Acute Effects of Varied Back Squat Activation Protocols on Muscle-Tendon Stiffness and Jumping Performance

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Abstract

Krzysztofik, M, Wilk, M, Pisz, A, Kolinger, D, Tsoukos, A, Zając, A, Stastny, P, and Bogdanis, GC. Acute effects of varied back squat activation protocols on muscle-tendon stiffness and jumping performance. *J Strength Cond Res* 37(7): 1419–1427, 2023—Intensity, movement velocity, and volume are the principal factors to successfully use postactivation performance enhancement. Therefore, 15 resistance-trained volleyball players completed 3 different back squat configurations as a conditioning activity (CA) in randomized order: (a) 3 sets of 3 repetitions at 85% 1RM (HL); (b) a single set of back squats at 60% 1RM until 10% mean velocity loss (VB); (c) and 2 sets of back squats at 60% 1RM until 10% mean velocity loss (2VB) on subsequent countermovement jump performance, Achilles tendon, and vastus lateralis stiffness with concomitant front thigh skin surface temperature assessment. The measurements were performed 5 minutes before the CA and at 2, 4, 6, 8, and 10 minutes. The jump height was significantly increased in the second minute and at peak, post-CA compared with baseline for all conditions ($p = 0.049$; ES = 0.23 and $p < 0.001$; ES = 0.37). Skin surface temperature was significantly increased for all post-CA time points compared with baseline in the 2VB condition (p from <0.001–0.023; ES = 0.39–1.04) and in the fourth minute and at peak post-CA in HL condition ($p = 0.023$; ES = 0.69 and $p = 0.04$; ES = 0.46), whereas for the VB condition, a significant decrease in peak post-CA was found ($p = 0.004$; ES = −0.54). Achilles tendon stiffness was significantly decreased for second, fourth, eighth, 10th, and peak post-CA in comparison to baseline for all conditions (p from $p = 0.004$–0.038; ES = −0.47 to −0.69). Vastus lateralis stiffness was significantly decreased for peak post-CA compared with baseline for all conditions ($p = 0.017$; ES = −0.42). We recommend using a single set of barbell squats with a 10% velocity loss as a mechanism of fatigue control to acutely improve jump height performance and avoid unnecessary increases in training volume.

Key Words: post-activation performance enhancement, post-activation potentiation, resistance training, velocity-based training, velocity-loss, volleyball

Introduction

Coaches and athletes seeking to acutely improve power performance often include a conditioning activity (CA) as a part of their precompetition warm-up or training session (4). An example of such a procedure is a combination of high-load (>80% one-repetition maximum [1RM]) back squat as a CA to potentiate subsequent explosive exercise with a similar movement structure, such as the vertical jump (35). The physiological mechanisms underlying the acute effect of a CA are still a matter of debate. The increase in voluntary performance usually occurs 5–7 minutes after the CA and is referred to as postactivation performance enhancement (PAPE), which is associated with changes commonly observed during the warm-up, such as increased muscle temperature, fiber water content, and muscle excitation (3). However, it cannot be ruled out that mechanisms underpinning the postactivation potentiation phenomena, such as myosin regulatory light chain phosphorylation also contribute to an increase in performance, especially because the CA may increase subsequent performance above and beyond that of the warm-up.

Although an exercise-induced muscle temperature increase is often reported as one of the explanations of the acute performance effects of CA, to the authors' knowledge, it has not been evaluated directly in studies devoted to the PAPE phenomena. It is well known that an increase in muscle temperature is associated with performance enhancement, and a rise as low as 0.3–0.9° C may contribute to neuromuscular performance improvements (33). However, in some studies, performance improvements are reported after very low-volume of the CA, which does not seem to cause a significant increase in muscle temperature (41,43). For example, in a study by Tsoukos et al. (41), a single set of bench press with 80% of one-repetition maximum (1RM) to a 10% decrease in mean velocity, which allowed the participants to perform between 2 and 5 repetitions, contributed to a significant mean propulsive velocity improvement in the subsequent bench press throw. Referring to the research devoted to changes in the temperature of muscles caused by exercise, it seems that such a training volume could even lead to a drop in muscle temperature, not its increase. For instance, a slight and nonsignificant drop in temperature was observed by Weigert et al. (45) after 10 repetitions of biceps curls at 70% 1RM. This phenomenon has already

Submitted for publication June 4, 2022; accepted October 21, 2022.

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Journal of Strength and Conditioning Research 37(7)/1419–1427

been confirmed in other studies by Formenti et al. (9) and Merla et al. (27) and could result from reactive vasoconstriction of the skin vessels and may indicate a redistribution of the blood immediately after a brief bout of intense activity. Therefore, other mechanisms may underpin the PAPE effect after a low volume CA (2–5 repetition like in study by Tsoukos et al. (41).

