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Research article

Acute Performance, Mechanical and Thermal Effects of Isometric Conditioning Versus Standardized Volleyball Pre-Training Activation in Highly Trained Male Players

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Abstract
This study compared acute performance, neuromuscular, and thermal responses to a maximal isometric conditioning activity (ICA) versus a standardized volleyball pre-training activation (VPA) in highly trained male volleyball players, and to explore putative mechanisms underpinning post-activation performance enhancement (PAPE) considering training load. In a randomized crossover, 14 men (27 ± 3 y) completed two sessions: VPA (mobility/plyometric drills; 9 min), and ICA comprising 3×5×3-s maximal isometric back-squat contractions (knee angle 120°; 3-min inter-set rest). Countermovement jump (CMJ) height (primary), relative peak power (PP), RSImod, and contraction time (CT) were recorded pre and 3, 6, 9, and 12 min post. Rectus femoris muscle viscoelastic properties and skin surface temperature (SST) were assessed at matched time points. Analyses used repeated-measures ANOVA, responder analysis, correlations, and regression. Period×Sequence interactions favored ICA for CMJ and PP when delivered in Period 2 (lower training volume): ΔCMJ was higher under ICA versus VPA ($p = 0.005$, $d = 1.20$); PP likewise greater ($p = 0.026$, $\eta p^2 = 0.35$). ICA yielded more beneficial responders than VPA (9/14 vs 1/14; McNemar exact $p = 0.021$). In Period 2, reductions in rectus femoris muscle stiffness independently predicted CMJ gains ($\beta\_std = -0.495$, $p = 0.005$), whereas SST changes did not ($p = 0.974$). RSImod and CT showed no differences. A brief, high-effort isometric squat protocol was associated with superior acute improvements in jump performance compared with a standard volleyball warm-up, but this advantage emerged specifically when the preceding training volume was reduced (Period 2), suggesting that residual fatigue from training may reduce the effects of PAPE. Gains align with neuro-mechanical rather than thermal mechanisms, supporting ICA as a practical, equipment-minimal priming strategy for elite volleyball.

Key words: Isometric contraction, plyometric exercise, musculoskeletal physiological phenomena, volleyball, athletic performance.

Introduction

A significant and acute enhancement of exercise capacity can be induced through a mechanism referred to as post-activation performance enhancement (PAPE) (Blazevich and Babault, 2019). This phenomenon has practical applications within complex training protocols, in which exercises are paired most commonly in the form of strength-power complexes (Thapa et al., 2024; Krzysztofik et al., 2025). In practice, PAPE protocols typically commence with a conditioning activity (CA), which may consist of heavy resistance isotonic, or isometric actions performed at maximal or near-maximal intensity (Xu et al., 2025). Such CAs are followed by ballistic athletic tasks of similar biomechanical patterns, as exemplified by vertical jumps performed subsequent to heavy squats (Wilson et al., 2013).

Isometric conditioning activities (ICA) are widely applied in both research and training due to their ease of use and lack of equipment requirements (Jarosz et al., 2025a; 2025b). Brief, maximal ICA can enhance athletic task performance across various sports (French et al., 2003; Krzysztofik et al., 2023a; Lum et al., 2023; Spieszny et al., 2022; Helbin et al., 2025; Jarosz et al., 2025a; 2025b; 2025c; Terbalyan et al., 2025). The PAPE effect of ICA depends on the interaction between total contraction duration (sets × duration) (Xu et al., 2025) and intra-set distribution (contraction × repetitions) (Helbin et al., 2025). Most studies used short, 3-s contractions with 1 - 5 repetitions (French et al., 2003; Bogdanis et al., 2014; Tsoukos et al., 2016; Spieszny et al., 2022; Krzysztofik et al., 2023a; Lum et al., 2023; Grzyb and Jarosz, 2025; Helbin et al., 2025; Jarosz et al., 2025a; 2025b; 2025c; Jarosz and Szwarc 2025; Terbalyan et al., 2025) but their effectiveness depended on total duration. A recent meta-analysis by Xu et al. (2025) identified an optimal total contraction duration of approximately 9.6 s for ICA. However, this estimate should be interpreted with caution, as more than half (58.3%) of the included studies employed a 9-s protocol, potentially biasing the pooled estimate toward shorter contraction durations. In contrast, more recent experimental evidence from highly trained volleyball players suggests that longer ICA may induce greater performance enhancement. Helbin et al. (2025) compared 9-s, 27-s, and 45-s ICA protocols and reported that the 45-s protocol (3 × 5 × 3 s) produced the greatest improvements in jump height (JH) and peak power output (PP). Despite these promising findings, the mechanisms underlying the superior effectiveness of the 45-s protocol remain unclear, as previous studies have focused primarily on performance outcomes without examining the accompanying physiological responses. The PAPE is primarily attributed to factors such

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as elevated muscle temperature, improved intramuscular blood flow, changes in muscle-tendon stiffness, reduced pH, and increased post-activation muscle activity (Wilson et al., 2013; Blazevich and Babault, 2019). Nevertheless, a possible contribution of mechanisms like phosphorylation of myosin regulatory light chains and enhanced recruitment of higher-threshold motor units cannot be completely excluded (Tillin and Bishop, 2009; Fischer and Paternoster, 2024). A substantial body of literature has already explored the physiological mechanisms of PAPE induced by traditional isotonic CA. Research in this area has focused, among others, on changes in passive muscle stiffness and tone (oscillation frequency) (Krzysztofik et al., 2023a; 2023b; Perenc et al., 2025), which may be linked to intramuscular fluid pressure alterations as well as to changes in skin surface temperature (Baena-Raya et al., 2023; Krzysztofik et al., 2023c; Perenc et al., 2025). Studies employing isotonic CA (e.g., barbell squats) indicated that CMJ height adaptations can be associated with both increases and decreases in muscle stiffness, tone, and skin surface temperature of the thigh, depending on the characteristics of the loading protocol (Klich et al., 2020; Trybulski et al., 2022; Baena-Raya et al., 2023; Perenc et al., 2025). However, little is known about the physiological mechanisms underpinning PAPE following ICA, especially during longer protocols (e.g., [45 s (3×5×3 s)]). Given the lower metabolic cost of isometric compared with isotonic contractions, ICA may induce distinct physiological responses, shifting the balance between potentiation and fatigue. Thus, PAPE mechanisms appear to be intervention-dependent, and elucidating those specific to ICA could enhance understanding and inform warm-up strategies in training and competition.

Given the limited evidence regarding PAPE responses following ICA, this study aimed to compare the acute effects of an ICA protocol with those of a VPA protocol on CMJ performance in highly trained male volleyball players. A secondary aim was to determine whether changes in the viscoelastic properties (VP) and skin surface temperature (SST) of the rectus femoris muscle were associated with individual performance responses. We hypothesized that the ICA protocol would induce greater improvements in CMJ performance than the VPA protocol and that these improvements would be associated with changes in the VP of the rectus femoris muscle, rather than with changes in SST.

Methods

Experimental Approach to the Problem

This study employed a randomized crossover design in which each participant completed two experimental trials aimed at examining the acute effects of maximal isometric squat contractions (used as ICA) on subsequent changes in SST, VP, and CMJ performance. Participants underwent one familiarization session followed by two experimental sessions:

1. VPA-a standardized volleyball pre-training activation protocol consisting of plyometric and mobility-based exercises: (1a) wall-supported “open” drill with foam roller, 2 sets of 5 repetitions; (1b) single-leg box hops, 2 sets of 15 repetitions; (2a) kettlebell windmill, 2 sets of 4 repetitions; and (2b) band-assisted progressive pogo jumps, 3 sets of 5 repetitions. All exercises were performed at a controlled tempo, with standardized rest intervals between drills to ensure comparability of workload. The total duration of the condition was matched to the ICA protocol and amounted to 9 minutes. This protocol reflected the team’s habitual pre-training activation routine rather than a complete pre-match volleyball warm-up.
2. ICA-3 sets of maximal isometric squat contractions, with each set consisting of 5 repetitions of 3-s maximal isometric contractions. The total contraction time was 45 s, with 3-min rest intervals between sets.

Measurements of SST, VP, and CMJ were obtained approximately 3 min before each experimental condition and subsequently at 3-, 6-, 9-, and 12-min after completion of the condition (Tsoukos et al., 2016; Jarosz et al., 2025b). In the VPA condition, measurements were collected at the same time points, but without the application of ICA (Figure 1). All sessions were separated by 7 days and conducted during the preseason training phase. Training plans of the two microcycles preceding the measurement sessions (Microcycle 1 and Microcycle 2; M1 and M2), each consisting of three resistance training sessions performed on Monday, Wednesday, and Friday, are presented in Supplementary Table S1. Participants were not informed about the specific study hypothesis; however, blinding to the order of experimental conditions was not feasible due to the overt nature of the ICA and VPA protocols. In contrast, the assessors responsible for SST, VP, and CMJ measurements, as well as subsequent data analyses, were blinded to the intervention conditions to minimize potential risk of bias.

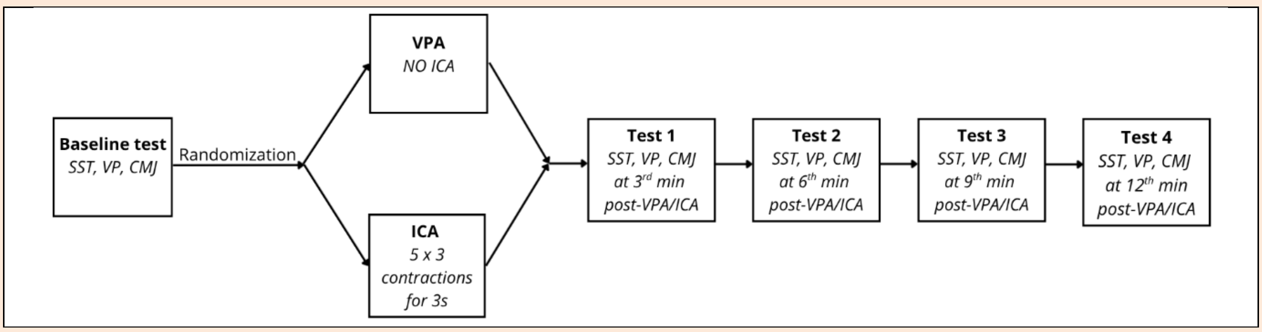

Figure 1. Study design flowchart. SST— skin surface temperature; VP— viscoelastic properties; CMJ—countermovement jump; ICA—isometric conditioning activity. VPA— standardized volleyball pre-training activation condition.

Participants

The investigation recruited highly trained male volleyball players (age: 27 ± 3 years; body mass: 93 ± 8 kg; height: 197 ± 7 cm; body fat: 12.2 ± 1.9 %; resistance-training experience: 10.5 ± 3.9 years; volleyball-specific training experience: 13.7 ± 3.3 years; relative back-squat 1RM: 1.55 ± 0.30 $kg \cdot kg^{-1}$), categorized according to training background and performance level following the framework proposed by McKay et al. (2022). All participants competed in the Polish First League (national Tier 2 competition) the sample included four middle blockers, four outside hitters, two setters, two opposite hitters, and two liberos. On average, players reported a weekly training load of approximately 13 hours, encompassing both volleyball-specific practice and resistance training, which was verified by the team's strength and conditioning specialist. Eligibility criteria included: (a) a minimum of 7 years of systematic volleyball training, (b) participation in at least 3 resistance training sessions per week during the preceding 5 years, (c) absence of musculoskeletal injuries requiring training cessation longer than 4 weeks within the 6 months prior to enrollment and (d) absence of tattoos on the rectus femoris muscle. Participants were instructed to maintain their usual dietary habits and to avoid consumption of ergogenic supplements or stimulants, except for habitual use of agents such as creatine during the week preceding the experimental trial. Body composition was evaluated under standardized laboratory conditions using a multi-frequency bioelectrical impedance device (InBody 770, Biospace Co., Ltd., Seoul, Republic of Korea). Prior to inclusion, all athletes received detailed oral and written information concerning study procedures, potential risks and benefits, and the voluntary nature of participation, after which written informed consent was obtained (Figure 2). Although participants were aware of the specific activity performed in each trial (e.g., isometric contraction versus plyometric and mobility-based exercises), they remained blinded to the broader research objectives and underlying hypotheses. Randomization was performed via randomizer.org, which generated a unique allocation sequence for each individual. After assignment, participants were not informed of subsequent experimental conditions until completion of the study. All procedures were conducted at the Academy of Physical Education in Katowice, Poland. Ethical approval was granted by the Bioethics Committee of the Academy of Physical Education in Katowice (2-X/2025), in accordance with the principles outlined in the Declaration of Helsinki (1964, as revised in 2013).

