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How repeatable is PAPE effect: the impact of in-season isometric squat activation on countermovement jump performance enhancement in national level soccer players

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Abstract

Background The post-activation performance enhancement (PAPE) effect has been widely studied; however, its repeatability across training sessions during the competitive season in team sports has not yet been verified. Therefore, this study investigates whether PAPE effect, as measured by the countermovement jump (CMJ) without arm swing, induced by an maximum voluntary isometric squat as a conditioning activity (ICA) three days after the match, could be replicated over a 4-week training period throughout the season. The study also explores whether the magnitude of acute PAPE responses correlates with match running variables, as monitored by global positioning system (GPS) data.

Methods Fifteen national level soccer players participated in the study (mean age: 26.9 ± 4.2 years, body mass: 79.2 ± 6.5 kg, height: 182.1 ± 6.5 cm, experience in soccer training: 11.2 ± 4.2 years, experience in strength training: 10.5 ± 4.6 years, relative maximal strength in squat: 1.84 kg/body mass). Each participant performed 1 repetition of the CMJ approximately 120 s before (pre-ICA) and approximately 60 s after (as post-ICA) 1 set of maximum voluntary isometric squat using a Smith machine as the ICA lasting 5 s. The measurements were repeated across 4 testing sessions performed week apart and each time 3 days after the soccer match. Moreover, running performance variables during matches including total distance, high-speed running distance, sprint distance, player load, total number of accelerations, total number of decelerations were collected via GPS system.

Results A two-way repeated-measures ANOVA showed a significant main effect of time, indicating an increase in CMJ height (mean difference = 1.05 ± 0.3 cm; Cohen's d = 0.222; p = 0.005) post-ICA compared to pre-ICA. The one-way ANOVA did not reveal significant differences between sessions, which may indicate repeatable acute PAPE responses (F = 0.093, p = 0.963, η2p = 0.006). Additionally, the one-way ANOVAs did not reveal significant differences in all GPS data between particular soccer matches (p > 0.145; for all). The interclass correlation coefficient for the PAPE response was poor to moderate (interclass correlation coefficient = 0.56, 95% confidence interval: 0.06–0.83). The Cochran's Q test indicated that PAPE response distributions varied across sessions (p = 0.018). However, pairwise McNemar tests did not reveal significant differences (p = 0.549–1.000), suggesting that while response distribution fluctuated, no specific session-to-session differences were detected. Moreover, Pearson's product-moment correlation

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coefficient, did not show significant correlation between the percentage PAPE responses and all of match GPS data variables ($p > 0.074$; for all).

Conclusions The findings suggest that ICA can consistently elicit a PAPE response of small magnitude in national-level soccer players with a short 60-s rest interval. However, the variability in individual responsiveness and the lack of a relationship with running variables monitored via GPS during soccer matches indicate that other physiological and neuromuscular factors may influence the magnitude of PAPE responses. Given this variability, individually monitoring PAPE responsiveness may be beneficial for optimizing its application.

Keywords Post-activation performance enhancement, Isometric conditioning activity, Vertical jump

Introduction

Post-activation performance enhancement (PAPE) is a training phenomenon in which specific conditioning activities are used to acutely enhance neuromuscular performance in subsequent exercises [1, 2]. These conditioning activities typically include high-intensity isotonic or isometric exercises performed prior to explosive activities with comparable movement patterns, such as performing high-load squats before vertical jumps [3, 4]. This is justified by the fact that the effect is primarily local in nature [5, 6] and can be explained by changes occurring in the muscles engaged during exercise, including the phosphorylation of myosin regulatory light chains, increased muscle temperature, decreased muscle pH (i.e., accumulation of H + ions), enhanced blood flow, increased intracellular water content, muscular activity, and increased musculo-tendinous stiffness [7]. Additionally, findings by Blazevich & Babault [7] indicate that central and peripheral fatigue are key factors influencing acute PAPE responses, potentially interfering with their magnitude. Hodgson et al., [8] suggest that a moderate level of fatigue can coexist with potentiation effect, while excessive fatigue may disrupt it [9, 10].