Another possible phenomenon that may contribute to the PAPE effect is muscle stiffness (1), but there is still little research regarding this issue (10,29). Pożarowszczyk et al. (29) found a CA-induced increase in Achilles stiffness (after single repetitions of progressive back squats at 60–100% 1RM with 10% steps); however, the authors did not evaluate subsequent changes in performance. However, a study by Gago et al. (10) showed no change in Achilles tendon stiffness despite the PAPE effect being reported (significant increase in peak twitch and rate of torque development in the plantar flexor). Because the stretch-shortening cycle is strongly related to stiffness (23), an increase in stiffness should positively affect physical fitness from the theoretical point of view. Interestingly, reduced tendon stiffness was reported after brief muscle contractions (20), with no influence on performance, whereas an increased muscle stiffness was accompanied by an acute fatigue (40,44). Therefore, it seems that the acute stiffness increase may be associated with increasing fatigue that may reduce the PAPE effect. It is speculated that elevated stiffness may be a compensatory or a protective mechanism for the body against fatigue (24). Increased stiffness may be accompanied by micro swelling within the muscle fibers, which was reported by Proske and Morgan (32). Another explanation may be a fatigue-induced increase in muscle metabolites causing myosin cross-bridges to adhere more tightly to the titin fibers (7) and reduce the relaxation time of the muscle through a lower cross-bridge detachment rate (8). Therefore, it seems that the acute stiffness increase may be associated with increasing fatigue rather than the PAPE effect. Assessing subtle modifications of muscle stiffness and viscoelastic properties of muscles may help identify the early development of muscle fatigue (36,40). This may be of great significance when optimizing the individual PAPE effect because performance enhancement is dependent on the CA-induced level of fatigue and potentiation. Therefore, when a state of fatigue exceeds potentiation, a lack or even a decrease in performance occurs, whereas improvements are noted when the potentiation state exceeds fatigue (35).

Regarding the previously reported high interindividual variability in the PAPE responses because of fatigue-potentiation balance (5), the individually determined CA volume and the rest-interval between the CA and the postactivation exercise should be considered. The determination of the appropriate CA volume can be investigated by recording the velocity loss during successive repetitions of CA, because this approach has been previously shown to be a sensitive indicator of neuromuscular fatigue (34) and effective in eliciting PAPE (41,43). The optimal rest interval can be determined when the peak PAPE response for each athlete occurred (22), which is called individualized peak performance time-points.

Because the influence of CA volume, intensity, recovery time, and velocity on musculotendinous stiffness temperature and performance remain unresolved, the purpose of the present study was to compare the acute effects of 3 different back squat configurations as a CA: (a) 3 sets of 3 repetitions at 85% 1RM; (b) a single set of back squats at 60% 1RM until 10% mean velocity loss; (c) and 2 sets of back squats at 60% 1RM until 10% mean velocity loss; on subsequent countermovement jump performance, Achilles tendon and vastus lateralis stiffness with concomitant front thigh skin surface temperature assessment. It was hypothesized that all CAs examined would significantly increase countermovement jump height, with a simultaneous decrease in the stiffness of the Achilles tendon and vastus lateralis muscle, whereas the skin temperature of the thigh would remain unchanged.

Methods

Experimental Approach to the Problem

The participants took part in a familiarization session and 3 experimental sessions within 4 weeks. The familiarization session included the determination of the 1RM load for the back squat followed by the completion of 2 sets with 60% 1RM until a 10% loss of vertical barbell velocity. The experimental sessions were performed in a randomized order, one week apart, where each participant performed: (a) 3 sets of 3 repetitions at 85% 1RM (HL); (b) a single set of back squats at 60% 1RM until 10% mean velocity loss (VB); (c) and 2 sets of back squats at 60% 1RM until 10% mean velocity loss (2VB). To examine the acute effects of the back squat exercise on subsequent countermovement jump height, a single set of 2 repetitions of the countermovement jump was performed 5 minutes before and at 2, 4, 6, 8, and 10 minutes after each activation protocol (Figure 1). Moreover, an Achilles tendon and vastus lateralis stiffness, and front thigh skin surface temperature assessments were performed approximately 30 seconds before each jumping set.

Subjects

Fifteen resistance-trained male volleyball players (age: 20-39 years; body mass: 92.1 ± 9.3 kg; height: 198 ± 10 cm; body fat: 8.7 ± 3.8%; experience in volleyball training: 15 ± 7 years; relative back squat one-repetition maximum [1RM]: 1.63 ± 0.15 kg/body mass) participated in the study. The participants had at least 3 years of resistance training experience and were free from any musculoskeletal injuries 3 months before enrollment into the study. During the study, the athletes were involved in a typical volleyball preseason preparation period. Two weeks before the start of the experiment, the athletes performed general conditioning as the first part of preseason preparation. Measurements were taken on Monday morning because the athletes had rested during the weekend. After the measurements, participants did their lower-body resistance training according to schedule, whereas on Thursdays, other upper and lower-body resistance training sessions were performed. Moreover, participants were performing volleyball-specific training, including skills and drills, small-sided games, and competition drills on Tuesdays, Wednesdays, and Fridays. Furthermore, they were asked to maintain their normal dietary and sleep habits throughout the study, and not to use any supplements or stimulants for 24 hours before testing. The study participants were allowed to withdraw from the experiment at any moment and were free from musculoskeletal disorders. They were informed about the benefits and potential risks of the study before providing their written informed consent for participation. The study protocol was approved by the Bioethics Committee for Scientific Research (3/2021) at The Jerzy Kukuczka Academy of Physical Education and performed according to the ethical standards of the Declaration of Helsinki, 2013. To calculate the sample size, statistical software (G*Power, Dusseldorf, Germany) was used. Considering the applied two-way analysis of variance (ANOVA) (3 conditions and 6 repeated measures), a small overall effect size (ES) = 0.31, an alpha-error <0.05, the desired power $(1 - ß \text{ error}) = 0.5$, and correlation among repeated measures = 0.85, the total sample