Each testing session commenced with a standardized warm-up protocol consisting of 5 minutes of stationary cycling, followed by a set of dynamic exercises: bodyweight squats (10 repetitions), forward lunges (10 repetitions), leg swings (10 repetitions), jumping jacks (10 repetitions), and CMJ (5 repetitions). This sequence reflected the athletes' habitual pre-training routine (Helbin et al., 2025; Jarosz et al., 2025a) and was performed before every experimental condition, including the baseline assessment, to standardize neuromuscular readiness across testing sessions. Following the warm-up, baseline assessments of SST, VP, and CMJ were conducted. In the present study, inter-session variability of baseline CMJ measurements was not analyzed. After approximately a 3-minute rest interval, participants completed either the ICA or no ICA (VPA), administered in randomized order.

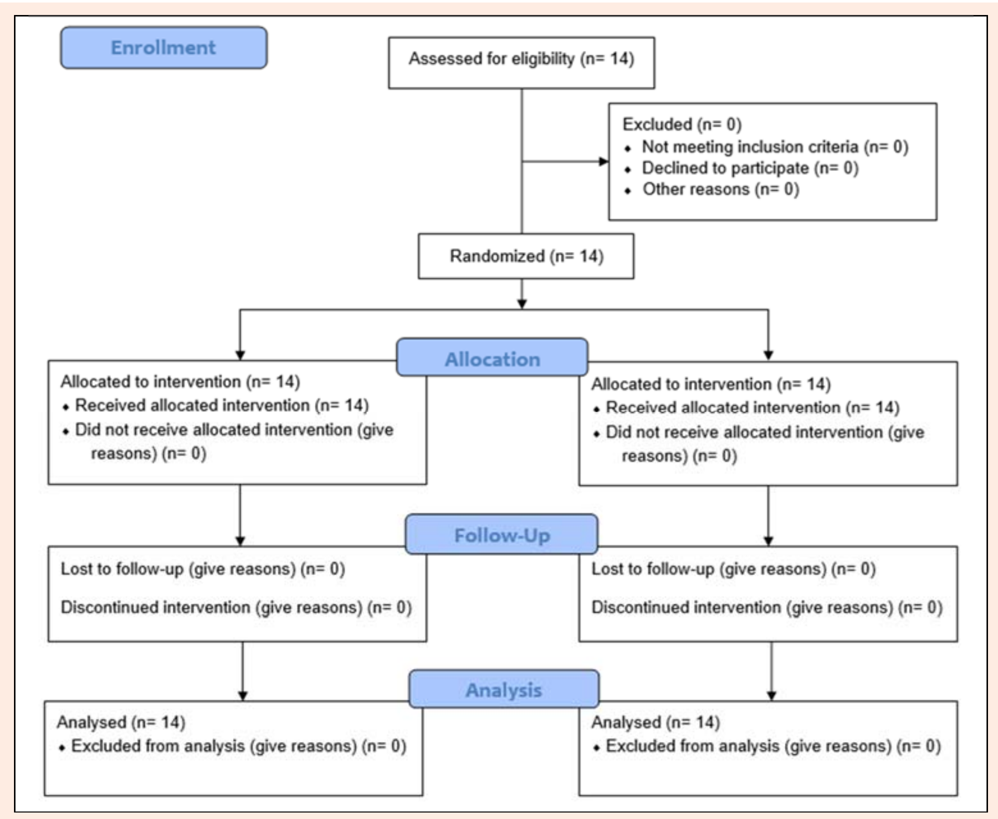

Figure 2. CONSORT flow diagram.

During the ICA, participants were positioned beneath a securely fixed, immovable barbell, resting across the upper trapezius. Squat depth was standardized at a knee joint angle of 120° (Helbin et al., 2025; Jarosz et al., 2025a; 2025b) (Figure 3), determined and verified by a certified strength and conditioning specialist using a goniometer (EasyAngle, Meloq AB, Stockholm, Sweden). Body positioning throughout all trials was supervised by a certified weightlifting coach to ensure an upright trunk posture. Upon receiving a verbal cue from the investigator, participants were instructed to “push the barbell vertically upward as hard and as fast as possible” while simultaneously maintaining full-body tension, stabilizing the back against the barbell, and applying maximal ground reaction force through the feet. To elicit maximal effort during each isometric contraction, strong verbal encouragement was provided, in line with established neuromuscular testing protocols (McNair et al., 1996). For subsequent CMJ trials, countermovement depth was not restricted, allowing athletes to self-select their preferred range of motion.

Figure 3. Position during isometric conditioning activity.

Measurement of muscle viscoelastic properties

The muscle viscoelastic properties of the rectus femoris muscle were evaluated using the MyotonPRO device (Myoton AS, Tallinn, Estonia), a non-invasive instrument designed to quantify superficial soft tissue mechanical responses. Measurements were conducted at the anatomical midpoint of the rectus femoris, following protocols established in earlier investigations (Jarosz et al., 2023; Gacto-Sanchez et al., 2024; Skotniczny et al., 2025). The measurement site was identified in the supine position with the knee supported on a foam roller (Muckelt et al., 2022). A tape measure was used to determine the midpoint along the line connecting the superior border of the patella and the anterior superior iliac spine. The rectus femoris was selected given its functional importance in knee extension and hip flexion, as well as its superficial anatomical location, which allows reliable non-invasive assessment (Jarosz et al., 2023). The parameters recorded included the natural oscillation frequency (Hz), representing the intrinsic tension of the muscle at rest and reflecting baseline tone, and dynamic stiffness, which characterizes resistance to deformation (Salagas et al., 2022). The device’s accelerometer was set to a sampling frequency of 3200 Hz, and for each measurement point the mean of five consecutive impulses (0.4 N for 15 ms) was calculated for analysis (Szymczyk et al., 2022).

Thermography

The anterior-thigh skin temperature was assessed using a handheld infrared thermal camera (E54, FLIR Systems, Inc., Wilsonville, OR, USA; 320 × 240 pixels; thermal sensitivity [NETD], 0.05 K). Before data collection, the camera was calibrated against a blackbody reference, and skin emissivity was fixed at 0.97 - 0.98, in accordance with the Glamorgan protocol (Ammer, 2008) and recommendations for standardization in sports and exercise thermography (Moreira et al., 2017). Participants stood facing the camera with the anterior thigh perpendicular to the optical axis at a fixed distance of 1.0 m, against a homogeneous background. Environmental conditions were controlled (ambient temperature 21 °C; relative humidity 60%), with stable illumination and no direct airflow. The camera was mounted on a tripod at mid-thigh height to minimize motion artefacts. Measurements were performed on the dominant leg, and the predefined point of interest over the rectus femoris matched the same anatomical location used for the assessment of the muscle’s viscoelastic properties. Temperature values were extracted using dedicated analysis software (FLIR Thermal Studio, FLIR Systems, Inc.).

Measurement of countermovement jump performance

Jump performance was assessed using a force platform (ForceDecks, Vald Performance, Australia) operating at a sampling frequency of 1000 Hz. This system has been extensively validated and is considered reliable for evaluating vertical jump kinematics (Collings et al., 2024). Vertical ground reaction force data were processed with the manufacturer’s software (valdperformance.com/forcedecks/), ensuring standardized procedures for data acquisition and computation. Each participant completed three CMJs without arm swing, with a fixed inter-trial rest of 5 seconds (Helbin et al., 2025). Trials were initiated from an upright standing position with hands placed on the iliac crests to minimize extraneous movement and maintain a neutral posture, thereby limiting hip angular displacement. Prior to initiating the countermovement, participants were instructed to remain motionless for at least one second. The countermovement depth was self-selected, immediately followed by a maximal vertical propulsion. Participants were required to land on the same spot, centered on the force platform. All assessments were performed by a single experienced operator to ensure consistency. For analysis, the best attempt (i.e., the jump with the greatest height) was selected. The primary outcome measure was JH, calculated from the center-of-mass velocity at take-off using an impulse-momentum approach. Secondary variables included PP, modified reactive strength index (RSImod; jump height divided by time to take-off) and contraction time (CT; time from the initiation of countermovement to take-off). These parameters were considered potential determinants of JH (Helbin et al., 2025).

Training volume calculation

For each microcycle (M1 vs M2) we extracted sets, reps (or seconds for isometrics). Dynamic volume as Σ(sets×reps) and isometric dose as Σ(sets×seconds) were computed; LL totals applied the per-limb adjustment. Plyometric exposure was monitored separately as reps. Between-microcycle differences were described as absolute and % changes.

Statistical analysis

The sample size was determined using G*Power version 3.1.9.2 (Dusseldorf, Germany), with the following parameters for the ANOVA for repeated measures with a within-factors (one group of participants, two experimental conditions, and five measurements), statistical power of 0.8, a significance level of 0.05, and an effect size of d = 0.5 based on previous studies evaluating the immediate impact of isometric activation exercises on jump performance (Spieszny et al., 2022; Krzysztofik et al., 2023a). The analysis indicated that the minimum required sample size for this study is 14 participants. Because this a priori calculation was powered for the primary within-between interaction, a sensitivity analysis ($\alpha = 0.05$, power = 0.80) was additionally performed for the secondary analyses; with n = 14 the multiple-regression model could reliably detect only large effects ($f2 \geq 1.16$, i.e., $R2 \geq 0.54$) and paired/responder contrasts $d\_z \geq 0.81$. The regression, correlation, and responder analyses were therefore treated as hypothesis-generating. Results presented as means with standard deviations and 95% confidence intervals [M ± SD (± 95% CI)]. Anchor for CMJ jump height was set as the smallest worthwhile change (SWC's δ) defined as 0.2× the between-subject SD of baseline CMJ height (Heishman et al., 2019). Responder analysis assessed individual benefit to ICA versus VPA in a 2×2 crossover (two periods; sequences VPA→ICA and ICA→VPA). Within each period, CMJ height changes $\Delta JH(t) = JH(t)\text{-}JH(pre)$ were averaged across time to form period aggregates, then mapped by sequence to intervention-specific values (ICA_meanΔ, VPA_meanΔ). Beneficial responders per intervention were defined as aggregate $\Delta \geq \delta$ (non-response $|\Delta| < \delta$). Paired ICA/VPA responder indicators were compared using McNemar's exact test, with sequence-stratified counts presented descriptively. Repeated-measures ANOVA followed a 2×2 crossover with [Period (P1, P2)] and [Time point (pre, 3', 6', 9', 12')] as within-subject factors and [Sequence (VPA→ICA, ICA→VPA)] as a between-subject factor. Outcomes were expressed as change from the period-specific pre value. For SST and VP, both pre- and post-warm-up measurements were collected to control acute warm-up effects, and change scores were referenced to pre. Assumptions were assessed as follows: normality with the Shapiro-Wilk; sphericity with Mauchly's test (no epsilon correction required); and homogeneity of variances for the between-subject factor with Levene's test. The crossover assumption of negligible carry-over was examined using the two-stage (Grizzle) approach (Castellana and Patel, 1985), comparing subject period-totals (P1 + P2) between sequences with an independent-samples t-test, where a non-significant result indicates no detectable carry-over. Where appropriate, pairwise post-hoc comparisons employed Tukey's procedure. Effect sizes are reported as ηp^2 and interpreted using conventional benchmarks for partial eta squared: small ≈ 0.01, medium ≈ 0.06, large ≈ 0.14. Responder vs non-responder comparisons conducted using Welch test. For each outcome, the mean difference with SE (and 95% CI if reported) and standardized effect size (Cohen's d) were provided. Cohen's benchmarks: $|d| \approx 0.20$ small, 0.50 moderate, 0.80 large (≥ 1.20 very large). Baseline comparisons were conducted using Student's t-tests (independent-samples for between-sequence differences and paired-samples for within-subject P1 vs P2 checks). Sequence mapped periods to interventions (VPA→ICA: VPA = P1, ICA = P2; ICA→VPA: ICA = P1, VPA = P2). Associations were quantified using Pearson correlation with effect sizes interpreted against conventional benchmarks: $|r| \approx 0.10$ small, 0.30 moderate, 0.50 large. Given the P2 effect, ΔJH2 (cm) was regressed on Sequence (ICA vs VPA in P2), ΔStiffness2 (N/m), and ΔSST2 (°C). Sequence×mediator interactions were tested a priori; as non-significant, they were dropped and the main-effects model reported. Ordinary least squares with two-sided $\alpha = 0.05$; unstandardized and standardized coefficients, SEs, 95% CIs, R2 and adjusted R2 were reported. Assumptions: Q-Q for normality, residuals-vs-fits for homoscedasticity, VIF for collinearity, Cook's distance for influence, Durbin-Watson for autocorrelation. The same specification was fitted to P1 aggregates (ΔJH1 with ΔStiffness1, ΔSST1, Sequence) and summarized briefly to check sensitivity via negative control. Analyses were run in jamovi (v2.6; The jamovi Project, Sydney, Australia), with $\alpha = 0.05$, and figures were designed in GraphPad Prism (v10; GraphPad Software, LLC, San Diego, CA, USA).