Given the impact of fatigue on the PAPE effect, the available literature lacks studies examining how PAPE responses change throughout a competitive season in well-trained athletes, as well as research assessing their consistency and repeatability. In this context, the use of Global Positioning System (GPS) data, which is commonly implemented at the national level in soccer, provides valuable insights into performance analysis and training optimization. Specific external load metrics, such as total distance covered, high-speed running, accelerations, decelerations, and distance covered per minute, can provide insights into match-related fatigue status [11], and may therefore be linked to the occurrence and magnitude of the PAPE effect [12, 13]. Therefore, GPS data may provide feedback needed to adjust subsequent training sessions in order to improve overall performance, for example, to maximize the benefits of the PAPE effect in subsequent training sessions if desired. However, to the best of the authors' knowledge, no existing study has examined the occurrence of PAPE responses in relation to running performance during match monitored via GPS or the impact of competition-induced fatigue, which may hinder performance in subsequent training sessions as well as the long-term adaptation process.

Considering the repeatability of PAPE responses there is only a few studies that have attempted to determine this issue [14–18]. Urbański et al. [15] examined PAPE effects within a single training session, while other studies, such as those by Biel et al. [17] and Krzysztofik et al. [18], investigated the effect at two distant time points, several weeks apart, assessing the impact of specific resistance training interventions. Their findings demonstrated that the PAPE response remained stable both within a single session and before and after six to eight weeks of complex training in basketball [17] and soccer players [18], respectively. However, these studies were conducted during the off-season, and data on the consistency of PAPE across successive in-season training sessions remain scarce.

When analyzing the impact of fatigue on the PAPE effect, it is also important to consider the fatigue induced by the applied conditioning activity. Numerous studies on the PAPE effect have evaluated different types of conditioning activity, particularly in relation to the type of muscle contraction involved in the exercise [19, 20]. Among there, isometric conditioning activities (ICA) have been successfully used to induce PAPE [3, 3, 14, 21, 22] and, in some cases, have even been shown to be more effective than isotonic exercises [19, 20]. Studies by Spieszny et al. [23] and Bogdanis et al. [19] demonstrated that three sets of maximal voluntary isometric squats, each consisting of three 3-s contractions (total 27 s), significantly improved countermovement jump (CMJ) height. Additionally, Bogdanis et al. [19] found that isometric contractions were more effective than concentric (concentric-only half squats) and eccentric (eccentric-only half squats) muscle actions when the impulse of the ground reaction force of the conditioning exercise was equated. Esformes et al. [20] demonstrated that a 7-s isometric barbell bench press acutely enhanced power output during subsequent bench press throw. Similarly, Lum

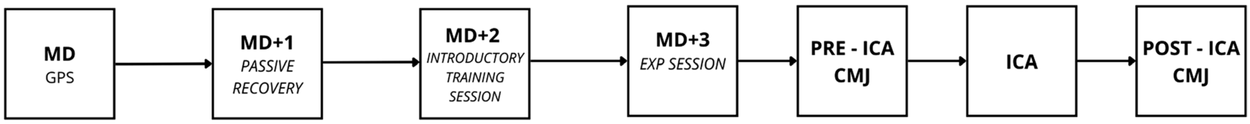

Fig. 1 Experimental design, repeated 4 consecutive weeks of the competitive season

et al. [14] found enhanced barbell velocity in the power clean when performed immediately after an isometric power clean starting position as the ICA with a total contraction duration of 6-s. Supporting these findings, Skurvydas et al. [12] identified that among various isometric contraction duration (5 – 60 s), a 5-s maximal voluntary isometric contraction was the most effective in eliciting potentiation of the twitch rate. These findings suggest that even a brief ICA lasting only a few seconds may be sufficient to induce a meaningful PAPE effect. This efficiency may be further supported by the lower energy demands of isometric contractions compared to dynamic contractions, as indicated by previous studies [24, 25], making them a viable option in PAPE protocols. As a result, incorporating ICA in place of dynamic exercises could help better manage fatigue while still facilitating beneficial neuromuscular adaptations through the PAPE effect. This approach may be particularly advantageous during the in-season training period in team sports, where athletes experience high overall training loads alongside frequent competitive matches.

Considering the aforementioned gaps in the literature regarding the PAPE effect, this study aimed to determine whether acute PAPE responses, assessed through changes in CMJ height following a 5-s maximum voluntary isometric squat (as an ICA), would be repeatable across successive measurement sessions and whether these responses would correlate with running variables during soccer matches, as monitored using GPS data throughout four consecutive weeks of the soccer season. We hypothesized that the applied ICA would lead to an immediate increase in CMJ height and that this effect would be consistently repeatable across four training sessions. Additionally, we expected that the occurrence of acute PAPE responses would negatively correlate with GPS data, with higher running variables values associated with a lower magnitude of the PAPE response.