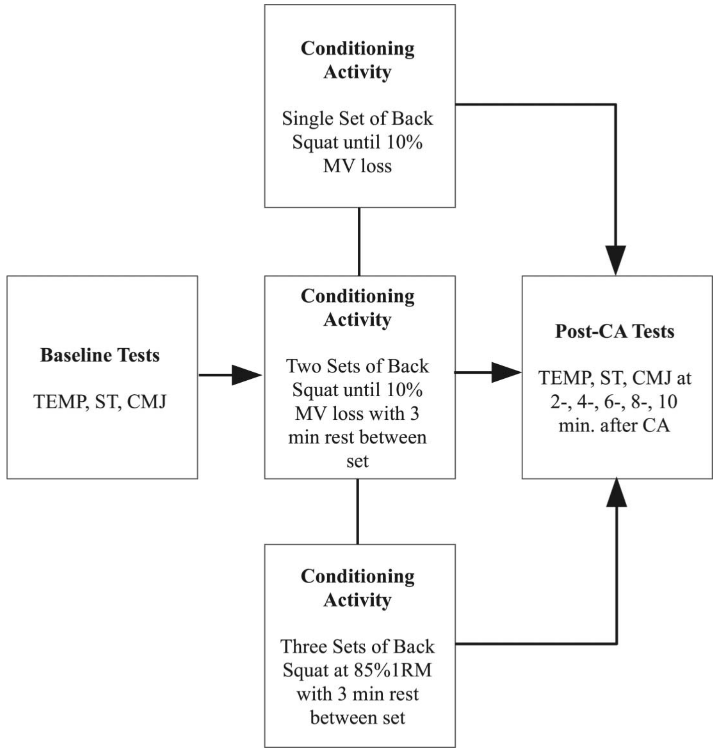

Figure 1. Schematic representation of the study design. TEMP = skin surface temperature; ST = Achilles tendon and vastus lateralis stiffness; CMJ = countermovement jump; MV = mean velocity; CA = conditioning activity. 1RM = one repetition maximum.

size resulted in 15 participants. This value of effect size was chosen according to findings from Seitz and Haff (35) on the impact of PAPE on jumping performance.

Procedures

Familiarization Session and 1RM Strength Test. The familiarization session started at the same time of the day as the upcoming experimental sessions (between 9:00 and 11:00 AM). Subjects performed a standardized warm-up consisting of cycling on a stationary bike for 5 minutes (Keiser M3 Indoor Bike, Keiser Corporation, Fresno CA) at a resistance of approximately 100 W and cadence within 70–80 rpm; followed by bodyweight exercises: squats, lunges, push-ups, forward bent overs, trunk rotations and side-bends, and submaximal vertical jumping. Next, the participants performed 10, 6, 4, and 3 repetitions of the back squat, at a load of 20 kg and 40, 60, and 80% of their estimated 1RM; respectively. The first testing load was set to an estimated 80% 1RM and was increased by 2.5–5 kg for each subsequent attempt until the participant was unable to perform a lift with the proper technique. The duration of each repetition was controlled by a metronome and fixed to 2 seconds of the eccentric phase and maximal velocity in the concentric phase of the movement. The participants started from an upright position, with the knees and hips fully extended, the stance (approximately shoulder-width apart) and feet position (flat on the floor in parallel or externally rotated to a maximum of 15°) were individually adjusted and carefully replicated on every lift (25). The barbell had to be in contact with the back and shoulders at all times (at the level of the acromion) (25). From this position, participants had to descend until they made contact with the bench and then perform the concentric phase of the movement in an explosive manner. The height of the bench was individually selected and allowed each participant to descend with the hips below the knee line. The highest load completed without any help from the spotters was defined as 1RM. Five-minute rest intervals were allowed between the 1RM attempts, and all 1RM values were obtained within 5 attempts. After the 1RM test, all participants performed 2 sets of back squats until a 10% mean velocity-loss at 60% 1RM and a set of 3 repetitions at 85% 1RM.

Experimental Sessions. In a randomized and counterbalanced order, after identical warm-up as before the 1RM test, the participants performed 3 different testing conditions, one-week apart: (a) 3 sets of 3 repetitions at 85% 1RM (HL); (b) a single set of back squats at 60% 1RM until 10% mean velocity loss (VB); and (c) 2 sets of back squats at 60% 1RM until 10% mean velocity loss (2VB). Each testing condition was completed at the same time of day for each athlete. During each CA, the participants were asked to perform each repetition with a constant duration of 2 seconds in the eccentric phase and as fast as possible during the concentric phase of the movement. The selection of CA variables was based on previous studies that showed their effectiveness in inducing the PAPE effect (35,43). Specifically, in a previous study using the bench press exercise, muscle activation was equal in the first repetitions performed as fast as possible using a load of 60% compared with 80%1RM (42). Also, a conditioning protocol using 60% of 1RM and a 10% reduction in mean movement velocity was found to optimize postactivation potentiation during bench press (43). Finally, 60%1RM falls within the optimal loading range for mean power output during back squats (37). To assess changes in jump height (JH), single sets of 2 repetitions of the countermovement jump (CMJ) were performed before and after the CA in 5 time-points with 2-minute rest intervals. Before each set of CMJ, front thigh surface temperature and viscoelastic properties of the vastus lateralis and Achilles tendon were performed.

The mean velocity-loss during the CA was evaluated by a linear position transducer Tendo Power Analyzer (Tendo Sport Machines, Trencin, Slovakia). This device is a reliable system for measuring movement velocity and power output (12). The external end of the cable was attached to the side of the bar and provided no resistance. The device was placed on the floor directly under the bar.