Results

Between-session (7-day) reliability of the baseline CMJ, computed from the two testing sessions, was moderate-to-moderate (ICC3, 1 = 0.72, 95% CI 0.33 - 0.90; typical error [TE] = 2.19 cm; CV = 5.5%). ICC for the resting MyotonPRO measures was moderate for stiffness (ICC3, 1 = 0.68, 95% CI 0.25 - 0.88; CV = 5.1%) and oscillation frequency (ICC3, 1 = 0.70, 95% CI 0.29 - 0.89; CV = 4.9%), whereas logarithmic decrement was less reliable (ICC3, 1 = 0.41; CV = 9.7%).

Baseline and training load

All descriptive statistics of primary and secondary variables can be found in Supplementary Tables (S2, S3, S4 and S5).

Across the two baseline sessions, the mean baseline was 40.25 cm (SD 3.84), yielding SWC δ = 0.77 cm (≈1.91% of baseline); session-specific SWC values were 0.70 cm for P1 and 0.94 cm for P2. For ΔCMJ between-period relative typical error indicated CV% of 6.4% at 3′, 6.4% at 6′, 4.7% at 9′, and 8.5% at 12′. Baseline comparability checks indicated no between-sequence/within subjects' differences across the assessed measures (all $p > 0.05$). No evidence of a carry-over effect was detected for the primary outcome (ΔCMJ period-totals: $t(12) = 1.49$, $p = 0.162$), and the period-adjusted crossover contrast still favoured ICA (mean ΔCMJ +0.93 vs -0.94 cm; $t = 2.74$, $p = 0.017$), supporting the adequacy of the 7-day washout. Between M1 and M2, external load decreased: total dynamic volume by 22% (372 to 289 reps), plyometric contacts by 27% (88 to 64), and isometric time by 25% (80 to 60 s). Lower-limb metrics showed the same trend: dynamic volume decreased by 18% (116 to 95 reps), plyometrics by 33% (66 to 44), and isometric dose by 25% (80 to 60 s). Relative intensities (%1RM/RPE) were largely preserved (see appendix/supplement). Microcyles loads are shown in Table 1.

Responder analysis

Paired comparison showed many more ICA-only than VPA-only cases (9/14 vs 1/14); McNemar $\chi2$ = 6.40, p = 0.011, exact p = 0.021. The paired odds ratio was 9.0 (95% CI 1.25 – 394.48), indicating a higher probability of benefit under ICA. By sequence (period assignment): in VPA→ICA (ICA delivered in P2), ICA-only was 5/7 and VPA-only 1/7 (Both 0/7, Neither 1/7); in ICA→VPA (ICA delivered in P1), ICA-only was 4/7 and VPA-only 0/7 (Both 0/7, Neither 3/7). Consistent with the period effect, P2 responders occurred in 5/7 when P2 contained ICA and in 0/7 when P2 contained VPA. Figure 4 represents responders' status in study.

Analysis of variance

Repeated-measures ANOVA examined Period, Time, Sequence, Period×Sequence, Period×Time, and Period×Time×Sequence are shown in Table 2. The full set of ANOVA effects and interactions can be found in Supplementary Table S5.

Jump height

The analysis yielded a significant Period × Sequence interaction, F(1, 12) = 6.94, p = 0.022, ηp^2 = 0.37 (Figure 5). Main effects of Period and Time point were not significant, F(1, 12) = 0.01, p = 0.939, F(3, 36) = 1.58, p = 0.210, respectively, and the between-subjects Sequence term was not significant, F(1, 12) = 2.22, p = 0.162. A Period × Time point interaction was observed, F(3, 36) = 4.25, p = 0.011, ηp^2 = 0.26, whereas the three-way Period × Time point × Sequence interaction was not, F(3, 36) = 0.54, p = 0.656. Contrast comparison showed that in P2 ΔJH was higher under ICA than VPA (Δ = 2.69, SE = 0.62, t(12) = 4.34, p = 0.005, d = 1.204); within P1, Δ at 3′ exceeded 9′ (Δ = 2.25, SE = 0.57, t(124) = 3.93, p = 0.03, d = 1.090), with all other time-point contrasts non-significant (p ≥ 0.27).

RSImod

The Period × Sequence term did not reach significance, F(1, 12) = 4.44, p = 0.057, and Time point × Sequence was not statistically significant, F(3, 36) = 2.65, p = 0.064. Main effects of period and time point were not significant, F(1, 12) = 0.00, p = 0.968; F(3, 36) = 0.64, p = 0.593, and the between-subjects sequence term was not significant, F(1, 12) = 4.05, p = 0.067. Period × Time point and the three-way Period × Time point × Sequence were also not significant, F(3, 36) = 0.94, p = 0.432, and F(3, 36) = 0.21, p = 0.885, respectively.

Table 1. Training load.

Metric	M1	M2	Δ (M2-M1)	Δ% vs M1
Dynamic volume [reps]	372	289	-83	-22.3%
Plyometrics [reps]	88	64	-24	-27.3%
Isometric dose [s]	80	60	-20	-25.0%
LL Dynamic volume [reps]	116	95	-21	-18.1%
LL Plyometrics [reps]	66	44	-22	-33.3%
LL Isometric dose [s]	80	60	-20	-25.0%

LL: lower limb; M1: microcycle 1; M2: microcycle 2

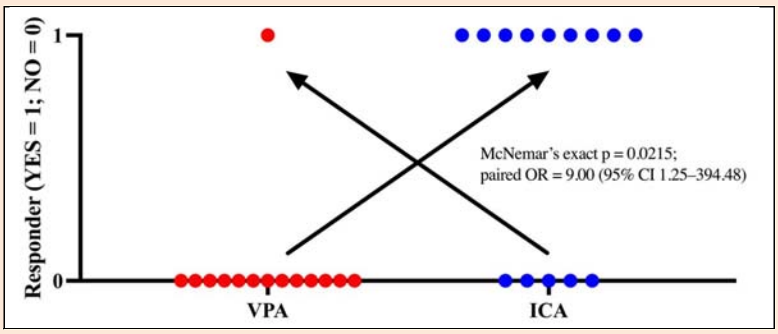

Figure 4. Paired responder status by condition. Dots show individual participants (1 = responder; ΔCMJ ≥ 0.77 cm; 0 = non-responder).

Table 2. Significant only effects for RM ANOVA (crossover) with contrasts

Outcome	Significant effect	F(df1, df2)	p	ηp^2	Contrasts (p; Cohen's d)
JH [cm]	Period × Sequence	6.94 (1, 12)	0.022	0.37	P2: ICA > VPA under ICA (p = 0.005; d = 1.20).
	Period × Time	4.25 (3, 36)	0.011	0.37	P1: 9′ > 3′ (p = 0.030; d = 1.09).
PP [W/kg]	Period × Sequence	6.47 (1, 12)	0.026	0.35	P2: ICA > VPA under ICA (p = 0.037; d = 0.87).
CT [ms]	Sequence (between)	5.49 (1, 12)	0.037	0.31	ICA→VPA vs VPA→ICA (pooled) (p = 0.037; d = 1.25).
SST (°C)	Period × Time	3.37 (4, 48)	0.016	0.22	all p ≥ 0.25
Frequency [Hz]	Time	3.64 (4, 48)	0.011	0.23	all p ≥ 0.16
Decrement	Sequence (between)	5.88 (1, 12)	0.032	0.33	ICA→VPA vs VPA→ICA (pooled) (p = 0.032; d ≈ 1.30).

The table lists only statistically significant effects (α = 0.05); entries report F-values with degrees of freedom, p-values, and partial eta squared (ηp^2). JH:jump height (cm); PP: relative peak power ($W \cdot kg^{-1}$); CT: contraction time (ms); SST: skin surface temperature (°C); Myoton Frequency: natural oscillation frequency (Hz); Myoton Decrement: logarithmic decrement (dimensionless); P1/P2: crossover periods 1/2; Sequence: order of conditions; ICA: isometric conditioning activity; VPA: standardized volleyball pre-training activation condition without ICA.

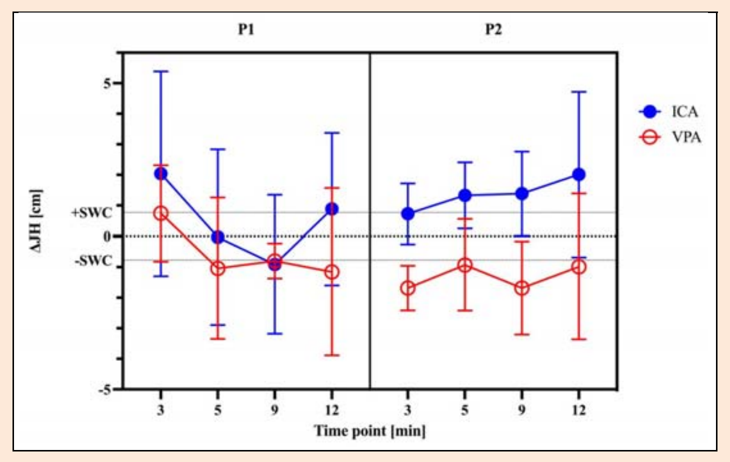

Figure 5. Timecourse of ΔCMJ height. VPA: standardized volleyball pre-training activation condition. ICA: isometric conditioning activity; P1: period 1; P2: period 2; SWC: smallest worthwhile change; JH: jump height.

Contraction time

Main effects of period and time point were not significant, $F(1, 12) = 0.00$, $p = 0.972$; $F(3, 36) = 1.91$, $p = 0.145$. Time point × Sequence was not statistically significant, $F(3, 36) = 2.60$, $p = 0.067$. Period × Time point and the three-way interaction were not significant, $F(3, 36) = 1.37$, $p = 0.269$; $F(3, 36) = 0.44$, $p = 0.725$. The between-subjects sequence effect was significant, $F(1, 12) = 5.49$, $p = 0.037$, $\eta p^2 = 0.31$. Post-hoc contrasts for Period × Time point × Sequence did not yield significant differences (all $p \geq 0.08$).

Peak power

The Period × Sequence term was significant, $F(1, 12) = 6.47$, $p = 0.026$, $\eta p^2 = 0.35$. Main effects of period and time point were not significant, $F(1, 12) = 0.02$, $p = 0.884$; $F(3, 36) = 1.93$, $p = 0.143$, and the between-subjects sequence term was not significant, $F(1, 12) = 1.26$, $p = 0.283$. The Period × Time point and Period × Time point × Sequence terms were not significant, $F(3, 36) = 1.31$, $p = 0.285$; $F(3, 36) = 0.71$, $p = 0.554$. Follow-up contrasts indicated that in P2 ΔPP was higher under ICA than VPA (VPA→ICA vs ICA→VPA, Δ = 2.73, SE = 0.87, $t(12) = 3.14$, $p = 0.037$, $d = 0.871$), with other simple effects not significant.

Surface skin temperature

The period × sequence term was not significant, $F(1, 12) = 0.74$, $p = 0.407$. Main effects of period and time point were not significant, $F(1, 12) = 2.40$, $p = 0.147$; $F(4, 48) = 0.72$, $p = 0.586$. A period × time point interaction was present, $F(4, 48) = 3.37$, $p = 0.016$, $\eta p^2 = 0.22$, whereas the three-way period × time point × sequence term was not, $F(4, 48) = 0.80$, $p = 0.533$, $\eta p^2 = 0.06$. The between-subjects sequence effect was not significant, $F(1, 12) = 2.26$, $p = 0.159$, $\eta p^2 = 0.16$. Post-hoc comparisons for the period × time point interaction did not yield consistent simple differences (all $p \geq 0.25$).

Stiffness

The period × sequence term was not significant, $F(1, 12) = 0.16$, $p = 0.698$. Main effects were not significant for period, $F(1, 12) = 2.62$, $p = 0.131$, and time point, $F(4, 48) = 1.34$, $p = 0.271$. No evidence appeared for time point × sequence, $F(4, 48) = 1.79$, $p = 0.146$, period × time point, $F(4, 48) = 1.47$, $p = 0.226$, or the three-way period × time point × sequence, $F(4, 48) = 1.21$, $p = 0.319$. The between-subjects sequence term was not significant, $F(1, 12) = 0.01$, $p = 0.925$.