Materials and methods

Experimental approach to the problem

This study aimed to investigate the repeatability of PAPE responses induced by ICA and to examine their relationship with running variables during soccer matches, as monitored using GPS. A within-subject repeated-measures study was conducted to assess changes in CMJ height before and after a 5-s maximum voluntary isometric squat, used as the ICA [3, 19, 21, 23]. Four training sessions were performed three days post-match (MD + 3) over four consecutive weeks of the competitive season. Moreover, the GPS data were collected to quantify external load during matches (Fig. 1). The relationship between these GPS data and the magnitude of PAPE responses was analyzed to determine whether higher running variables values resulted in a diminished PAPE effect.

Subjects

Fifteen highly trained/national level soccer players, classified based on training status and performance caliber according to McKay et al. [26] classification (mean age: 26.9 ± 4.2 years, body mass: 79.2 ± 6.5 kg, height: 182.1 ± 6.5 cm, experience in soccer training: 11.2 ± 4.2 years, experience in strength training: 10.5 ± 4.6 years, relative maximal strength in squat: 1.84 kg/body mass) participated in this study. Inclusion criteria were as follows: 1) no neuromuscular or musculoskeletal disorders, 2) no lower limb surgery within 2 years prior to the study, 3) at least 7 years of experience in soccer training and matches, 4) regular soccer and resistance training, and competition 6 years before the study. The exclusion criteria included goalkeepers and players who participated in fewer than 70 min in matches. Participants were instructed to maintain their usual dietary and supplementation habits throughout the study period. They were informed about the study's benefits and potential risks before providing written consent to participate. They had the right to withdraw from the experiment at any time. One participant was excluded during the experiment due to being called up to the national team training camp; therefore, the experiment was completed by 15 participants (Fig. 2). The Research Ethics Committee for Scientific Research at the Academy of Physical Education in Katowice, Poland, (3/2021) approved the study protocol. Additionally, the study was conducted in accordance with the 2013 Helsinki Declaration.

Pre-experimental sessions

The first day after the match, referred to as MD + 1, was consistently designated as passive recovery day, during which participants spent their time outside the club. On the first day of each training microcycle (MD + 2), participants underwent an introductory training session,