Measurement of Skin Surface Temperature. The FLIR E54 infrared camera (FLIR Systems, Inc., Wilsonville, OR) was used for thermographic images and then analyzed with FLIR Research Software (FLIR Systems, Inc., Wilsonville, OR). The average temperature from the quadriceps muscle zone according to criteria set out by Gomez Carmona (14) was evaluated. The camera was calibrated by a black body; the emissivity was set at the range of 0.97–0.98. Thermal images were made taking into consideration a checklist directed at standardizing thermographic imaging in sports and exercise medicine by Moreira et al. (28). All the participants were instructed to avoid behaviors that may alter skin temperature (heat or cold exposure, massage, tobacco, alcohol, caffeine etc). The participants stood perpendicular, at a distance of 1.5 m from the camera in front of a white uniform background. There was a constant room temperature (21° C), intensity of light, and no direct ventilation in the test room.

Measurement of Viscoelastic Muscle Properties. The MyotonPRO hand-held myometer (MyotonPRO, Myoton AS, Tallinn, Estonia) was used for the noninvasive assessment of the dominant limb vastus lateralis and Achilles tendon stiffness. The measurement for vastus lateralis was at 50% of the straight-line distance between the greater trochanter and fibulae capitulum (2), whereas for the Achilles tendon, it was 2 cm proximal to the superior aspect of the calcaneus (38). The Myoton's accelerometer was set at 3,200 Hz with an average value obtained from 3 consecutive measurements (0.4 N for 15 ms).

Measurement of Countermovement Jump Performance. The Optojump photoelectric cells (Microgate, Bolzano, Italy) device was used to measure jump height. It is an infrared platform with proven validity and reliability for assessing vertical jump height (13). The device measures the flight time of vertical jumps with a sampling frequency of 1,000 Hz. The jump height was calculated from flight time ($9.81 \times [\text{flight time}]^2/8$).

Each participant performed 2 CMJs without arm swing at pre-CA as a baseline and in 5 time-points post-CA (2, 4, 6, 8, and 10 minutes after completion of the CA). The participant started in the standing position with hands placed on the hips. Then, they were instructed to perform a quick downward movement at a self-selected depth and, afterward, a fast-upward movement to jump as high as possible. The participant reset to the starting position after each jump, and the procedure was completed for a total of 2 jumps. The jump height was evaluated, and the best attempt was kept for further analysis. Because of the high interindividual variability in the potentiation responses (5) and the individualized recovery time approach (5,22), also the highest value obtained post-CA was analyzed.

Statistical Analyses

All statistical analyses were performed using SPSS (version 25.0; SPSS, Inc., Chicago, IL) and were expressed as means with standard deviations (±*SD*). Moreover, the 95% confidence intervals for mean values and relative differences (i.e., in percentages) between baseline (BA) and post-CA values were also calculated. Statistical significance was set at $p < 0.05$. The relative (two-way mixed effects, absolute agreement, single rater intraclass correlation coefficient) and absolute (coefficient of variation; dispersion of the variable) reliability were calculated from the baseline measurements taken for each of the dependent variables (21). The Shapiro-Wilk and Mauchly's tests were used to verify the normality and sphericity of the sample data variances, respectively. The one-way ANOVAs were used to compare load and number of performed repetitions during CAs. The two-way repeated measures ANOVAs (3 conditions × 6 time points) were used to investigate the influence of CA on the tendon and muscle stiffness, skin surface temperature, and jump height. Additional two-way ANOVAs (3 conditions × 2 time points [pre-CA; best post-CA]) were used to examine individual peak PAPE responses (the values of stiffness and skin surface temperature at the corresponding time point in which the highest post-CA jump height was recorded were selected for further analysis, i.e., if the highest post-CA jump height occurred at fourth min, then a stiffness and skin surface temperature value recorded at fourth min were evaluated). When a significant main effect or interaction was found, the post-hoc tests with Bonferroni correction were used to analyze the pairwise comparisons. The magnitude of mean differences was expressed with standardized effect sizes. Thresholds for qualitative descriptors of Hedges *g* was interpreted as ≤0.20 "small", 0.21–0.79 "medium", and >0.80 as "large" (6). Pearson's product-moment correlation coefficient was used to analyze the relationship between 1RM back squat, baseline jump height, baseline viscoelastic muscle properties, and percentage changes between baseline and best post-CA value vs. the magnitude of PAPE response. Thresholds for qualitative descriptors of correlations were interpreted as: trivial (0.0–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.0) (17).

Results

The descriptive statistics of CAs are presented in Table 1. The ICC and CV were respectively: for AT stiffness: 0.89 (95% CI: 0.74–0.96) and 4.7%; for VL stiffness: 0.81 (95% CI: 0.55–0.93) and 6.3%; for skin surface temperature: 0.94 (95% CI: 0.83–0.98); and for JH: 0.97 (95% CI: 0.93–0.99) and 3.2%. The best jump height was recorded respectively: 3:36 ± 2:02 minutes after VB, 4:16 ± 2:30 minutes after 2VB, and 3:28 ± 1:46 minutes after HL.

The one-way ANOVA indicated a significant difference between the lifted load ($F = 75.347$; $p < 0.001$) and the number of performed repetitions ($F = 59.897$; $p < 0.001$) between particular CAs. The post-hoc analysis showed that a significantly higher load was lifted during the 2VB and HL conditions compared with the VB condition ($p < 0.001$ for both; ES = 2.42 and 3.03; respectively). Furthermore, a significantly greater number of repetitions was performed during the 2VB condition in comparison to the VB and HL conditions ($p < 0.001$ for both; ES = 2.75 and 2.36), and a significantly greater load was lifted during the HL than VB condition ($p = 0.004$; ES = 1.38).