Frequency

Period × sequence was not significant, $F(1, 12) = 0.51$, $p = 0.487$. Period showed a non-significant trend, $F(1, 12) = 3.32$, $p = 0.094$. Time point was significant, $F(4, 48) = 3.64$, $p = 0.011$, $\eta p^2 = 0.23$, while time point × sequence, period × time point, and the three-way interaction were not, $F(4, 48) = 0.86$, $p = 0.494$; $F(4, 48) = 0.79$, $p = 0.538$; $F(4, 48) = 0.63$, $p = 0.641$. The between-subjects sequence term was not significant, $F(1, 12) = 0.45$, $p = 0.514$. Pairwise comparisons for time point did not yield significant differences (all $p \geq 0.16$).

Decrement

Period × sequence was not significant, $F(1, 12) = 0.01$, $p = 0.938$. Period and time point main effects were not significant, $F(1, 12) = 0.72$, $p = 0.413$; $F(4, 48) = 0.90$, $p = 0.470$. Interactions involving time were not significant (time point × sequence: $F(4, 48) = 0.54$, $p = 0.704$; period × time point: $F(4, 48) = 0.67$, $p = 0.619$; period × time point × sequence: $F(4, 48) = 1.28$, $p = 0.293$. The between-subjects sequence term was significant, $F(1, 12) = 5.88$, $p = 0.032$, $\eta p^2 = 0.33$.

Associations between measured variables

Correlations among the individual contrasts showed no clear association of ΔJH [ICA-VPA] mean [cm] with the candidate mediators: with ΔSST [ICA-VPA] mean (°) $r = 0.122$, 95% CI (-0.436, 0.613), $p = 0.677$; with ΔStiffness [ICA-VPA] mean (N/m) $r = -0.460$, 95% CI (-0.796, 0.094), $p = 0.098$; with ΔFrequency [ICA-VPA] mean (Hz) $r = -0.282$, 95% CI (-0.707, 0.293), $p = 0.330$; and with ΔDecrement [ICA-VPA] mean $r = 0.397$, 95% CI (-0.169, 0.766), $p = 0.160$. Among mediators, ΔStiffness [ICA-VPA] mean (N/m) correlated negatively with ΔSST [ICA-VPA] mean (°) ($r = -0.561$, 95% CI (-0.841, -0.043), $p = 0.037$; moderate) and positively with ΔFrequency [ICA-VPA] mean (Hz) ($r = 0.546$, 95% CI (0.022, 0.835), $p = 0.043$; moderate); all other inter-mediator associations were non-significant ($p \geq 0.099$).

In P2, ΔJH was higher under ICA than under VPA (Estimate = 2.985 cm, SE = 0.435, $t = 6.868$, $p < 0.001$;

standβ = 1.674, 95% CIβ [1.131, 2.217]). ΔStiffness2 showed a negative association with ΔJH2 (Estimate = -0.090 cm·(N/m)-1, SE = 0.025, t = -3.606, p = 0.005; standβ = -0.495, 95% CIβ [-0.800, -0.189]), whereas ΔSST2 was not related to ΔJH2 (Estimate = -0.008 cm·°C-1, SE = 0.242, t = -0.034, p = 0.974; standardized β = -0.005, 95% CIβ [-0.306, 0.296]). Model fit was R2 = 0.846 (adjusted R2 = 0.800). Collinearity was low (VIF 1.04 - 1.22). Residual autocorrelation was not detected (Durbin-Watson = 1.47, p = 0.192). Cook's distance did not indicate gross influence (max = 0.352; below 1, slightly above the 4/n heuristic). In P1, the analogous model did not yield significant effects; the Sequence term and covariates were non-significant (all p ≥ 0.10). Results are presented in Figure 6 below.

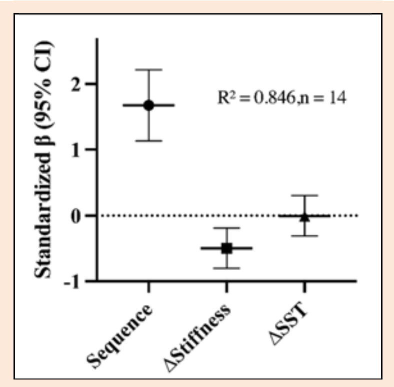

Figure 6. Standardized regression coefficients (β) with 95% CIs for predictors of change in jump height (ΔJH) in P2.

Responders' differences

Responders (ΔJH2 ≥ SWC in P2) demonstrated greater improvements in peak power compared with non-responders (Δ = +2.99 W·kg^{-1}, p = 0.007, d = 1.94). Responders also exhibited a smaller reduction in decrement (Δ = +0.133, p = 0.033, d = 1.24). Between-group differences for ΔSST, ΔStiffness, ΔFrequency, ΔRSImod, and ΔCT were not statistically significant (p ≥ 0.290). There were no differences in P1.

Discussion

This randomized crossover study compares the PAPE effect of an isometric conditioning activity, performed as three sets of five three-second maximal isometric squats with standardized volleyball pre-training activation. The study also examined the changes in muscle mechanical properties and skin temperature and their association with the magnitude of PAPE. The results indicated that, relative to the volleyball-specific warm-up, the ICA was associated with greater CMJ performance, although this advantage was confined to Period 2 and was therefore conditional on the preceding training context. Greater jump gains co-occurred with reductions in rectus femoris muscle stiffness (estimate -0.090 cm·(N·m^{-1})$^{-1}$; standardized β = -0.495; p = 0.005), whereas changes in thigh skin surface temperature were unrelated to performance (p = 0.974). These findings suggest that changes in VP may be more closely associated with the observed potentiation than changes in SST. However, as no direct measures of neuromuscular activation or tendon mechanical behavior were obtained, these findings should be interpreted with caution and cannot be considered evidence of the underlying mechanisms responsible for the PAPE response.

The ICA elicited superior gains in CMJ of JH and PP when delivered in P2, with significant period-by-sequence interactions (JH: F(1, 12) = 6.94, p = 0.022; PP: F(1, 12) = 6.47, p = 0.026) and large simple effects (P2: ICA > VPA; JH d = 1.20; PP d = 0.87), while no between-condition differences emerged in P1. Individual responsiveness favored the ICA (paired OR 9.0, 95% CI 1.25 – 394.48; exact p = 0.021). Crucially, in P2 the responder subgroup (ΔJH2 ≥ SWC) showed greater gains in peak power than non-responders by 2.99 W·kg^{-1} (p = 0.007, d = 1.94) and a smaller reduction in logarithmic decrement by 0.133 (p = 0.033, d = 1.24), with no such differences in P1. Notably, P2 coincided with a reduction in external load across the preceding M2 (total dynamic volume -22%, plyometric contacts -27%, isometric dose -25%; lower-limb dynamic -18%, plyometrics -33%, isometric dose -25%), with relative intensity largely preserved, showing that the isometric advantage was most evident under a lower-volume training context. Collectively, these results suggested that a brief, high-effort isometric protocol can meaningfully augment performance beyond a sport-specific warm-up, particularly when antecedent training volume is reduced, and that the enhancement aligns more with alterations in muscle mechanical state than with superficial thermal responses.

These findings expand upon earlier meta-analyses showing that PAPE protocols can improve vertical jump performance, but with considerable variability in effect magnitude (Seitz and Haff, 2016; Kasicki et al., 2024). Previous studies have reported positive effects of both heavy dynamic resistance exercise (e.g., squats, loaded jump squats) and isometric protocols (Kozlenia and Domaradzki, 2023; Jarosz et al., 2025a; Wu et al., 2025). The present results are also consistent with evidence showing that ICA can be effective stimuli for inducing PAPE. Rixon et al. (2007) reported improved CMJ performance following maximal isometric squats, while Spieszny et al. (2022) showed that three sets of three-second maximal isometric back squats enhanced both squat jump and CMJ performance. In addition, Krzysztofik et al. (2023c) demonstrated that maximal isometric half-squats improved sprint performance and reduced vastus lateralis muscle tone and stiffness, suggesting that isometric PAPE may be accompanied by changes in muscle mechanical properties. These observations align with the present results, where the ICA enhanced CMJ performance and the magnitude of improvement was associated with changes in rectus femoris muscle stiffness.

The volleyball-specific literature also supports the use of priming strategies to enhance jumping performance. McCann and Flanagan (2010) showed that Division I volleyball players improved CMJ performance after both back squat and hang clean CA, whereas Berriel et al. (2022) reported that a PAPE intervention increased CMJ height in professional male volleyball players and that this effect was maintained following a technical-tactical session. Our results extend this evidence by showing that a brief maximal isometric squat protocol can provide additional performance benefits beyond a volleyball-specific warm-up. This is particularly relevant from an applied perspective, as volleyball performance depends heavily on repeated high-intensity jumping actions, and pre-training or pre-competition strategies should enhance explosive performance without adding excessive fatigue.

Importantly, the potentiating effects in our study were most pronounced after a week of reduced training volume, echoing prior evidence that neuromuscular potentiation is strongly modulated by fatigue status and training background (Bevan et al., 2010; Boullosa et al., 2013). This observation may help explain inconsistencies in the literature, where some investigations have reported null or even detrimental effects of conditioning activities when athletes were tested in a fatigued state (Tsolakis et al., 2011; Rappelt et al., 2024). The present findings should therefore also be interpreted in light of elite-athlete warm-up research, where the balance between potentiation and fatigue is critical. Studies in professional rugby players have shown that explosive performance may improve only after sufficient recovery following heavy CA, with optimal effects often occurring several minutes after the stimulus (Kilduff et al., 2007; Kilduff et al., 2008; Bevan et al., 2010). This is consistent with our observation that the isometric advantage was most evident when prior training volume was reduced, suggesting that isometric priming should be individualized according to the athlete's current readiness, residual fatigue, and available recovery window.

A foundational study by Rassier and MacIntosh (2000) proposed that potentiation and fatigue coexist and interact to determine the net performance outcome following a CA. Seitz and Haff (2016) further emphasized that the success of a CA depends on balancing activation and fatigue through appropriate intensity, volume, and rest. Empirical support for this dual-process model was provided by Andrews et al. (2016), who showed that unilateral conditioning exercises can induce local potentiation in the trained limb while simultaneously eliciting contralateral neural fatigue. This confirms that potentiation and fatigue can coexist within the same session and that their relative balance determines the net PAPE response. Our data extend these frameworks by showing that the same CA can yield distinct outcomes depending on the athlete's current level of readiness. The superior response to the isometric protocol during the lower-volume M2 suggested that the effectiveness of a CA should be interpreted in the context of the athlete's acute readiness or residual fatigue. Consequently, individualization of CA should not only account for chronic characteristics such as maximal strength but also for real-time indicators of neuromuscular status, ensuring that the selected activity truly enhances performance rather than adding fatigue.

Our results also showed that reduction in rectus femoris muscle passive stiffness were positively associated with performance improvements, whereas changes in skin surface temperature were not. This supports the notion that mechanical factors, particularly viscoelastic adjustments in the muscle-tendon unit, play a central role in PAPE (Blazevich and Babault, 2019; Fukutani and Herzog, 2019). Elevated passive stiffness may reflect fatigue-related mechanical tension and impair subsequent performance (Wang et al., 2017; Matuszczyk et al., 2025), whereas moderate reductions in passive tendon stiffness after isotonic squat-based CAs have been associated with enhanced jump efficiency (Krzysztofik et al., 2023a). Decreased muscle stiffness may enhance the storage and release of elastic energy during the stretch-shortening cycle, thereby improving jump efficiency (Kubo et al., 2000). Comparable relationships between tendon compliance and jump performance have been observed in previous CA studies (Cormie et al., 2010; Tsoukos et al., 2016).

By contrast, we observed no significant role for thermal responses following the applied CA. Studies examining thermal influences on muscle function have shown that increases in muscle temperature enhance contraction velocity and power output (Bergh and Ekblom, 1979; Oksa et al., 1997; De Ruiter and De Haan, 2000) yet this effect appears insufficient to account for the magnitude of PAPE observed in our study. In the present protocol, the lack of additional temperature change is likely a consequence of a well-executed, standardized warm-up that elevated muscle temperature to near-optimal levels before the CA. Although temperature elevation is recognized as one of the principal mediators of warm-up induced performance improvements via faster cross-bridge cycling, reduced viscous resistance, and accelerated nerve conduction (Bishop, 2003; McGowan et al., 2015) there is, as recently noted, no consensus on its effect on force production (Wilson et al., 2025). Accordingly, when temperature is already optimized by the warm-up, any additional gains following isometric conditioning are more parsimoniously attributed to non-thermal (neuromechanical) mechanisms.