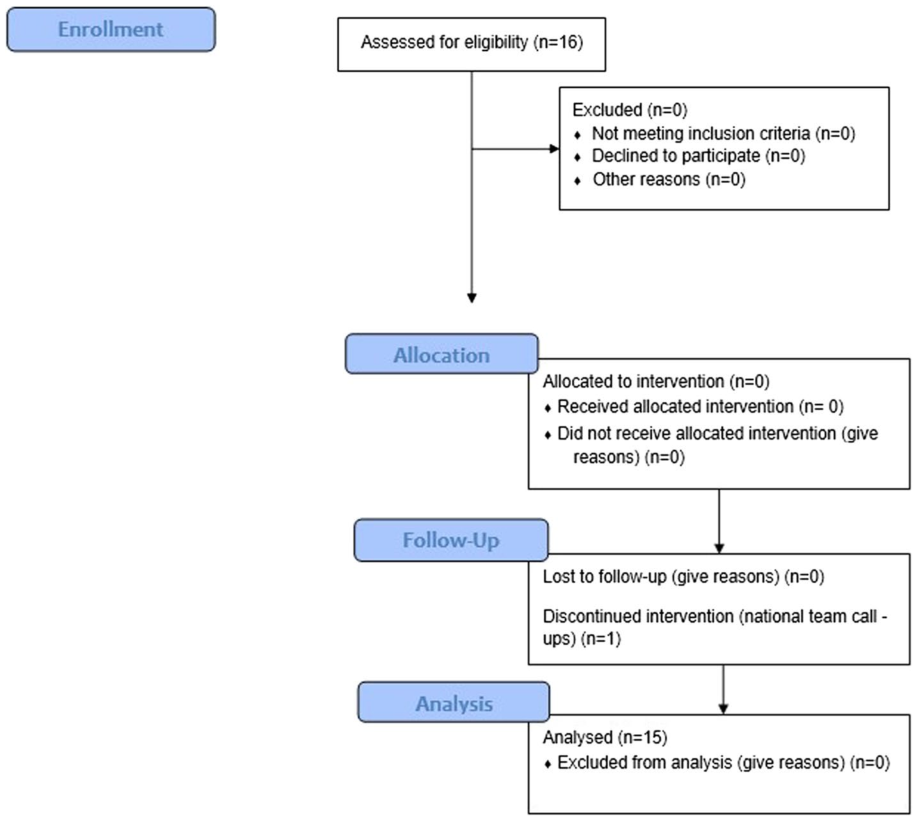

Fig. 2 Participant flow diagram

as shown in Fig. 3. This training session was designed to maintain a consistent loading pattern, ensuring comparable intensity across all MD + 2 sessions.

Familiarization and experimental sessions

All experimental sessions were conducted between 9:00 AM and 11:00 AM, always on the third day after the match. At least seven days prior to the first experimental session, participants underwent a familiarization session that included maximum isometric squats and a CMJ. The session began with a standard warm-up routine, which was typically performed before resistance training sessions. The routine began with 10 min of cycling or jogging, followed by 2 sets of 8 repetitions of each exercise performed in place: hip rotations (inward and outward), knee hugs, heel-to-glute touches, and lunges in forward, backward, and lateral directions. Next, participants performed 10 repetitions of ankle hops and 4 repetitions of CMJ, both with and without an arm swing. The warm-up concluded with two circuits of 8 repetitions of arm circles, push-ups, forward and lateral leg swings, inchworms, squats, single-leg hip thrusts, and a 30-s plank. Subsequently, each participant performed a single repetition of CMJ, followed by a 120 s rest period before executing a single set of a 5 s maximum voluntary isometric squat as an ICA using a Smith machine. After the ICA, participants rested for 60 s before performing one more CMJ attempt. A single CMJ attempt was selected as soccer players rarely get multiple chances to perform maximal jumps in match situations (e.g., aerial duels). Additionally, multiple attempts could introduce motor learning adaptations, potentially affecting data consistency. This approach reflects game demands while fitting within the structured nature of training sessions. A single attempt ensures that the PAPE effect is measured in its purest form.

The ICA was performed on a Smith machine with the barbell loaded with a supramaximal load, preventing any movement. The squat depth was individually determined for each participant based on the knee angle defined as their "*individual descent during the eccentric phase of the CMJ.*" An experienced strength and conditioning coach ensured proper body positioning to maintain a vertical torso during the isometric squat and the correct placement of the barbell on the participants' shoulders. Upon the coach's command, participants were instructed to "*push the barbell vertically upward as forcefully and as quickly as possible,*" pressing their

Fig. 3 Example of MD + 2 training

backs against the bar and their feet against the floor. They were required to maintain tension for 5 s. The experimental sessions followed the same procedure as the familiarization session.

Measurements of countermovement jump height

Jumping performance was assessed using a force platform (Force Decks, Vald Performance, Australia), previously validated as a significant and reliable tool for measuring vertical jump kinematics [27]. Each participant performed 1 repetition of CMJ without arm swing approximately 120-s pre-ICA and approximately 60-s post-ICA. During the measurement, the participant started from a standing position with hands on the hips. They then descended into a squat position to a chosen depth, followed by exerting maximum effort in a vertical jump. Participants were instructed to land in the same position as during takeoff, centrally on the force platform. The jump height from the flight time (9.81 × [flight time]2/8) was estimated.

Match load assessment

The 4 matches were analyzed (3 championship matches and 1 friendly match). GPS data were collected using the Playertek device (Catapult Innovations, Melbourne, Australia) sampling at 10 Hz, which is integrated with a 400 Hz triaxial accelerometer and a 10 Hz triaxial magnetometer. The reliability of this device has been documented in previous studies [28–30]. The compact unit, measuring 85 mm × 40 mm × 20 mm, was securely placed in a protective pouch between the participants shoulder blades, specifically in the upper thoracic region. GPS units were activated 15 min before each match to ensure that satellite connection was established. To quantify running performance during matches, various parameters were analyzed, including total distance (TD) [km], high-speed running distance (HSR) [m] at 19.8–25.2 km/h, sprint distance (SD) [m] at > 25.2 km/h.],

Table 1 Countermovement jump height before and after isometric conditioning activity across training sessions