Table 1
Characteristics of the conditioning activity (back squat using 60% of one-repetition maximum) in the 10% mean velocity-loss trial.*†

	VB	2VB	HL
Lifted load [kg]	85 ± 8	85 ± 8	121 ± 12
Volume load [kg]	598 ± 196‡	1,175 ± 263	1,089 ± 107
Total number of repetitions [n]	7 ± 2‡	14 ± 3§	9 ± 0
Maximum mean barbell velocity in set [m·s^{-1}]	0.92 ± 0.05	0.93 ± 0.06	—
Minimum mean barbell velocity in set [m·s^{-1}]	0.78 ± 0.06	0.79 ± 0.07	—
Maximal number of repetitions in set [n]	11	12	3
Minimal number of repetitions in set [n]	4	4	3

*VB = condition used a single set of velocity-controlled conditioning activity; 2VB – = condition used two sets of velocity-controlled conditioning activity; HL – = condition used high load conditioning activity.
†Results are mean ± *SD*.
‡Significant difference in comparison to other condition.
§Significant difference in comparison to HL condition.

Jump Height

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 0.511$; $p = 0.88$), but a main effect of time for jump height ($F = 7.567$; $p < 0.001$). The post-hoc analysis showed a statistically significant increase in jump height in the second minute post-CA in comparison to baseline for all conditions ($p = 0.049$; ES = 0.23).

Individual Peak Responses in Jump Height

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 0.276$; $p = 0.761$), but a main effect of time for peak jump height ($F = 52.449$; $p < 0.001$). The post-hoc analysis showed a statistically significant increase in peak post-CA jump height in comparison to baseline for all conditions ($p < 0.001$; ES = 0.37) (Figure 2).

Front Thigh Skin Surface Temperature

The repeated measures two-way ANOVA indicated a statistically significant interaction ($F = 8.967$; $p < 0.001$). The post-hoc analysis showed a statistically significant increase in skin surface temperature for all post-CA time points compared with baseline in the 2VB condition (p from <0.001 to 0.023; ES = 0.39–1.04) and in the fourth minute post-CA in HL condition ($p = 0.023$; ES = 0.69) (Figure 2).

Individual Peak Responses in Front Thigh Skin Surface Temperature

The repeated measures two-way ANOVA indicated a statistically significant interaction ($F = 30.351$; $p < 0.001$). The post-hoc analysis showed a statistically significant increase in skin surface temperature at peak post-CA in 2VB ($p < 0.001$; ES = 0.83) and HL ($p = 0.04$; ES = 0.46) condition, and a decrease in the VB condition ($p = 0.004$; ES = −0.54) compared with baseline. Furthermore, skin surface temperature at peak post-CA in the VB condition was significantly lower in comparison to 2VB ($p <$ 0.001; ES = 0.96) and HL ($p < 0.001$; ES = 0.46) conditions (Figure 2).

Achilles Tendon Stiffness

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 0.978$; $p = 0.465$), but a main effect of time for AT stiffness ($F = 5.714$; $p < 0.001$). The post-hoc analysis showed a statistically significant decrease in Achilles tendon stiffness in the second ($p = 0.038$; ES = −0.47), fourth (p = 0.012; ES = −0.41), eighth ($p = 0.023$; ES = −0.6), and 10th minute ($p = 0.024$; ES = −0.69) post-CA in comparison to baseline for all conditions (Figure 3).

Individual Peak Responses in Achilles Tendon Stiffness

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 0.119$; $p = 0.888$), but a main effect of time for Achilles tendon peak stiffness values (F = 12.092; $p = 0.004$). The post-hoc analysis showed a statistically significant decrease in Achilles tendon stiffness at peak post-CA compared with baseline for all conditions ($p = 0.004$; ES = −0.53) (Figure 3).

Vastus Lateralis Stiffness

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 1.568$; $p = 0.184$) nor main effect of time ($F = 1.304$; $p = 0.286$) and condition ($F = 0.994$; p = 0.383) (Figure 3).

Individual Peak Responses in Vastus Lateralis Stiffness

The repeated measures two-way ANOVA indicated no statistically significant interaction ($F = 0.212$; $p = 0.81$), but a main effect of time for vastus lateralis stiffness ($F = 7.334$; $p = 0.017$). The post-hoc analysis showed a statistically significant decrease in VL stiffness at peak post-CA compared with baseline for all conditions ($p = 0.017$; ES = −0.42) (Figure 3).

Relationship Between Subjects' Characteristics and the Magnitude of Postactivation Performance Enhancement

No statistically significant correlations were found between 1RM back squat, baseline jump height, and stiffness vs. the magnitude of PAPE response (Figure 4). Also, in the case of the percentage changes in the baseline values and at peak PAPE response in skin surface temperature, and stiffness vs. the magnitude of PAPE response, no significant correlations were found (Figure 5).

