscle power output during jumping performance, a 7 (warm-up loading conditions) by 3 (time) factorial analysis of variance (ANOVA) was conducted on the vertical jump and maximal power scores for CMJ, jumps with loads, and DJ. Any significant differences found by the ANOVA were followed by Tukey post hoc analysis.

**Table 2** Outline of the timetable baseline measurements and active warm-up loading conditions

| Weeks | Days | Procedure | Rest time | Measure |
|---|---|---|---|---|
| 1 | Monday | $1RM_{PS}$/concentric PS power output load curve | 2 min | Baseline measurement |
| 1 | Wednesday | Load that maximizes power output during jump squat | 2 min | Baseline measurement |
| 1 | Friday | Maximal CMJ/optimal vertical height of DJ | 15 s | Baseline measurement |
| 2 | Monday | WP 1 (3 × 5 jumps with optimal loaded CMJ) | 1 min | Prewarm-up/post-5-min/post-6-hours |
| 2 | Thursday | WP 2 (2 × 4 reps × 80% 1RM HS; 2 × 3 × 85% 1RM HS) | 1 min | Prewarm-up/post-5-min/post-6-hours |
| 3 | Monday | WP 3 (2 × 4 reps × 80% 1RM HS; 2 × 2 × 90% 1RM HS; 2 × 1 × 95% 1RM HS) | 1 min | Prewarm-up/post-5-min/post-6-hours |
| 3 | Thursday | WP 4 (3 × 5 DJ from optimal height) | 1 min | Prewarm-up/post-5-min/post-6-hours |
| 4 | Monday | WP 5 (Specific warm-up for volleyball mach) | | Prewarm-up/post-5-min/post-6-hours |
| 4 | Thursday | WP 6 (3 × 5 reps × 30% 1RM HS) | 1 min | Prewarm-up/post-5-min/post-6-hours |
| 4 | Sunday | No preload (e.g., control) | | Prewarm-up/post-5-min/post-6-hours |

The study had a randomized, balanced, test-retest design in which subjects were assessed in a series of exercise measures under seven warm-up stimulus (WP1–WP6 and no preload condition) on non-consecutive days

When differences between the means were reported it must be assumed that significant interaction group × time was also located. All data were analyzed using the Statistical Package for Social Sciences (Version 13.0; SPSS Inc., Chicago, IL, USA) for Microsoft Windows. Statistical significance was accepted at an α level of $P \leq 0.05$.

## Results

### Performance baseline measures

Baseline strength and muscle power values (i.e., optimal load that maximizes power output during parallel squat and CMJ and optimal vertical height that maximizes power output during DJ) were determined to define the prior warm-up loading conditions. The value of 1RM Squat was 158.3 ± 24.8 kg. The muscle power output and the corresponding optimal load that maximize power output during parallel squat were 1,290 ± 164.1 W and 36.52 ± 3.2% of 1RM, respectively. The power output and load that maximize power output during CMJ were 2,381.13 ± 331.3 W, and −4.58 ± 2.3 kg of BW, respectively. The optimal height that maximizes power output during DJ was 43.33 ± 14.3 cm. The results of these tests are shown in Table 3.

### Acute effects of different types of active warm-up stimuli

At baseline, no significant differences were observed between the warm-up conditions in any of the jumping variables (CMJ, DJ, and CMJ with loads). Height in CMJ significantly improved ($P < 0.05$) after subjects performed WP1 (4.1%; 1.90 cm; $P = 0.06$) WP2 (5.01%; 2. 14 cm), WP3 (4.59%; 2.02 cm), and WP5 (6.96%; 3.08 cm), although these changes were not maintained 6 h after the postwarm-up protocol (Post-6-h warm-up) (Fig. 1). Height in DJ flight significantly improved ($P < 0.05$) after subjects performed WP1 (4.18%; 1.56 cm), WP2 (2.98%; 1.18 cm), WP3 (5.47%; 2.19 cm), and WP5 (4.49%; 1.84 cm). Furthermore, after the 6-h period followed the warm-up protocols, the increases achieved in height in DJ were maintained or slightly improved in WP1, WP2, and WP3 (Fig. 2). Finally, maximal power output during jump with extra load significantly improved ($P < 0.05$) after four active warm-up loading conditions (11.39%, 1.58 cm; 10.90%, 1.53 cm; 9%, 1.26 cm, and 2.47%, 0.34 cm in WP2, WP5, WP3, and WP1, respectively). However, a significant improvement was only maintained in WP1 (9.03%, 1.27 cm) after the 6-h period (Fig. 3).