	Pre-ICA [cm]	Post-ICA [cm]*	ES (pre- vs. post-ICA)	Difference [%]
Session 1	43.9 ± 4.3 (41.5 to 46.2)	44.7 ± 4.0 (42.6 to 46.9)	0.18	+ 2.2
Session 2	44.8 ± 4.8 (42.2 to 47.3)	45.8 ± 4.8 (43.2 to 48.3)	0.22	+ 2.4
Session 3	43.9 ± 4.1 (41.7 to 46.1)	45.1 ± 4.8 (42.5 to 47.6)	0.25	+ 2.6
Session 4	44.7 ± 4.8 (42.1 to 47.4)	45.8 ± 5.0 (43.1 to 48.5)	0.25	+ 2.6

Values are presented as mean ± SD (95% confidence intervals); *ICA* isometric conditioning activity; *a significant main effect of time ($p = 0.005$) indicating increase in CMJ height from pre-ICA to post-ICA; *ES* effect size of Cohen's d was interpreted as < 0.20 "small", 0.21–0.79 "medium", and .0.80 as "large"

player load (PL), total number of accelerations (ACC) at > 3–4 $m \cdot s^{-2}$, as well as total number of decelerations (DCC) at > 3–4 $m \cdot s^{-2}$ [29]. Data analysis was performed by retrospectively downloading the information from the Playertek software to a Microsoft Excel spreadsheet (Excel, Redmond, WA, USA). Only GPS data from players who participated in at least 70 min of each match were included in the analysis.

Statistical analyses

All statistical analyses were performed using JASP (version 0.18.2.0). Data were expressed as means with standard deviations (SD) with 95% confidence intervals for mean values. Statistical significance was set at $p < 0.05$. The Shapiro–Wilk and Mauchly's tests were used to verify the normality and sphericity of the sample data variances, respectively. The two-way repeated measures ANOVAs (4 sessions × 2 time points [pre- and post-]) were used to investigate the influence of CA and each session on jump height. When a significant main effect or interaction was found, the post-hoc tests with Bonferroni correction were used to analyze the pairwise comparisons. Additionally, the one-way ANOVAs were employed to investigate the differences among kinematic GPS data across all sessions. Partial eta-squared (η^2_p) was calculated to estimate the effect size of ANOVA results and interpreted as small ($\eta^2 p \geq 0.01$), medium ($\eta^2 p \geq 0.06$), or large ($\eta^2 p \geq 0.14$). The magnitude of mean differences was expressed using Cohen's effect sizes, with thresholds interpreted as < 0.20 "small", 0.21–0.79 "medium", and 0.0.80 as "large". Pearson's product-moment correlation coefficient was used to analyze the relationship between GPS data and percentage 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) [30]. Additionally, a two-way random-effects model with absolute agreement for a single rater was used to calculate the intraclass correlation coefficient (ICC) and its 95%CI based on the absolute differences between pre-ICA and post-ICA jump height values, serving as an indicator of PAPE response. Moreover, pre-ICA CMJ height values across sessions were used to assess the ICC and coefficient of variation of CMJ height measurements. ICC values were interpreted as follows: less than 0.5 indicated poor reliability, between 0.5 and 0.75 indicated moderate reliability, between 0.75 and 0.9 indicated good reliability, and greater than 0.90 indicated excellent reliability [31]. Furthermore, the smallest worthwhile change (SWC) was calculated using the formula 0.2 × standard deviation of test values, with the highest value across sessions being used [32]. This SWC threshold was then applied to classify participants as responders, non-responders, or negative responders to the CA. Participants were categorized as: (i) responders if their CMJ height increased beyond the SWC value, (ii) non-responders if the change remained within the SWC range, and (iii) negative responders if their CMJ height decreased beyond the SWC threshold. To examine differences in the frequency of responders, non-responders, and negative responders across the four experimental sessions, a Cochran's Q test was applied. Then to determine where these differences occurred, pairwise McNemar tests were performed for all session comparisons.