Discussion

The purpose of this study was to examine the acute effects of 3 distinct back squat CA protocols on countermovement jump height, Achilles tendon and vastus lateralis stiffness, and front thigh

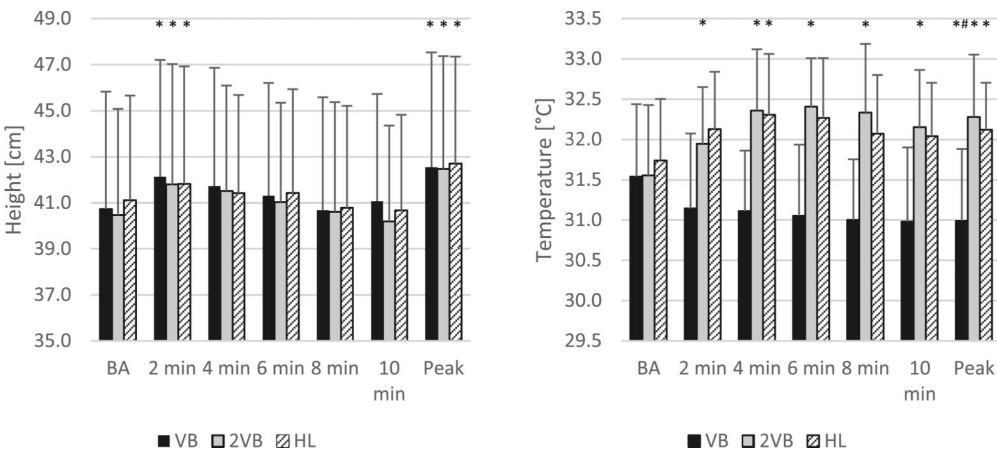

Figure 2. Time course of changes in jump height and skin surface temperature. Results are presented as mean ± SD; BA = baseline; VB = condition used a single set of velocity-controlled conditioning activity; 2VB = condition used 2 sets of velocity-controlled conditioning activity; HL = condition used high load conditioning activity; *significant difference in comparison to baseline within the condition; #Significant difference in comparison to a corresponding time point in 2VB and HL condition.

skin surface temperature. Three distinct methods of eliciting PAPE were investigated: 3 sets of 3 repetitions at 85% 1RM; (a) a single set of 60% 1RM back squats until 10% mean velocity loss; and (b) 2 sets of 60% 1RM back squats until 10% mean velocity loss. The main finding of this study was that all examined CAs acutely improved the countermovement jump height at the second minute after the CA and in individualized peak performance time-point among a group of volleyball players. However, the CAs affected skin surface temperatures differently. After the 2VB, an increase in skin surface temperature was registered at all time-points. Similarly, after the HL CA, skin surface temperature increased in individualized peak performance time-points and during the fourth minute after the CA. However, a significant decrease in skin surface temperature was recorded after the VB CA in individualized peak performance time-points. Therefore, it may be argued that the PAPE magnitude is not skin surface temperature-dependent.

Furthermore, there was an overall trend to slightly decrease Achilles tendon and vastus lateralis stiffness after all examined CAs. However, in the case of the Achilles tendon, a decrease reached significance in all time points except the sixth minute and in individualized peak performance time-points after the CA for all conditions. On the contrary, for the vastus lateralis, a significant decrease was registered only in individualized peak performance time-point for all conditions.

The increase in temperature after a CA has recently been suggested as one of the major mechanisms explaining performance enhancement because of the PAPE effect (3). However, according to the authors' knowledge, no studies directly evaluated the impact of CA on muscle or skin surface temperature changes and its relationship with PAPE magnitude. Although in the current study, a skin surface temperature may be unrelated to muscle temperature in uncontrolled conditions (18,19), an increase in skin temperature under controlled conditions has been shown to be related to muscle activation during incremental cycling (30) and dynamic bicep curl exercises (31). Thus, skin temperature may offer useful information regarding muscle function during CAs, although this has to be further examined. Indeed, after 2VB and HL, we noted a significant increase in skin surface temperature with concomitant

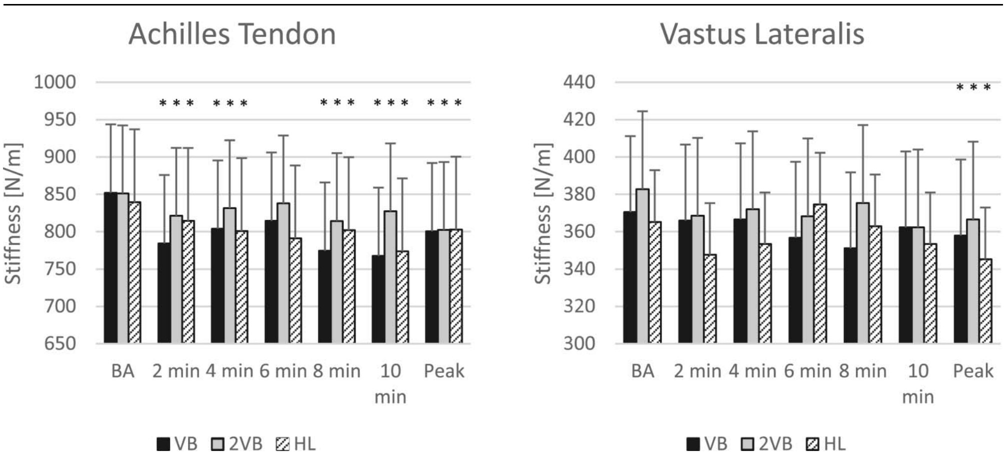

Figure 3. Time course of changes in Achilles tendon and vastus lateralis stiffness. Results are mean ± SD; BA = baseline; VB = condition used a single set of velocity-controlled conditioning activity; 2VB = condition used 2 sets of velocity-controlled conditioning activity; HL = condition used high load conditioning activity; *significant difference in comparison to baseline within condition.