From an applied perspective, our findings support the inclusion of maximal isometric squats as an effective and time-efficient pre-competition priming strategy. Unlike dynamic CA protocols that often require external loads and equipment, isometric contractions can be implemented with minimal resources, making them practical in both training and competition settings (Boullosa, 2021). Comparable outcomes were reported by Durovic et al. (2022), who emphasized the ecological validity of such CA strategies under varying competition conditions. Moreover, our findings reinforce the importance of considering training background: potentiation was most evident after a lower-volume M2, echoing suggestions that managing cumulative fatigue is key to maximizing PAPE (Bevan et al., 2010; Chen et al., 2023). Thus, coaches should tailor pre-match CAs not only to the immediate warm-up but also to the preceding training load.

Several limitations should be acknowledged. First, the modest sample size may have limited our ability to detect smaller effects or subtle moderator variables. Second, although the crossover design controlled for inter-individual variability, the strong period effect suggests that background training volume remains a potential confounder. Formally, no carry-over was detected (period-totals $t(12) = 1.49$, $p = 0.162$) and baseline measures were comparable across sequences, so the 7-day washout appears adequate; however, because the two microcycles differed in external load (≈18 - 33% lower in M2), the Period × Sequence interaction means the isometric advantage is statistically entangled with the reduced preceding training volume. The data should therefore be read as indicating that ICA was more effective under lower antecedent load, rather than as establishing unconditional superiority over the volleyball warm-up. Moreover, the a priori sample size was powered for the primary interaction only; with n = 14 the secondary regression and responder analyses were sensitive to large effects alone (regression f2 ≥ 1.16; d_z ≥ 0.81), so smaller associations may have gone undetected and the number of tests raises the possibility of Type I error. Third, while we included measures of muscle mechanical properties and skin temperature, we did not assess central neural contributions (e.g., surface electromyography, motor unit firing rates) or intramuscular metabolic variables (e.g., muscle oxygenation), which may further clarify the mechanisms underpinning PAPE. Finally, our participants were exclusively highly trained male volleyball players, which restricts the generalizability of our findings to female athletes or other populations. We acknowledge that responder classification is sensitive to biological and measurement variability and that day-to-day variation may approach or exceed the SWC; indeed, in the present data the SWC (0.77 cm) was smaller than the measured typical error (2.19 cm). Responder counts are therefore reported descriptively, as a complement to not a substitute for the group-level analyses.

Our study also has several important strengths. First, we propose a ready-to-use practical solution in the form of a preparation strategy for athletes that can realistically enhance performance. Importantly, we considered the training period, expanding the contextual dimension of our work by embedding the applied CA within the athletes' current training cycle. We also addressed factors that may help identify potential mechanisms underlying our observations. At the same time, our analyses go beyond a classical focus on simple effects, providing a deeper understanding through the evaluation of responders and non-responders and by assessing performance outcomes in the context of changes in the analyzed physiological and mechanical factors. This provided a more nuanced interpretation of the findings, strengthening both their reliability and their practical relevance for training applications.

Future studies should explore PAPE responses in female athletes, younger players, or athletes from sports with different neuromuscular demands to enhance external validity. Incorporating advanced techniques such as intramuscular temperature assessment, near-infrared spectroscopy, or high-density electromyography could provide a more comprehensive understanding of both peripheral and central mechanisms. Finally, given the inter-individual variability observed, future research should aim to identify predictors of responder versus non-responder status, including muscle architecture, fiber type distribution, and prior training history, thereby supporting a more individualized approach to PAPE implementation.

Conclusion

This study indicated that a high-intensity ICA, consisting of three sets of five three-second maximal isometric squats, was associated with enhanced CMJ performance in highly trained volleyball players — an advantage that was most evident, and statistically confined to, the period of reduced preceding training volume. The observed potentiation was associated with reductions in rectus femoris passive stiffness rather than changes in skin surface temperature. Specifically, decreases in rectus femoris passive stiffness were associated with improvements in CMJ performance, whereas changes in SST were not. These findings should be interpreted as associative rather than mechanistic, as they do not establish a causal relationship between changes in VP and the PAPE response. Importantly, the beneficial effects of the isometric protocol were most pronounced when applied after a period of reduced training volume, suggesting that the athletes' acute readiness and preceding workload critically modulate the expression of PAPE. These findings reinforce the dual-process framework in which potentiation and fatigue coexist and underscore the necessity of balancing activation and recovery to achieve optimal performance benefits.

From a practical standpoint, maximal isometric squats represent a simple, time-efficient, and equipment-minimal strategy that can be easily implemented in warm-up or pre-competition settings to acutely improve jump performance. Coaches and practitioners are encouraged to individualize the application of conditioning activities according to the athlete's neuromuscular state and training load, ensuring that potentiation is achieved without excessive fatigue.

Acknowledgements

The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

References

Ammer, K. (2008) The Glamorgan protocol for recording and evaluation of thermal images of the human body. *Thermology International* **18**(4), 125-144.

Andrews, S.K., Horodyski, J.M., MacLeod, D.A., Whitten, J. and Behm, D.G. (2016) The interaction of fatigue and potentiation following an acute bout of unilateral squats. *Journal of Sports Science & Medicine* **15**(4), 625-632. https://pubmed.ncbi.nlm.nih.gov/27928208/

Baena-Raya, A., Diez-Fernandez, D.M., Garcia-Ramos, A., Martinez-Tellez, B., Boullosa, D., Soriano-Maldonado, A. and Rodriguez-Perez, M.A. (2023) Acute mechanical and skin temperature responses to different interrepetition rest intervals during full-squat exercise. *International Journal of Sports Physiology and Performance* **18**(6), 674-681. https://doi.org/10.1123/ijspp.2022-0482

Bergh, U. and Ekblom, B. (1979) Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiologica Scandinavica* **107**(1), 33-37. https://doi.org/10.1111/j.1748-1716.1979.tb06439.x

Berriel, G.P., Cardoso, A.S., Costa, R.R., Rosa, R.G., Oliveira, H.B., Kruel, L.F.M. and Peyré-Tartaruga, L.A. (2022) Effects of postactivation performance enhancement on the vertical jump in high-level volleyball athletes. *Journal of Human Kinetics* **82**, 145. https://doi.org/10.2478/hukin-2022-0041

Bevan, H.R., Cunningham, D.J., Tooley, E.P., Owen, N.J., Cook, C.J. and Kilduff, L.P. (2010) Influence of postactivation potentiation on sprinting performance in professional rugby players. *Journal of Strength and Conditioning Research* **24**(3), 701-705. https://doi.org/10.1519/jsc.0b013e3181c7b68a

Bishop, D. (2003) Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. *Sports Medicine* **33**(6), 439-454. https://doi.org/10.2165/00007256-200333060-00005

Blazevich, A.J. and Babault, N. (2019) Post-activation potentiation versus post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues. *Frontiers in Physiology* **10**, 1359. https://doi.org/10.3389/fphys.2019.01359

Bogdanis, G.C., Tsoukos, A., Veligekas, P., Tsolakis, C. and Terzis, G. (2014) Effects of muscle action type with equal impulse of conditioning activity on postactivation potentiation. *Journal of Strength and Conditioning Research* **28**, 2521-2528. https://doi.org/10.1519/jsc.0000000000000444

Boullosa, D. (2021) Post-activation performance enhancement strategies in sport: a brief review for practitioners. *Human Movement* **22**(3), 101-109. https://doi.org/10.5114/hm.2021.103280

Boullosa, D.A., Abreu, L., Beltrame, L.G. and Behm, D.G. (2013) The acute effect of different half squat set configurations on jump potentiation. *Journal of Strength and Conditioning Research* **27**(8), 2059-2066. https://doi.org/10.1519/jsc.0b013e31827ddf15

Castellana, J.V. and Patel, H.I. (1985) Analysis of two-period crossover design in a multicenter clinical trial. *Biometrics* **41**(4), 969-977. https://doi.org/10.2307/2530968

Chen, Y., Su, Q., Yang, J., Li, G., Zhang, S., Lv, Y. and Yu, L. (2023) Effects of rest interval and training intensity on jumping performance: a systematic review and meta-analysis investigating post-activation performance enhancement. *Frontiers in Physiology* **14**, 1202789. https://doi.org/10.3389/fphys.2023.1202789

Collings, T.J., Lima, Y.L., Dutaillis, B. and Bourne, M.N. (2024) Concurrent validity and test-retest reliability of VALD ForceDecks' strength, balance, and movement assessment tests. *Journal of Science and Medicine in Sport* **27**(8), 572-580. https://doi.org/10.1016/j.jsams.2024.04.014

Cormie, P., McGuigan, M.R. and Newton, R.U. (2010) Adaptations in athletic performance after ballistic power versus strength training. *Medicine and Science in Sports and Exercise* **42**(8), 1582-1598. https://doi.org/10.1249/mss.0b013e3181d2013a

De Ruiter, C.J. and De Haan, A. (2000) Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. *Pflügers Archiv* **440**(1), 163-170. https://doi.org/10.1007/s004240051035

Durovic, M., Stojanovic, N., Stojiljkovic, N., Karaula, D. and Okicic, T. (2022) The effects of post-activation performance enhancement and different warm-up protocols on swim start performance. *Scientific Reports* **12**(1), 9038. https://doi.org/10.1038/s41598-022-13003-9

Fischer, J. and Paternoster, F.K. (2024) Post-activation-performance enhancement: possible contributing factors. *Journal of Sports Science and Medicine* **23**(1), 34-45. https://doi.org/10.52082/jssm.2024.34

French, D.N., Kraemer, W.J. and Cooke, C.B. (2003) Changes in dynamic exercise performance following a sequence of preconditioning isometric muscle actions. *Journal of Strength and Conditioning Research* **17**(4), 678-685. https://doi.org/10.1519/00124278-200311000-00009

Fukutani, A. and Herzog, W. (2019) Current understanding of residual force enhancement: cross-bridge component and non-cross-bridge component. *International Journal of Molecular Sciences* **20**(21), 5479. https://doi.org/10.3390/ijms20215479

Gacto-Sanchez, M., Lozano-Meca, J.A. and Montilla-Herrador, J. (2024) The pain attitudes and beliefs scale for physiotherapists: development and psychometric assessment of the Spanish version among physiotherapy students. *Physiotherapy Theory and Practice* **40**(7), 1436-1446. https://doi.org/10.1080/09593985.2023.2190396

Grzyb, W. and Jarosz, J. (2025) Acute effects of rapid versus sustained isometric contraction durations on countermovement jump performance in national level young male soccer players. *Scientific Reports* **15**(1), 33147. https://doi.org/10.1038/s41598-025-18657-9

Heishman, A., Daub, B., Miller, R., Brown, B., Freitas, E. and Bemben, M. (2019) Countermovement jump inter-limb asymmetries in collegiate basketball players. *Sports* **7**(5), 103. https://doi.org/10.3390/sports7050103

Helbin, J., Gawel, D., Terbalyan, A., Wilk, M., Krzysztofik, M., Lum, D. and Jarosz, J. (2025) Acute effects of isometric contraction distribution on jump performance in volleyball players. *Journal of Functional Morphology and Kinesiology* **10**(3), 343. https://doi.org/10.3390/jfmk10030343

Jarosz, J., Gawel, D., Socha, I., Ewertowska, P., Wilk, M., Lum, D. and Krzysztofik, M. (2025a) Acute effects of isometric conditioning activity with different set volumes on countermovement jump performance in highly trained male volleyball players. *Applied Sciences* **15**(5), 2393. https://doi.org/10.3390/app15052393

Jarosz, J., Drozd, M., Gawel, D., Wilk, M., Helbin, J. and Krzysztofik, M. (2025b) Acute effects of isometric conditioning activity with different distribution contraction on countermovement jump performance in resistance trained participants. *Scientific Reports* **15**(1), 16960. https://doi.org/10.1038/s41598-025-02126-4

Jarosz, J., Gawel, D., Grycmann, P., Aschenbrenner, P., Spieszny, M., Wilk, M. and Krzysztofik, M. (2025c) How repeatable is PAPE effect: the impact of in-season isometric squat activation on countermovement jump performance enhancement in national level soccer players. *BMC Sports Science, Medicine and Rehabilitation* **17**(1), 115. https://doi.org/10.1186/s13102-025-01148-9