Results

The two-way ANOVA did not reveal significant interaction for CMJ ($F = 0.112$, $p = 0.952$, $\eta^2 p = 0.008$). However, a main effect of time was observed ($F = 11.268$, $p = 0.005$, $\eta^2 p = 0.446$), indicating significant increase in CMJ height post-ICA (mean difference = 1.05 ± 0.3 cm; Cohen's d = 0.222; $p = 0.005$) compared to pre-ICA (Table 1). Additionally, a significant main effect of the session was observed for CMJ height ($F = 2.876$, $p = 0.047$, $\eta^2 p = 0.17$), however, post-hoc analysis did not reveal any significant differences between sessions. The one-way ANOVA did not reveal significant

Table 2 Distribution of responders, non-responders, and negative responders to the isometric conditioning activity

	Session 1 [n]	Session 2 [n]	Session 3 [n]	Session 4 [n]
Responders	8 (53.3%)	7 (46.6%)	8 (53.3%)	7 (46.6%)
Non-responders	5 (33.3%)	6 (40%)	4 (26.6%)	6 (40%)
Negative Responders	2 (13.3%)	2 (13.3%)	3 (20%)	2 (13.3%)

Table 3 GPS descriptive data

Variable	TD [m]	HSR [m]	SD [m]	PL [a.u.]	ACC [n]	DCC [n]
Game 1	10,293 ± 960	658 ± 199	182 ± 83	401 ± 42	90 ± 11	100 ± 13
Game 2	10,364 ± 1228	642 ± 82	190 ± 139	409 ± 55	93 ± 12	101 ± 15
Game 3	10,463 ± 1470	655 ± 146	185 ± 98	410 ± 66	91 ± 15	100 ± 19
Game 4	10,461 ± 1242	642 ± 188	193 ± 117	412 ± 42	94 ± 11	102 ± 14

TD total distance, *HSR* high-speed running distance, *SD* sprint distance, *PL* player load, *ACC* total number of accelerations, *DCC* total number of decelerations

differences in baseline CMJ height between weeks ($F = 2.667$, $p = 0.059$, $\eta^2p = 0.151$). The one-way ANOVA did not reveal significant differences between sessions, which may indicate repeatable acute PAPE responses ($F = 0.093$, $p = 0.963$, $\eta^2p = 0.006$). Additionally, the one-way ANOVA did not reveal significant differences between matches in: PL ($F = 0.230$, $p = 0.874$, $\eta^2p = 0.028$), HSR ($F = 1.279$, $p = 0.304$, $\eta^2p = 0.138$), SD ($F = 0.458$, $p = 0.714$, $\eta^2p = 0.054$), TD ($F = 0.308$, $p = 0.819$, $\eta^2p = 0.042$), ACC ($F = 1.996$, $p = 0.145$, $\eta^2p = 0.222$), and DCC ($F = 1.240$, $p = 0.320$, $\eta^2p = 0.150$).

The ICC for pre-ICA CMJ height measurement across sessions was found to be 0.97 (95%CI: 0.93 to 0.99), indicating excellent reliability, while the ICC for the PAPE response was 0.56 (95%CI: 0.06 to 0.83), indicating poor to moderate reliability. Additionally, the coefficient of variation for pre-ICA CMJ height measurements across sessions was 3.3% ± 1.1%. The SWC for CMJ height ranged from 0.82 to 0.95 cm within sessions. A Cochran's Q test did not reveal significant differences between sessions, $Q(3) = 8$, $p = 0.018$, indicating that the PAPE response distributions were not consistent across sessions. However, pairwise McNemar test show that either of comparisons reached significance ($p =$ from 0.549 to 1.000), suggesting that while the overall distribution varied across sessions (Table 2).

Descriptive data for all GPS variables is shown in Table 3. Pearson's product-moment correlation coefficient test did not reveal a significant correlation between the percentage difference in the PAPE effect and individual GPS data ($p > 0.074$; for all) (Table 4).

Discussion

The primary aim of this study was to determine the repeatability of acute PAPE responses over a 4-week period during the season and to investigate whether these responses correlated with running variables monitored via GPS during soccer match. The results confirmed our hypothesis regarding the effectiveness of the applied ICA in immediately enhancing CMJ height and the repeatability of this effect across sessions. This study demonstrated that a 5 s maximum isometric squat acutely increased CMJ height with a medium effect size. However, considering that the observed PAPE effect (+2.2 to 2.6%) falls within the measurement variability (3.3% ± 1.1%), its practical significance is questionable. Moreover, the repeatability of these acute PAPE responses was poor to moderate across training sessions, performed one week apart during the in-season period. Furthermore, while the overall distribution of PAPE responses among

Table 4 Pearson's product-moment correlation coefficients between match running variables and PAPE response