## Discussion

A novel approach in this study was to examine the effect of an intensity loading range of several warm-up procedures (e.g., "traditional" warm-up, experimental condition of no preload verses different loaded concentric and jumping actions from 30 to 95% of 1RM) to maximize jumping ability in volleyball players. The primary findings of this investigation indicate that an acute positive effect on jumping performance (e.g., height in the CMJ without and with extra load, and in DJ) was promoted after a warm-up protocol including high-intensity dynamic resistance (i.e., 80–95% of 1RM), as well as a specific volleyball warm-up protocol (including several displacements and four different plyometric exercises). This increase in muscle performance following a warm-up procedure showed an intensity-dependent relationship, so that the highest warm-up loading intensities can have the greatest positive effects on subsequent jumping performance enhancement. It was also interesting to observe that the acute positive effects on jumping

**Table 3** Individual results of baseline measures

| Subject | 1RM squat (kg) | Maximal power squat load (Watts) | Maximal power CMJ with extra load (Watts) | Optimal height DJ (cm) |
|---|---|---|---|---|
| 1 | 160 | 1,215 (37.9% 1RM) | 2,148.187 (CMJ BW − 10 kg) | 60 |
| 2 | 170 | 1,585 (36.6% 1RM) | 3,042.47 (CMJ BW + 5 kg) | 40 |
| 3 | 180 | 1,597 (31.6% 1RM) | 2,563.817 (CMJ BW − 10 kg) | 20 |
| 4 | 130 | 1,292 (36.3% 1RM) | 1,864.431 (CMJ BW − 5 kg) | 40 |
| 5 | 160 | 1,137 (37.5% 1RM) | 2,374.612 (CMJ BW − 10 kg) | 40 |
| 6 | 120 | 1,267 (40% 1RM) | 1,917.677 (CMJ BW − 5 kg) | 60 |
| 7 | 150 | 1,345 (39.5% 1RM) | 2,304.547 (CMJ BW − 20 kg) | 40 |
| 8 | 140 | 1,125 (41.7% 1RM) | 2,446.367 (CMJ BW − 10 kg) | 60 |
| 9 | 180 | 1,275 (33.33% 1RM) | 2,635.584 (CMJ BW) | 40 |
| 10 | 130 | 1,352 (38.07% 1RM) | 2,144.157 (CMJ BW + 10 kg) | 60 |
| 11 | 180 | 1,213 (32.5% 1RM) | 2,596.217 (CMJ BW + 5 kg) | 20 |
| 12 | 200 | 1,077 (33,3% 1RM) | 2,535.561 (CMJ BW − 5 kg) | 40 |

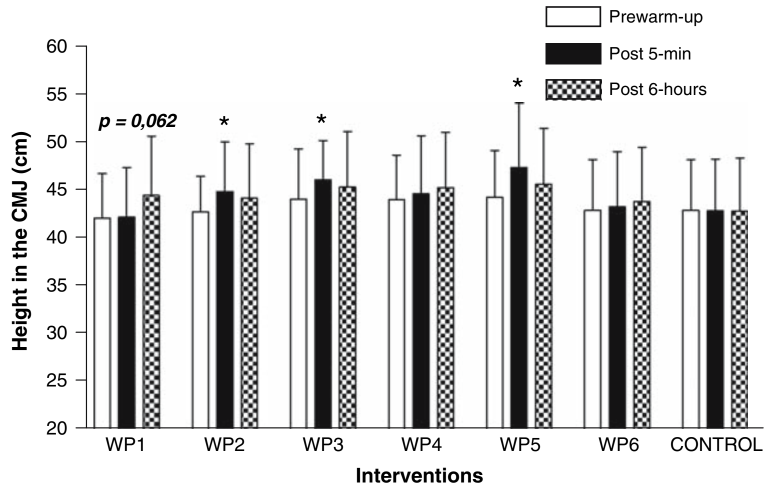


**Fig. 1** Maximal height in the CMJ (cm) performance for the seven stimuli at the specified time intervals. Data is represented as mean ± SD. *Asterisks* indicates $P < 0.05$ = significant difference from prewarm-up to post-5 min