Jarosz, J., Gawel, D., Krzysztofik, M., Zajac, A., Tsoukos, A., Bogdanis, G.C. and Wilk, M. (2023) Effects of blood flow restriction on mechanical properties of the rectus femoris muscle at rest. *Frontiers in Physiology* **14**, 1244376. https://doi.org/10.3389/fphys.2023.1244376

Jarosz, J. and Szwarc, A. (2025) Isometric conditioning activity and jump performance: impact of training status in male participants. *Journal of Clinical Medicine* **14**(17), 6214. https://doi.org/10.3390/jcm14176214

Kasicki, K., Rydzik, L., Ambrozy, T., Spieszny, M. and Koteja, P. (2024) The impact of post-activation performance enhancement protocols on vertical jumps: systematic review. *Applied Sciences* **14**(21), 9664. https://doi.org/10.3390/app14219664

Kilduff, L.P., Bevan, H.R., Kingsley, M.I., Owen, N.J., Bennett, M.A., Bunce, P.J. and Cunningham, D.J. (2007) Postactivation potentiation in professional rugby players: Optimal recovery. *Journal of Strength and Conditioning Research* **21**(4), 1134-1138. https://doi.org/10.1519/00124278-200711000-00026

Kilduff, L.P., Owen, N., Bevan, H., Bennett, M., Kingsley, M.I. and Cunningham, D. (2008) Influence of recovery time on post-activation potentiation in professional rugby players. *Journal of Sports Sciences* **26**(8), 795-802. https://doi.org/10.1080/02640410701784517

Klich, S., Ficek, K., Krymski, I., Klimek, A., Kawczynski, A., Madeleine, P. and Fernandez-de-Las-Penas, C. (2020) Quadriceps and patellar tendon thickness and stiffness in elite track cyclists: an ultrasonographic and myotonometric evaluation. *Frontiers in Physiology* **11**, 607208. https://doi.org/10.3389/fphys.2020.607208

Kozlenia, D. and Domaradzki, J. (2023) The effectiveness of isometric protocols using an external load or voluntary effort on jump height enhancement in trained females. *Scientific Reports* **13**(1), 13535. https://doi.org/10.1038/s41598-023-40912-0

Krzysztofik, M., Jarosz, J., Urbanski, R., Aschenbrenner, P. and Stastny, P. (2025) Effects of 6 weeks of complex training on athletic performance and post-activation performance enhancement effect magnitude in soccer players: a cross-sectional randomized study. *Biology of Sport* **42**(1), 211-221. https://doi.org/10.5114/biolsport.2025.139849

Krzysztofik, M., Spieszny, M., Trybulski, R., Wilk, M., Pisz, A., Kolinger, D., Filip-Stachnik, A. and Stastny, P. (2023c) Acute effects of isometric conditioning activity on the viscoelastic properties of muscles and sprint and jumping performance in handball players. *Journal of Strength and Conditioning Research* **37**(7), 1486-1494. https://doi.org/10.1519/JSC.0000000000004404

Krzysztofik, M., Wilk, M., Pisz, A., Kolinger, D., Bichowska, M., Zajac, A. and Stastny, P. (2023b) Acute effects of high-load vs. plyometric conditioning activity on jumping performance and the muscle-tendon mechanical properties. *Journal of Strength and Conditioning Research* **37**(7), 1397-1403. https://doi.org/10.1519/JSC.0000000000004398

Krzysztofik, M., Wilk, M., Pisz, A., Kolinger, D., Tsoukos, A., Zajac, A., Stastny, P. and Bogdanis, G.C. (2023a) Acute effects of varied back squat activation protocols on muscle-tendon stiffness and jumping performance. *Journal of Strength and Conditioning Research* **37**(7), 1419-1427. https://doi.org/10.1519/JSC.0000000000004453

Kubo, K., Kanehisa, H., Kawakami, Y. and Fukunaga, T. (2000) Elastic properties of muscle-tendon complex in long-distance runners. *European Journal of Applied Physiology* **81**(3), 181-187. https://doi.org/10.1007/s004210050028

Lum, D., Yang Ong, K. and Haischer, M.H. (2023) Postactivation performance enhancement with maximal isometric contraction on power-clean performance across multiple sets. *International Journal of Sports Physiology and Performance* **19**(3), 265-270. https://doi.org/10.1123/ijspp.2023-0383

Matuszczyk, F., Trybulski, R., Gałęziok, K., Olaniszyn, G., Terbalyan, A. and Wilk, M. (2025) Effect of 10-week plyometric training on anaerobic performance and biomechanical properties of the muscles in football players: randomized controlled trial. *Applied Sciences* **15**(3), 1451. https://doi.org/10.3390/app15031451

McCann, M.R. and Flanagan, S.P. (2010) The effects of exercise selection and rest interval on postactivation potentiation of vertical jump performance. *Journal of Strength and Conditioning Research* **24**(5), 1285-1291. https://doi.org/10.1519/jsc.0b013e3181d6867c

McGowan, C.J., Pyne, D.B., Thompson, K.G. and Rattray, B. (2015) Warm-up strategies for sport and exercise: mechanisms and applications. *Sports Medicine* **45**(11), 1523-1546. https://doi.org/10.1007/s40279-015-0376-x

McKay, A.K.A., Stellingwerff, T., Smith, E.S., Martin, D.T., Mujika, I., Goosey-Tolfrey, V.L., Sheppard, J. and Burke, L.M. (2022) Defining training and performance caliber: a participant classification framework. *International Journal of Sports Physiology and Performance* **17**(2), 317-331. https://doi.org/10.1123/ijspp.2021-0451

McNair, P.J., Depledge, J., Brettkelly, M. and Stanley, S.N. (1996) Verbal encouragement: effects on maximum effort voluntary muscle action. *British Journal of Sports Medicine* **30**(3), 243-245. https://doi.org/10.1136/bjsm.30.3.243

Moreira, D.G., Costello, J.T., Brito, C.J., Adamczyk, J.G., Ammer, K., Bach, A.J.E., Costa, C.M.A., Eglin, C., Fernandes, A.A., Fernandez-Cuevas, I., Ferreira, J.J.A., Formenti, D., Fournet, D., Havenith, G., Howell, K., Jung, A., Kenny, G.P., Kolosovas-Machuca, E.S., Maley, M.J., Merla, A., Pascoe, D.D., Priego Quesada, J.I., Schwartz, R.G., Seixas, A.R.D., Selfe, J., Vainer, B.G. and Sillero-Quintana, M. (2017) Thermographic imaging in sports and exercise medicine: a Delphi study and consensus statement on the measurement of human skin temperature. *Journal of Thermal Biology* **69**, 155-162. https://doi.org/10.1016/j.jtherbio.2017.07.006

Muckelt, P.E., Warner, M.B., Cheliotis-James, T., Muckelt, R., Hastermann, M., Schoenrock, B., Martin, D., MacGregor, R., Blottner, D. and Stokes, M. (2022) Protocol and reference values for minimal detectable change of MyotonPRO and ultrasound imaging measurements of muscle and subcutaneous tissue. *Scientific Reports* **12**(1), 13654. https://doi.org/10.1038/s41598-022-17507-2

Oksa, J., Rintamaki, H. and Rissanen, S. (1997) Muscle performance and electromyogram activity of the lower leg muscles with different levels of cold exposure. *European Journal of Applied Physiology and Occupational Physiology* **75**(6), 484-490. https://doi.org/10.1007/s004210050193

Perenc, D., Stastny, P., Urbanski, R. and Krzysztofik, M. (2025) Acute effects of supramaximal loaded back squat activation on countermovement jump performance, muscle mechanical properties, and skin surface temperature in powerlifters. *European Journal of Sport Science* **25**(1), e12245. https://doi.org/10.1002/ejsc.12245

Rappelt, L., Held, S., Wiedenmann, T., Micke, F. and Donath, L. (2024) Post-activation performance enhancement (PAPE) protocols do not further increase jumping performance beyond warm-up effects: findings from three acute randomized crossover trials. *Frontiers in Physiology* **15**, 1447421. https://doi.org/10.3389/fphys.2024.1447421

Rassier, D.E. and Macintosh, B.R. (2000) Coexistence of potentiation and fatigue in skeletal muscle. *Brazilian Journal of Medical and Biological Research* **33**(5), 499-508. https://doi.org/10.1590/S0100-879X2000000500003

Rixon, K.P., Lamont, H.S. and Bemben, M.G. (2007) Influence of type of muscle contraction, gender, and lifting experience on postactivation potentiation performance. *Journal of Strength and Conditioning Research* **21**(2), 500-505. https://doi.org/10.1519/00124278-200705000-00037

Salagas, A., Tsoukos, A., Terzis, G., Paschalis, V., Katsikas, C., Krzysztofik, M., Wilk, M., Zajac, A. and Bogdanis, G.C. (2022) Effectiveness of either short-duration ischemic pre-conditioning, single-set high-resistance exercise, or their combination in potentiating bench press exercise performance. *Frontiers in Physiology* **13**, 1083299. https://doi.org/10.3389/fphys.2022.1083299

Seitz, L.B. and Haff, G.G. (2016) Factors modulating post-activation potentiation of jump, sprint, throw, and upper-body ballistic performances: a systematic review with meta-analysis. *Sports Medicine* **46**(2), 231-240. https://doi.org/10.1007/s40279-015-0415-7

Skotniczny, K., Terbalyan, A., Krzysztofik, M., Roczniok, R., Drozd, M., Radziminski, L. and Jarosz, J. (2025) Acute heterogeneous changes in muscle and tendon viscoelastic properties following a VO_2max treadmill test in high-level male soccer players. *Applied Sciences* **15**(13), 6986. https://doi.org/10.3390/app15136986

Spieszny, M., Trybulski, R., Biel, P., Zajac, A. and Krzysztofik, M. (2022) Post-isometric back squat performance enhancement of squat and countermovement jump. *International Journal of Environmental Research and Public Health* **19**(19), 12720. https://doi.org/10.3390/ijerph191912720

Szymczyk, P., Wegrzynowicz, K., Trybulski, R., Spieszny, M., Ewertowska, P., Wilk, M. and Krzysztofik, M. (2022) Acute effects of percussive massage treatment on drop jump performance and Achilles tendon stiffness. *International Journal of Environmental Research and Public Health* **19**(22), 15187. https://doi.org/10.3390/ijerph192215187

Terbalyan, A., Mikolajec, K., Krzysztofik, M., Urbanski, R., Jarosz, J., Stastny, P. and Spieszny, M. (2025) Effects of overcoming isometric unilateral conditioning activity on subsequent single-leg drop jump in elite and amateur volleyball players: a randomized crossover trial. *BMC Sports Science, Medicine and Rehabilitation* **17**(1), 30. https://doi.org/10.1186/s13102-025-01083-9

Thapa, R.K., Weldon, A., Freitas, T.T., Boullosa, D., Afonso, J., Granacher, U. and Ramirez-Campillo, R. (2024) What do we know about complex-contrast training? A systematic scoping review. *Sports Medicine Open* **10**(1), 104. https://doi.org/10.1186/s40798-024-00771-z

Tillin, N.A. and Bishop, D. (2009) Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Medicine* **39**, 147-166. https://doi.org/10.2165/00007256-200939020-00004

Trybulski, R., Wojdala, G., Alexe, D.I., Komarek, Z., Aschenbrenner, P., Wilk, M., Zajac, A. and Krzysztofik, M. (2022) Acute effects of different intensities during bench press exercise on the mechanical properties of triceps brachii long head. *Applied Sciences* **12**(6), 3197. https://doi.org/10.3390/app12063197

Tsolakis, C., Bogdanis, G.C., Nikolaou, A. and Zacharogiannis, E. (2011) Influence of type of muscle contraction and gender on postactivation potentiation of upper and lower limb explosive performance in elite fencers. *Journal of Sports Science and Medicine* **10**(3), 577-583. https://pubmed.ncbi.nlm.nih.gov/24150636/

Tsoukos, A., Bogdanis, G.C., Terzis, G. and Veligekas, P. (2016) Acute improvement of vertical jump performance after isometric squats depends on knee angle and vertical jumping ability. *Journal of Strength and Conditioning Research* **30**(8), 2250-2257. https://doi.org/10.1519/jsc.0000000000001328

Wang, D., De Vito, G., Ditroilo, M. and Delahunt, E. (2017) Effect of sex and fatigue on muscle stiffness and musculoarticular stiffness of the knee joint in a young active population. *Journal of Sports Sciences* **35**(16), 1582-1591.