Variable	TD	HSR	SD	PL	ACC	DCC
DIFFERENCE CMJ	-0.141	-0.311	-0.283	-0.198	-0.022	-0292
% DIFFERENCE CMJ	-0.23	-0.338	-0.043	-0.282	-0.094	-0.351

TD total distance, *HSR* high-speed running distance, *SD* sprint distance, *PL* player load, *ACC* total number of accelerations, *DCC* total number of decelerations participants varied, no significant session-to-session differences were observed. The proportion of responders, non-responders, and negative responders to the applied ICA fluctuated across sessions: responders ranged from 46.6% to 53.3%; non-responders varied between 26.6% and 40%; and negative responders remained relatively stable between 13.3% and 20%. However, the assumption that the magnitude of PAPE effect would be negatively correlated with GPS data was not supported, as no significant relationship was found between GPS data and PAPE responses on the third day after a match in highly trained soccer players.

To the best of authors knowledge this study is the first to analyze the occurrence of repeatable acute PAPE responses and correlate their magnitude with GPS match data over a 4-week period during the soccer season. The findings demonstrated that while the PAPE effect was repeatable, its consistency ranged from poor to moderate. One of the few studies that assessed the PAPE effect at two distant time points, several weeks apart, was conducted by Biel et al. [17] and Krzysztofik et al. [18]. The authors examined the magnitude of the PAPE effect before and after six to eight weeks of complex training, providing insight into its long-term consistency. Biel et al. [17] found that the PAPE effect was present both before and after the 8-week complex training intervention, with no significant changes in its magnitude in a group of basketball players. Similarly, Krzysztofik et al. [18] observed that, after six weeks of complex training, the PAPE response remained stable in a group of soccer players, further supporting the idea that PAPE can be maintained over an extended period. However, these studies were conducted during the off-season, meaning that the impact of competition-induced fatigue on PAPE magnitude was not assessed. Additionally, individual participant responses were not evaluated, leaving uncertainty regarding intra-individual variability in PAPE effects. In contrast, the present study highlights significant variability in individual PAPE responsiveness across sessions, with fluctuations in the proportion of responders and non-responders. This suggests that the acute effects of ICA may not be entirely consistent among participants. Notably, in each session, the majority of participants were classified as either responders or non-responders, while only 2–3 individuals exhibited a substantial decrease in CMJ height. This suggests that, in practice, coaches and practitioners can expect the applied ICA to consistently elicit a PAPE response across multiple sessions or, at the very least, have a neutral impact on performance, with only a small proportion of highly trained soccer players experiencing a negative response.

Additionally, no significant correlation was found between the magnitude of the PAPE effect and GPS data over the 4-week soccer season. Similarly, no changes in CMJ height were observed between sessions prior to performing the ICA. This result may also indicate a sustained level of neuromuscular performance and can be considered in the context of studies evaluating seasonal variations in physical fitness among team sport athletes. Specifically, Cardoso Marques and González-Badillo [35] demonstrated that CMJ height significantly improved over a 12-week in-season resistance training program in elite team handball players. Similarly, Bishop et al. [34] found significant improvements in CMJ height from the preseason to midseason, with these gains largely maintained until the end of the season in elite academy soccer players. On the other hand, Caldwell and Peters [33] examined fitness fluctuations in soccer players and found that CMJ performance tends to improve from the preseason to midseason, followed by a plateau or slight decline in the latter part of the competitive period. These findings suggest that lower-body power adaptations acquired during the competitive period can be relatively well-maintained, aligning with our observation of a consistent CMJ height and PAPE response across multiple training sessions. However, this maintenance may depend on the phase of the season, as suggested by the performance trends observed in the later stages of the competitive period in Caldwell and Peters' [33] study. Therefore, longer-term studies covering the entire season are needed to evaluate whether the occurrence of the PAPE effect remains stable over a longer period and how it responds to the varying demands of different phases of the soccer season.