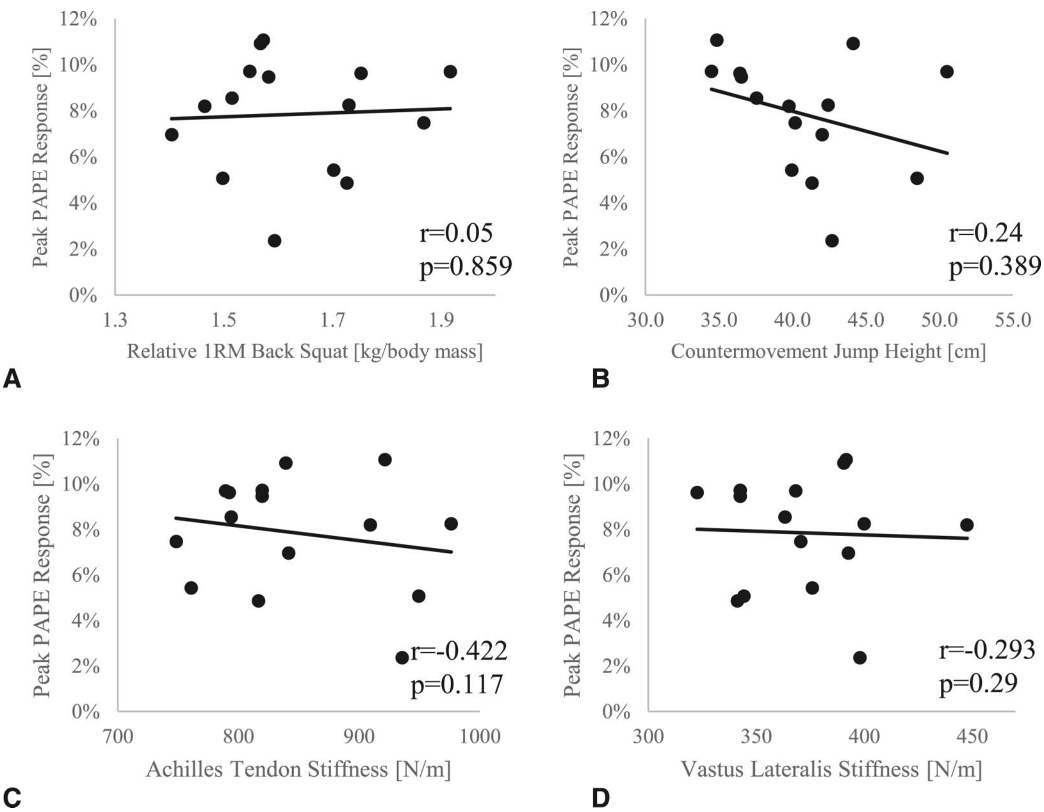

Figure 4. Correlations between one-repetition maximum back squat (A), baseline jump height (B), Achilles tendon (C), and vastus lateralis stiffness (D) with the magnitude of the postactivation performance enhancement response.

improvements in jump height. However, after the VB condition, a comparable enhancement of jump height was reported despite a significant decrease in skin surface temperature. These results are related to the volume of particular CAs. In the HL and 2VB, the participants performed a significantly higher volume in the number of performed repetitions and higher load compared with VB, which is a probable cause of temperature increase after the HL and 2VB activation protocols and its decrease after the VB. The decrease in skin temperature after the VB CA may be surprising, yet this phenomenon has been previously reported and described (9,45). A study by Weigert et al. (45) found a slight and nonsignificant drop in temperature after a single set (10 repetitions) of biceps curls at 70% 1RM. Therefore, it can be speculated that the reported performance enhancement in this study was related to the co-existence of other mechanisms rather than to an increase in muscle temperature or fluid accumulation in muscles (3), at least in the case of the VB condition. In this instance, the performance enhancement can be attributed to neural factors, such as increased recruitment of motor units or increased excitability of motoneurons, but also a contribution of regulatory myosin light-chain phosphorylation cannot be ruled out (3,41). Theoretically, because we observed peak performance enhancement approximately 4 minutes after the CAs, while phosphorylation of the myosin regulatory light chain persists up to 5 minutes, this explanation seems fully justified (16).

Another mechanism that could potentially affect the PAPE effect includes changes in muscle-tendon stiffness triggered by the CA (3). Recent studies indicate that the increase in stiffness after exercise is associated with fatigue (36) and impaired performance (40,44) or as in the studies by Gago et al. (10,11) in which no changes in Achilles' stiffness were recorded despite an increase in twitch force. In part, this may be confirmed by the results of the current study because each CA led to a jump height enhancement with a slight decrease in stiffness. Therefore, it seems that the CA applied did not cause meaningful fatigue. This may be quite meaningful considering that the optimal balance between fatigue and potentiation is crucial for enhancing subsequent performance (35). If potentiation exceeds fatigue, performance increases; however, it will remain unchanged if fatigue and potentiation are at similar levels or decrease if fatigue dominates over the potentiation (35). Therefore, it seems that one should not expect an increase after the applied CA but a decrease, which means induction of an insignificant level of fatigue. The decrease in stiffness could be related to the increase in the pennation angle (44), which could also explain the performance enhancement. Smaller pennation angles have a mechanical advantage with respect to force transmission to the tendon (39). Nevertheless, although a significant decrease in muscle-tendon stiffness was reported, it did not reflect the magnitude of the PAPE effect. Therefore, it is more likely that muscle-tendon stiffness changes (assessed via myotonometry) are primarily related to the fatigue state than to the mechanisms underlying the PAPE effect. However, this could help to determine the fatigue level elicited by the CA.