Wilson, C.J., Nunes, J.P. and Blazevich, A.J. (2025) The effect of muscle warm-up on voluntary and evoked force-time parameters: a systematic review and meta-analysis with meta-regression. *Journal of Sport and Health Science* **14**, 101024. https://doi.org/10.1016/j.jshs.2025.101024

Wilson, J.M., Duncan, N.M., Marin, P.J., Brown, L.E., Loenneke, J.P. and Wilson, S.M.C. (2013) Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. *Journal of Strength and Conditioning Research* **27**, 854-859. https://doi.org/10.1519/jsc.0b013e31825c2bdb

Wu, D., Feng, S., Zhou, A. and Xie, Y. (2025) Heavy load chain squats: a promising method for enhancing lower extremity explosive strength via post-activation performance enhancement. *Frontiers in Physiology* **16**, 1596200. https://doi.org/10.3389/fphys.2025.1596200

Xu, K., Blazevich, A.J., Boullosa, D., Ramirez-Campillo, R., Yin, M., Zhong, Y., Tian, Y., Finlay, M., Byrne, P.J., Cuenca-Fernandez, F. and Wang, R. (2025) Optimizing post-activation performance enhancement in athletic tasks: a systematic review with meta-analysis for prescription variables and research methods. *Sports Medicine* **55**(4), 977-1008. https://doi.org/10.1007/s40279-024-02170-6

Key points

- The study used a randomized crossover design to compare a maximal isometric conditioning activity (ICA; 3 × 5 × 3 s maximal isometric squats) with standardized volleyball pre-training activation (VPA) in 14 highly trained male volleyball players.
- ICA produced greater improvements in countermovement jump height and relative peak power than VPA only in Period 2, which followed a lower-volume training microcycle.
- Individual response patterns favored ICA, with nine ICA-only responders compared with one VPA-only responder; however, these findings should be interpreted cautiously because of the small sample and measurement variability.
- In Period 2, greater reductions in rectus femoris muscle stiffness were associated with larger improvements in jump height, whereas changes in skin surface temperature were unrelated to performance; these relationships are associative rather than mechanistic.
- Maximal isometric squats may provide a practical, time-efficient, and equipment-minimal priming strategy when athletes are sufficiently recovered, highlighting the need to individualize conditioning activities according to preceding training load and current readiness.

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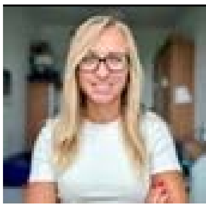

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Supplementary Materials

Supplementary Table S1. Training program

Exercise	Microcycle 1					Microcycle 2				
	Sets	Reps	Tempo	Rest	Intensity	Sets	Reps	Tempo	Rest	Intensity
0a Hip rotation with a medicine ball	2	5	2/0/1/0	-	RPE5	2	5	2/0/1/0	-	RPE5
0b Straight-arm pullover isometric stretch	2	10	-	-	5 - 10kg	2	10	-	-	5 - 10kg
0c Single-leg squat with TRX	2	6	4/0/1/0	60s	RPE5	2	6	4/0/1/0	60s	RPE5
1a Dumbbell high pull in split stance	3	5;4;3	max	-	65;75; 85%1RM	2	5;4	max	-	65;75%1RM
1b Side plank + band row	3	5	2/0/1/0	90s	RPE6	2	5	2/0/1/0	90s	RPE6
2a Dumbbells Bulgarian split squat	3	5;4;3	3/0/1/0	30s	65;75; 85%1RM	2	5;4	3/0/1/0	30s	65;75%1RM
2b Bird dog row with pause	3	4	2/0/1/1	90s	RPE6	2	4	2/0/1/1	90s	RPE6
3a Single-arm DB press in single-leg bridge on bench	3	5;4;3	2/1/1/0	-	65;75; 85%1RM	2	5;4	2/1/1/0	-	65;75%1RM
3b Single-leg hip bridge on fitness ball ISO (upper back on bench)	3	10s	-	90s	RPE6	2	10s	-	90s	RPE6
4a Chin-up	3	3;3;2	4/0/1/0	-	65;75; 85%1RM	2	3;3	4/0/1/0	-	65;75%1RM
4b Glute crusher with fitness ball	3	8	3/0/1/0	90s	RPE6	2	8	3/0/1/0	90s	RPE6
5a Triceps rolling dumbbells	3	10;8;6	3/0/1/0	-	RPE6	2	10;8	3/0/1/0	-	RPE6
5b Superman ball rollouts	3	6	2/0/1/0	60s	RPE6	2	6	2/0/1/0	60s	RPE6
0a Calf raises on leg press	2	8	3/2/1/0	-	RPE5	2	8	3/2/1/0	-	RPE5
0b Spinal rotation with medicine ball (kneeling)	2	5	2/0/1/0	-	RPE5	2	5	2/0/1/0	-	RPE5
0c Rotator drop and catch	2	8	-	60s	2 - 3kg	2	8	-	60s	2 - 3kg
1a Split-stance trap bar deadlift	3	3;3;2	max	30s	65;75; 85%1RM	2	3;3	max	30s	65;75%1RM
1b Seated bilateral box jump	3	2	max	90s	-	2	2	max	90s	-
2a Split squat on toes ISO hold (lead leg elevated)	3	10s	-	-	RPE6;7;8	2	10s	-	-	RPE6;7
2b Y-raise	3	6	3/0/1/0	60s	2kg	2	6	3/0/1/0	60s	2kg
3a Hip thrust	3	5;4;3	3/0/1/0	-	65;75; 85%1RM	2	5;4	3/0/1/0	-	65;75%1RM
3b Renegade row	3	4;4;4	2/0/1/0	90s	RPE6;7;8	2	4;4	2/0/1/0	90s	RPE6;7
4a Push-up (external load on back)	3	5;4;3	4/0/1/0	-	RPE6;7;8	2	5;4	4/0/1/0	-	RPE6;7
4b Single-leg landmine deadlift (sideways stance)	3	4;3;2	4/0/1/0	90s	RPE6;7;8	2	4;3	4/0/1/0	90s	RPE6;7
5a Single-arm split jerk with landmine	3	2	max	-	RPE6	2	2	max	-	RPE6
5b Face pulls from low pulley	3	6	3/0/1/0	60s	RPE6	2	6	3/0/1/0	60s	RPE6
0a Single-leg wall sit with support on fitness ball	2	10s	-	-	RPE5	2	10s	-	-	RPE5
0b TRX Cossack squat	2	5	3/0/1/0	-	RPE5	2	5	3/0/1/0	-	RPE5
0c Poliquin flys	2	6	3/2/1/0	60s	3 - 4kg	2	6	3/2/1/0	60s	3 - 4kg
1a Pogo jumps with bands from below (fast, low amplitude)	3	20	-	30s	6 - 8kg	2	20	-	30s	6 - 8kg
1b Woodchopper low-to-high (band or cable)	3	8	2/0/1/0	90s	RPE6	2	8	2/0/1/0	90s	RPE6
2 Power clean	3	3;2;1	max	90s	65;75; 85%1RM	2	3;2	max	90s	65;75%1RM
3a Pendlay row	3	3;2;2	max	-	65;75; 85%1RM	2	3;2	max	-	65;75%1RM
3b Single-leg medicine ball slam	3	2	max	90s	3 - 4kg	2	2	max	90s	3 - 4kg
4 Half-kneeling landmine press	3	2	max	60s	RPE6;7;8	2	2	max	60s	RPE6;7
5 Quarter squat with pause	3	3;2;2	2/1/1/0	60s	RPE6;7;8	2	3;2	2/1/1/0	60s	RPE6;7

Supplementary Table S2. Jump characteristics.

Period	Sequence	Pre	Δ3′	Δ6′	Δ9′	Δ12′
		JH [cm] (M±SD; 95%CI)				
P1	ICA→VPA	39.99 ± 2.71 (37.48; 42.49)	2.04 ± 3.62 (−1.30; 5.39)	−0.03 ± 3.10 (−2.89; 2.84)	−0.91 ± 2.45 (−3.18; 1.35)	0.89 ± 2.69 (−1.60; 3.37)
	VPA→ICA	38.96 ± 4.32 (34.96; 42.95)	0.74 ± 1.70 (−0.83; 2.31)	−1.04 ± 2.49 (−3.35; 1.26)	−0.80 ± 0.62 (−1.37; −0.23)	−1.16 ± 2.95 (−3.89; 1.57)
P2	ICA→VPA	42.97 ± 3.23 (39.99; 45.96)	−1.69 ± 0.79 (−2.41; −0.96)	−0.93 ± 1.61 (−2.42; 0.56)	−1.69 ± 1.64 (−3.21; −0.17)	−0.99 ± 2.57 (−3.37; 1.40)
	VPA→ICA	39.10 ± 5.35 (34.15; 44.05)	0.73 ± 1.07 (−0.26; 1.72)	1.33 ± 1.17 (0.25; 2.41)	1.39 ± 1.49 (0.01; 2.76)	2.01 ± 2.92 (−0.69; 4.72)
		PP [W/kg] (M±SD; 95%CI)				
P1	ICA→VPA	53.27 ± 3.73 (49.82; 56.72)	2.04 ± 3.63 (−1.31; 5.40)	0.16 ± 2.06 (−1.75; 2.06)	−1.11 ± 1.65 (−2.64; 0.41)	0.76 ± 3.23 (−2.23; 3.74)
	VPA→ICA	51.69 ± 5.78 (46.34; 57.03)	0.24 ± 2.77 (−2.31; 2.80)	−1.29 ± 2.61 (−3.70; 1.13)	−0.73 ± 2.29 (−2.84; 1.39)	−1.80 ± 3.65 (−5.18; 1.58)
P2	ICA→VPA	56.27 ± 4.44 (52.16; 60.38)	−1.13 ± 1.87 (−2.86; 0.60)	−1.11 ± 1.87 (−2.85; 0.62)	−1.73 ± 2.35 (−3.90; 0.45)	−1.87 ± 2.52 (−4.20; 0.46)
	VPA→ICA	52.11 ± 5.94 (46.62; 57.61)	1.09 ± 1.93 (−0.70; 2.87)	1.51 ± 1.38 (0.23; 2.79)	1.19 ± 2.00 (−0.67; 3.04)	1.29 ± 3.54 (−1.99; 4.56)
		RSImod (M±SD; 95%CI)				
P1	ICA→VPA	0.46 ± 0.04 (0.42; 0.51)	0.02 ± 0.04 (−0.01; 0.06)	0.00 ± 0.04 (−0.04; 0.04)	−0.01 ± 0.04 (−0.05; 0.03)	0.00 ± 0.06 (−0.06; 0.06)
	VPA→ICA	0.44 ± 0.07 (0.37; 0.50)	−0.02 ± 0.02 (−0.04; 0.00)	0.00 ± 0.02 (−0.02; 0.02)	0.00 ± 0.05 (−0.04; 0.05)	−0.01 ± 0.06 (−0.06; 0.04)
P2	ICA→VPA	0.55 ± 0.14 (0.43; 0.68)	−0.08 ± 0.16 (−0.22; 0.07)	−0.07 ± 0.17 (−0.22; 0.08)	−0.08 ± 0.17 (−0.24; 0.07)	−0.05 ± 0.15 (−0.19; 0.08)
	VPA→ICA	0.43 ± 0.07 (0.37; 0.50)	0.05 ± 0.07 (−0.02; 0.11)	0.07 ± 0.07 (0.00; 0.13)	0.07 ± 0.08 (0.00; 0.14)	0.08 ± 0.07 (0.01; 0.15)
		CT [ms] (M±SD; 95%CI)				
P1	ICA→VPA	862.29 ± 72.38 (795.34; 929.23)	2.86 ± 61.62 (−54.13; 59.84)	−3.00 ± 53.74 (−52.70; 46.70)	4.57 ± 63.92 (−54.55; 63.69)	27.14 ± 83.46 (−50.04; 104.33)
	VPA→ICA	943.00 ± 129.95 (822.82; 1063.18)	24.00 ± 45.96 (−18.51; 66.51)	−62.29 ± 67.47 (−124.68; 0.11)	−51.43 ± 67.24 (−113.61; 10.76)	−36.86 ± 89.01 (−119.18; 45.46)
P2	ICA→VPA	808.14 ± 157.14 (662.82; 953.47)	62.00 ± 173.24 (−98.22; 222.22)	71.29 ± 176.68 (−92.11; 234.68)	79.57 ± 195.79 (−101.51; 260.65)	39.29 ± 180.83 (−127.95; 206.53)
	VPA→ICA	908.00 ± 87.91 (826.69; 989.31)	−64.71 ± 109.27 (−165.77; 6.34)	−89.00 ± 116.20 (−196.46; 18.46)	−98.14 ± 129.80 (−218.18; 21.90)	−107.29 ± 115.11 (−213.74; −0.83)

Values are mean ± SD (95% CI), with CI in round brackets using a semicolon (e.g., (lower; upper). Pre: measurement after the standardized general warm-up in that period. Δ3′/Δ6′/Δ9′/Δ12′: change from Pre at 3/6/9/12 min (positive = increase; negative = decrease). Period: P1 and P2 in the crossover design. Sequence: order of conditions—ICA→VPA (P1: isometric squat ICA; P2: volleyball activation without ICA) and VPA→ICA (reverse). Conditions: ICA = isometric conditioning activity (3×5×3 s; total 45 s; 3-min interset rest); VPA— standardized volleyball pre-training activation condition. JH—Jump Height (cm); CT—Contraction time (s); PP—Peak Power (W/kg); RSImod—modified reactive strength index; Frequency—natural oscillation frequency (Hz); Decrement—logarithmic decrement (dimensionless); P1/P2—crossover periods 1/2; Sequence—order of VPA— standardized volleyball pre-training activation condition.