Furthermore, this study showed also that the applied ICA, consisting of a single 5-s maximum voluntary isometric squat, significantly improved CMJ height when performed 60 s later. This finding aligns with previous research demonstrating the effectiveness of ICA in inducing the PAPE response [3, 19, 23], while also confirming that this effect can be achieved even after a short rest interval [12, 14]. However, this finding contrasts with previous recommendations suggesting longer rest periods (4–6 min) following high-intensity resistance training to maximize acute PAPE responses [5, 36]. However, it is important to note that the guidelines by Seitz and Haff [5] and Wilson et al. [36] were primarily developed for exercises performed in coupled eccentric-concentric manner, rather than isometric exercises, which may explain the observed differences. A recent study by Lum et al. [14] further supports the effectiveness of ICA with short recovery periods, showing that barbell velocity increased during the power clean when performed immediately after three sets of three maximum voluntary isometric contractions, with a total contraction duration of six seconds, at the starting position of the power clean. The results of this study and Lum et al. [14] suggest that shorter rest intervals may be sufficient for ICA to elicit acute PAPE responses, which has significant implications for training organization in elite sports. One possible explanation is that isometric exercises engage a large number of motor units, leading to greater muscle fiber recruitment [37, 38]. Additionally, isometric exercises are characterized by lower energy expenditure compared to eccentric-concentric muscle actions (e.g., back squat), allowing post-conditioning activity to be performed with full muscle potential shortly after its completion [12, 14, 25]. While longer rest intervals may still be optimal in certain contexts, shorter intervals could be more practical during regular training sessions, as they increase training density and help maintain athlete focus [16, 39]. However, it is essential to interpret these findings with caution, as the observed PAPE effect (+2.2 to 2.6%) falls within the measurement variability (3.3% ± 1.1%), raising questions about its practical significance. This suggests that while ICA may elicit acute improvements in CMJ height, these changes could be influenced by intra-individual variability rather than a consistent physiological response. Therefore, while a 60-s rest interval may be sufficient to induce PAPE in some cases, further research is needed to determine the reliability of this effect across different contexts and athletic populations.

In addition to the indicated research results, several limitations should be acknowledged. A significant limitation of this study was the lack of a control condition (i.e. without performing ICA) only GPS data from four matches were analyzed, and assessments were conducted at a single time point post match (MD+3). This limitation prevented comparisons of running loads and fatigue monitoring across all training microcycles (including all training sessions), which could have provided additional context for interpreting the results. Additionally, no biochemical or perceptual alterations following matches were assessed, further limiting insight into the physiological and subjective responses on PAPE effect. From a practical perspective, although this ICA protocol effectively elicited acute PAPE responses, its applicability may be constrained in athletes with varying levels of experience or in sports disciplines with physical demands that differ from those characteristic of high-intensity microcycles. Additionally, as jump height was estimated based on flight time, comparisons with studies that used the impulse-momentum method should be made cautiously due to potential methodological discrepancies. Moreover, placing these findings into context within the existing body of research is challenging due to the limited availability of studies examining the repeatability of PAPE responses across multiple in-season training sessions. This underscores the need for further research to explore this aspect in greater detail and validate the present findings in different athletic contexts.

Conclusions and practical applications

These findings suggest that ICA can consistently elicit a PAPE response in national-level soccer players with a short 60-s rest interval, though its magnitude falls within measurement variability, requiring cautious interpretation. However, the variability in individual responsiveness and the lack of a relationship with running variables monitored via GPS during soccer matches indicate that other physiological and neuromuscular factors may influence magnitude of PAPE responses. Given this variability, it may be beneficial to individually monitor PAPE responsiveness to optimize its application. Future research should explore the long-term stability of PAPE responses across different phases of the season, as well as its occurrence at various time intervals following match competition. Additionally, further studies should investigate its applicability to athletes of different competitive levels and sports disciplines to determine its broader effectiveness in various sporting contexts.

Abbreviations

PAPE	Post-activation performance enhancement
ICA	Isometric conditioning activity
MD+3	Three days post-match
CMJ	Countermovement jump
TD	Total distance
HSR	High-speed running distance
SD	Sprint distance
PL	Player load
ACC	Total number of accelerations
DCC	Total number of decelerations

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Authors' contributions
Conceptualization, MK and JJ; methodology, MK and JJ; software, DG and PA; validation, PA and MS; formal analysis, JJ and DG; investigation, JJ and PG; data curation, JJ and MS; writing – original draft preparation, JJ; writing – review and editing, JJ, MW, MK; supervision, MK and MW; project administration, JJ and PG. All authors have read and agreed to the published version of the manuscript.

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Data availability
The datasets analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The study was conducted in accordance with the principles of the Helsinki Declaration and was approved by the Bioethical Committee for Scientific

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Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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