The high interindividual variability in PAPE responses is well-known (5,22), and has been confirmed in this study. All tested CAs led to significant jump height enhancement at the second minute after the CA and when an individualized peak performance time-point was analyzed, despite significant differences in the CA volume between conditions. The effect of the volume used during the CA has been analyzed in previous studies, indicating that low volume (<5 repetitions), and high loaded exercise should be preferred to achieve a significant performance enhancement (35,41,43). However, this study showed that despite performing

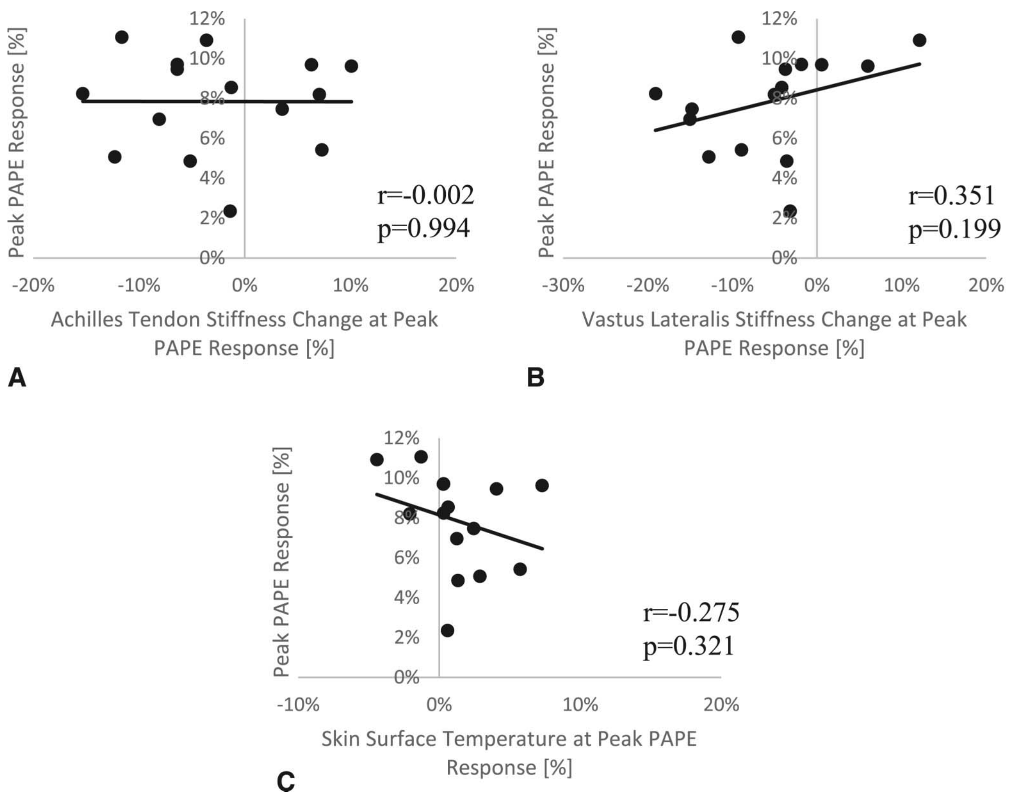

Figure 5. Correlations between percentage changes in the baseline values and peak postactivation performance enhancement response in Achilles tendon (A), vastus lateralis stiffness (B), and skin surface temperature (C) with the magnitude of the post-activation performance enhancement response.

the highest number of repetitions during 2VB compared with VB and HL, a comparable PAPE effect was still achieved. In addition, the wide range of repetitions performed until 10% velocity loss during VB (from 4 to 11 repetitions) and 2VB (from 4 to 12 repetitions) conditions is noteworthy, but has been previously reported in similar loading conditions (43). This phenomenon may be explained by differences in the level of resistance training experience (26) or the muscle fiber composition (15). Presumably, participants who completed more repetitions may possess greater proportions of slow-twitch muscle fibers. Thus, to individually control the degree of CA-induced fatigue, the number of performed repetitions should be determined based on velocity control rather than using a predetermined number of repetitions. Moreover, for an in-depth analysis of the effectiveness of the CA used, the time points where the peak performance occurred (the highest magnitude of PAPE response) should be taken into account.

In the current study, some limitations can be identified. Although this is a common approach, it should be mentioned that in the current study, 2-minute rest intervals after the CA between evaluations were adopted. Therefore, it could inadvertently act as a CA, affecting the magnitude of the changes in jump height, stiffness, or skin surface temperature. In addition, we did not make any assessments immediately after CA; therefore, it is not possible to verify their influence after shorter periods of time (<2 minutes). Furthermore, a limitation of the present study is the lack of a control condition (i.e., a condition without the application of a CA). Moreover, only male participants with a moderate level of muscular strength took part in this study. Therefore, bearing in mind high interindividual variability in PAPE responses (5,22) and also possible differences in the magnitude of PAPE between post-CA activities (35), caution is needed when extrapolating these results to other populations and conditions.

Practical Applications

Coaches and practitioners can use low-volume and high-loaded back squats (i.e., 3 sets of 3 repetitions at 85% 1RM) and velocity-controlled and moderate-load back squats (i.e., 1–2 sets until 10% velocity loss at 60% 1RM) to acutely improve CMJ height during complex training sessions or before a competition. However, findings from this study suggest that a single set of barbell back squats with a 10% velocity loss may be the best approach for avoiding excessive loading while still gaining the benefits of the CA. Importantly, given the large variability of PAPE responses across athletes, our findings imply that individual evaluation of the optimal post-CA rest-interval is essential to gain the highest benefits in explosive lower-limb performance.

Acknowledgments

The research was supported by the Charles University, by project PRIMUS/22/HUM/019.

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