Supplementary Table S3. Skin surface temperature.

Period	Sequence	Pre	Δ3′	Δ6′	Δ9′	Δ12′
		SST (°C) (M ± SD; 95%CI)				
P1	ICA→VPA	31.07 ± 0.88 (30.26; 31.89)	0.13 ± 1.08 (-0.87; 1.12)	-0.14 ± 1.06 (-1.12; 0.84)	0.41 ± 0.50 (-0.05; 0.87)	-0.03 ± 0.92 (-0.88; 0.82)
	VPA→ICA	31.10 ± 0.85 (30.32; 31.88)	0.56 ± 1.09 (-0.45; 1.57)	1.09 ± 0.72 (0.42; 1.76)	0.61 ± 1.17 (-0.47; 1.69)	0.99 ± 1.82 (-0.69; 2.67)
P2	ICA→VPA	31.81 ± 0.78 (31.09; 32.54)	0.37 ± 0.81 (-0.38; 1.12)	-0.57 ± 1.15 (-1.63; 0.49)	-0.59 ± 1.13 (-1.63; 0.46)	-0.34 ± 1.04 (-1.30; 0.62)
	VPA→ICA	31.84 ± 1.08 (30.85; 32.84)	0.31 ± 0.72 (-0.35; 0.98)	-0.74 ± 2.75 (-3.28; 1.80)	-0.31 ± 1.06 (-1.29; 0.66)	-0.24 ± 1.31 (-1.45; 0.97)

Values are mean ± SD (95% CI) with CI in round brackets using a semicolon. Pre: SST after the standardized general warm-up in that period. Δ3′/Δ6′/Δ9′/Δ12′: absolute change (°C) from Pre at 3/6/9/12 min (positive = warmer; negative = cooler). Period: P1, P2 (crossover). Sequence: ICA→VPA or VPA→ICA (order of conditions). Conditions: ICA = isometric conditioning activity (3×5×3 s; total 45 s; 3-min interset rest); VPA—standardized volleyball pre-training activation condition

Supplementary Table S4. Myotonometry characteristics.

Period	Sequence	Pre	Δ3′	Δ6′	Δ9′	Δ12′
Stiffness [N/m] (M ± SD; 95%CI)						
P1	ICA→VPA	296.43 ± 20.30 (277.65; 315.21)	-0.29 ± 9.11 (-8.71; 8.14)	-6.43 ± 8.10 (-13.92; 1.06)	-1.71 ± 6.34 (-7.58; 4.15)	-5.43 ± 4.31 (-9.42; -1.44)
	VPA→ICA	314.00 ± 24.64 (291.21; 336.79)	-2.14 ± 10.07 (-11.46; 7.17)	-3.57 ± 8.20 (-11.16; 4.01)	-4.14 ± 10.29 (-13.66; 5.37)	-10.00 ± 23.78 (-31.99; 11.99)
P2	ICA→VPA	284.14 ± 14.25 (270.96; 297.32)	2.14 ± 7.47 (-4.77; 9.05)	1.43 ± 10.39 (-8.18; 11.04)	-3.14 ± 9.86 (-12.26; 5.97)	2.86 ± 8.71 (-5.20; 10.91)
	VPA→ICA	296.71 ± 28.48 (270.37; 323.06)	5.14 ± 17.95 (-11.46; 21.74)	3.43 ± 11.06 (-6.80; 13.66)	6.57 ± 14.11 (-6.47; 19.62)	1.43 ± 12.43 (-10.07; 12.93)
Decrement (M ± SD; 95%CI)						
P1	ICA→VPA	1.41 ± 0.26 (1.17; 1.65)	-0.09 ± 0.05 (-0.14; -0.04)	-0.06 ± 0.12 (-0.18; 0.05)	-0.07 ± 0.10 (-0.16; 0.02)	-0.01 ± 0.07 (-0.07; 0.06)
	VPA→ICA	1.40 ± 0.31 (1.12; 1.69)	0.00 ± 0.09 (-0.08; 0.09)	0.04 ± 0.15 (-0.10; 0.18)	0.01 ± 0.14 (-0.13; 0.14)	-0.05 ± 0.10 (-0.14; 0.04)
P2	ICA→VPA	1.67 ± 0.20 (1.48; 1.85)	-0.11 ± 0.16 (-0.26; 0.04)	-0.11 ± 0.15 (-0.25; 0.03)	-0.13 ± 0.18 (-0.30; 0.03)	-0.08 ± 0.14 (-0.21; 0.05)
	VPA→ICA	1.71 ± 0.24 (1.48; 1.93)	-0.04 ± 0.12 (-0.15; 0.07)	-0.08 ± 0.14 (-0.21; 0.05)	-0.03 ± 0.13 (-0.16; 0.09)	0.03 ± 0.20 (-0.15; 0.22)
Frequency [Hz] (M ± SD; 95%CI)						
P1	ICA→VPA	15.74 ± 1.42 (14.43; 17.05)	0.07 ± 0.71 (-0.59; 0.73)	-0.07 ± 0.59 (-0.61; 0.47)	0.10 ± 0.60 (-0.46; 0.66)	-0.13 ± 0.52 (-0.61; 0.35)
	VPA→ICA	16.76 ± 0.91 (15.91; 17.60)	0.06 ± 0.72 (-0.61; 0.72)	-0.01 ± 0.92 (-0.87; 0.84)	0.13 ± 0.71 (-0.53; 0.79)	-0.48 ± 1.29 (-1.68; 0.71)
P2	ICA→VPA	15.93 ± 0.85 (15.15; 16.71)	0.64 ± 0.81 (-0.10; 1.39)	0.54 ± 0.58 (0.01; 1.08)	0.43 ± 0.75 (-0.27; 1.13)	0.31 ± 0.46 (-0.11; 0.74)
	VPA→ICA	16.79 ± 1.61 (15.30; 18.27)	0.26 ± 0.92 (-0.59; 1.11)	0.20 ± 0.94 (-0.67; 1.07)	0.33 ± 0.75 (-0.36; 1.02)	0.07 ± 0.78 (-0.65; 0.80)

Values are mean ± SD (95% CI), with CI in round brackets using a semicolon (e.g., (lower; upper). Pre: measurement after the standardized general warm-up in that period. Δ3′/Δ6′/Δ9′/Δ12′: change from Pre at 3/6/9/12 min (positive = increase; negative = decrease). Period: P1 and P2 in the crossover design. Sequence: order of conditions—ICA→VPA (P1: isometric squat ICA; P2: volleyball activation without ICA) and VPA→ICA (reverse). Conditions: ICA = isometric conditioning activity (3×5×3 s; total 45 s; 3-min interset rest); VPA— standardized volleyball pre-training activation condition.

Supplementary Table S5. Full set of ANOVA main effects and interactions

Outcome	Period	Time	Sequence	P×Seq	P×Time	Time×Seq	P×Time×Seq
JH [cm]	F(1, 12) = 0.01 p = 0.939 ηp² = 0.00	F(3, 36) = 1.58 p = 0.210 ηp² = 0.12	F(1, 12) = 2.22 p = 0.162 ηp² = 0.16	**F(1, 12) = 6.94 p = 0.022 ηp² = 0.37**	**F(3, 36) = 4.25 p = 0.011 ηp² = 0.26**	F(3, 36) = 0.62 p = 0.608 ηp² = 0.05	F(3, 36) = 0.54 p = 0.656 ηp² = 0.04
PP [W/kg]	F(1, 12) = 0.02 p = 0.884 ηp² = 0.00	F(3, 36) = 1.93 p = 0.143 ηp² = 0.14	F(1, 12) = 1.26 p = 0.283 ηp² = 0.10	**F(1, 12) = 6.47 p = 0.026 ηp² = 0.35**	F(3, 36) = 1.31 p = 0.285 ηp² = 0.10	F(3, 36) = 0.82 p = 0.490 ηp² = 0.06	F(3, 36) = 0.71 p = 0.554 ηp² = 0.06
RSImod	F(1, 12) = 0.00 p = 0.968 ηp² = 0.00	F(3, 36) = 0.64 p = 0.593 ηp² = 0.05	F(1, 12) = 4.05 p = 0.067 ηp² = 0.25	F(1, 12) = 4.44 p = 0.057 ηp² = 0.27	F(3, 36) = 0.94 p = 0.432 ηp² = 0.07	F(3, 36) = 2.65 p = 0.064 ηp² = 0.18	F(3, 36) = 0.21 p = 0.885 ηp² = 0.02
CT [ms]	F(1, 12) = 0.00 p = 0.972 ηp² = 0.00	F(3, 36) = 1.91 p = 0.14 ηp² = 0.14	**F(1, 12) = 5.49 p = 0.037 ηp² = 0.31**	F(1, 12) = 1.84 p = 0.200 ηp² = 0.13	F(3, 36) = 1.37 p = 0.269 ηp² = 0.10	F(3, 36) = 2.60 p = 0.067 ηp² = 0.18	F(3, 36) = 0.44 p = 0.725 ηp² = 0.04
SST [°C]	F(1, 12) = 2.40 p = 0.147 ηp² = 0.17	F(4, 48) = 0.72 p = 0.58 ηp² = 0.06	F(1, 12) = 2.26 p = 0.159 ηp² = 0.16	F(1, 12) = 0.74 p = 0.407 ηp² = 0.06	**F(4, 48) = 3.37 p = 0.016 ηp² = 0.22**	F(4, 48) = 0.27 p = 0.896 ηp² = 0.02	F(4, 48) = 0.80 p = 0.533 ηp² = 0.06
Stiffness [N/m]	F(1, 12) = 2.62 p = 0.131 ηp² = 0.18	F(4, 48) = 1.34 p = 0.27 ηp² = 0.10	F(1, 12) = 0.01 p = 0.925 ηp² = 0.00	F(1, 12) = 0.16 p = 0.698 ηp² = 0.01	F(4, 48) = 1.47 p = 0.226 ηp² = 0.11	F(4, 48) = 1.79 p = 0.146 ηp² = 0.13	F(4, 48) = 1.21 p = 0.319 ηp² = 0.09
Frequency [Hz]	F(1, 12) = 3.32 p = 0.094 ηp² = 0.22	**F(4, 48) = 3.64 p = 0.011 ηp² = 0.23**	F(1, 12) = 0.45 p = 0.514 ηp² = 0.04	F(1, 12) = 0.51 p = 0.487 ηp² = 0.04	F(4, 48) = 0.79 p = 0.538 ηp² = 0.06	F(4, 48) = 0.86 p = 0.494 ηp² = 0.07	F(4, 48) = 0.63 p = 0.641 ηp² = 0.05
Decrement	F(1, 12) = 0.72 p = 0.413 ηp² = 0.06	F(4, 48) = 0.90 p = 0.470 ηp² = 0.07	**F(1, 12) = 5.88 p = 0.032 ηp² = 0.33**	F(1, 12) = 0.01 p = 0.938 ηp² = 0.00	F(4, 48) = 0.67 p = 0.619 ηp² = 0.05	F(4, 48) = 0.54 p = 0.704 ηp² = 0.04	F(4, 48) = 1.28 p = 0.29 ηp² = 0.10

Entries report F-values with degrees of freedom, p-values, and partial eta squared (ηp²). Each cell reports F, p, and ηp² (computed as F·df1/(F·df1+df2); effects significant at $p < 0.05$ are shown in bold. SST—skin surface temperature (°C); JH—Jump Height (cm); CT—Contraction time (s); PP—Peak Power (W/kg); RSImod—modified reactive strength index; Frequency—natural oscillation frequency (Hz); Decrement—logarithmic decrement (dimensionless); P1/P2—crossover periods 1/2; Sequence—order of VPA— standardized volleyball pre-training activation condition.