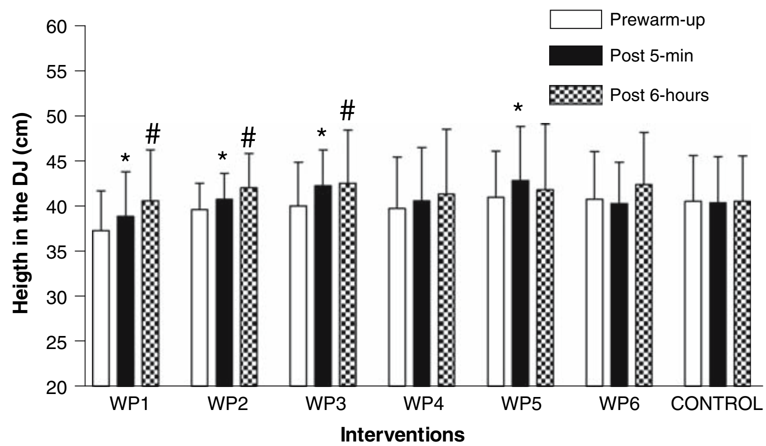


**Fig. 2** Maximal height of DJ (cm) from the optimal vertical height for the seven stimuli at the specified time intervals. Data is represented as mean ± SD. *Asterisks* indicate $P < 0.05$ = significant difference from prewarm-up to post-5 min. *Hash* indicate $P < 0.05$ = significant difference from prewarm-up to post-6 h

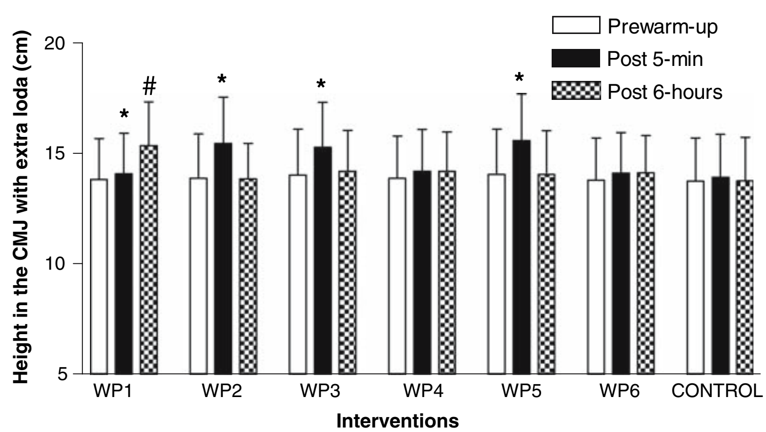


**Fig. 3** Maximal height in the CMJ with extra load (cm) performance for the seven stimuli at the specified time intervals. Data is represented as mean ± SD. *Asterisks* indicate $P < 0.05$ = significant difference from pre to post-test. *Hash* indicate $P < 0.05$ = significant difference from prewarm-up to post-6 h

performance after warm-up that included different loaded concentric and jumping actions were maintained after long recovery periods (e.g., 6 h following warm-up), particularly when prior high-intensity dynamic actions were performed.

An acute positive effect on jumping ability was observed following a warm-up protocol that included a dynamic bout of repetitions with heavy loads (80–95% of 1RM), whereas performance was unaffected after control warm-up protocols involving low intensity (e.g., 30% of 1RM) or no active warm-up (e.g., control). We also provide evidence that a specific high-intensity jumping warm-up procedure can also have a significant influence on neuromuscular jumping performance. In contrast, experimental conditions consisting of a general warm-up, no preload (i.e., control) or low-intensity dynamic contractions with 30% of 1RM had no beneficial effect on explosive dynamic muscle actions. These findings are consistent with previous reports of improvements in jumping performance (e.g., CMJ, DJ, long jump) (Gullich and Schmidtbleicher 1996; Young et al. 1998; Gourgoulis et al. 2003; Radcliffe and Radcliffe 1996) following an acute bout of heavy resistance exercise (e.g., maximal voluntary contractions, half squats with a 5RM or with increased resistance protocols from 20 to 90% of 1RM). Conceptually, this would indicate that the phenomenon of an increase in muscle jumping performance following an active warm-up protocol that includes exercises with submaximal loads and explosive execution may be intensity-dependent, necessitating higher intensity loads (>80% of 1RM) or specific jumping exercises to optimize enhancement of explosive performance.

To the best of the authors' knowledge there is a scarcity of data on the effectiveness of traditional warm-up or no preloading verses different prior power-specific stimuli on jumping performance [e.g., the load that maximizes power during jumping and parallel squat, the optimal jumping drop height and/or concentric loading range from low (30% of 1RM) to high (80–90% of 1RM) intensities] that would be more similar to the current dynamic explosive exercises used in strength and conditioning programmes (e.g., squat or jumping with optimal loads) than maximal isometric/dynamic contractions mostly used in warm-up studies. Recent research provides evidence that warm-up protocols that include maximal voluntary isometric contractions (Gullich and Schmidtbleicher 1996) and maximal or high-intensity dynamic exercises (e.g., 1–5 repetition maximum squats/snatches) (Radcliffe and Radcliffe 1996; Young et al. 1998; Gourgoulis et al. 2003) can subsequently enhance the rate of force development and increase jump height and, therefore, the acceleration attained with loads between "zero" (i.e., unloading condition) and the maximal isometric force (Vandenboom et al. 1993; Sale 2002). In doing so, a warm-up protocol that includes exercises with submaximal loads and explosive actions may be beneficial for jumping performance enhancement. However, a unique finding in this study was that only heavy intensity loading "conditioning" contractions (i.e., 80–95% of 1RM) or specific high-demand jumping warm-up may be optimal to enhance jumping performance without and with extra load. This suggests that, in order to induce optimal performance enhancement, setting the intensity of the warm-up protocol with high-dynamic loading intensities (>80% of 1RM) or specific jumping warm-up may provide the greatest benefit for jumping performance enhancement.

Because no biochemical or neuromuscular responses were measured in the present study, the determination of physiological mechanisms responsible for the different training adaptations that take place following different warm-up protocols that include different submaximal loading intensities and explosive actions is beyond its scope. Morphological changes in skeletal muscle are unlikely in such a short time (Schmidtbleicher 1987), but a warm-up that includes a heavy loading may induce a high-frequency stimulation of motor neurons (French et al. 2003) for several minutes afterwards. The result of this enhanced motor neuron excitability can be seen in a considerable improvement of rate of force development and therefore in power production (Schmidtbleicher 1991; Vandenboom et al. 1993; Sale 2002). It also appears that active warm-up has also an acute positive effect to enhance jumping performance, mainly related to an increase in muscle temperature (i.e., decreased stiffness and an improved force–velocity relationship) (Binkhorst et al. 1977; Febbrario et al. 1996; Ranatunga et al. 1987; Bishop 2003).

However, the use of prior low-intensity dynamic intensities (i.e., concentric actions with 30% of 1RM) and a series of DJ from the optimal vertical height that maximizes power output failed to enhance subsequent jumping ability. There are several possibilities why a treatment effect after these warm-up protocols was not found. One major reason may be related to the high-neuromuscular fatigue provided by the DJ, together with the short recovery period (i.e., 5 min) between the end of the plyometric exercise and the beginning of the performance. Furthermore, the lack of benefit to jumping performance of a warm-up protocol that includes low-intensity dynamic muscle actions within the population of volleyball players, mainly due to the fact that the stimulation frequency of motor units involved in explosive movements performed with low-intensity loading (i.e., 30% of 1RM) over a short period of time (three sets of five reps) are beyond the frequency stimulation limit of motoneurons, and hence will not be enough to enhance jumping performance. (Gullich and Schmidtbleicher 1996; Sale 2002).

In addition to the influence of intensity and duration of the warm-up protocol, the benefit of a warm-up technique for enhancing performance is also related to the recovery period between the end of the warm-up protocol and the beginning of the performance (Bishop 2003; Sale 2002). Some studies have shown that, in some instances, performance was not improved due to the warm-up being followed by a long recovery period. Some recent studies (Radcliffe and Radcliffe 1996; Young et al. 1998; Bishop 2003) have determined that a recovery period of more than 5 min but less than 15–20 min may be optimal to promote the greatest acute positive effect on performance. In contrast, a unique finding of this study was that the acute positive effects on jumping performance warm-up that included different loaded concentric and jumping actions were maintained after long recovery periods (e.g., 6 h following warm-up), particularly when prior high-intensity dynamic actions were performed. These findings may have important practical relevance to support the argument that the extent of acute positive effects on jumping performance after some of these warm-up protocols, and especially those that include high-loading intensities and explosive executions, would not only remain immediately after the stimulus but also for several hours afterwards. Finally, active warm-up techniques could be useful in controlling and optimizing daily training sessions that involve heavy loads in the morning and an exercise set that emphasizes speed or power (e.g., plyometric exercises) in the afternoon. It also appears that information about the time-course of acute active warm-up related performance increases could be useful to optimize the effectiveness of the warm-up protocol in the morning in order to play an official match several hours later (i.e., up to 6 h after warm-up).

In summary, the results of this study suggest that the use of warm-up protocols that include high-intensity dynamic loading (e.g., 80–95% of 1RM) as well as a specific volleyball warm-up protocol can lead to greater acute positive effects on explosive jumping performance (e.g., height in CMJ without and with extra load, and in DJ). In contrast, experimental warm-up protocols consisting of a general warm-up, the experimental condition of no active warm-up (i.e., control), a series of DJ from the optimal vertical height that maximizes power output, and low-intensity dynamic action with 30% of 1RM had no beneficial effect on explosive dynamic muscle actions. In addition, acute positive effects on jumping performance after warm-up that included different loaded concentric and jumping actions were maintained after long recovery periods (e.g., 6 h after warm-up), especially when prior high-intensity dynamic actions were performed.

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