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Acute effects of unilateral conditioning activity on unilateral and bilateral jumping performance and bilateral strength asymmetry

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The majority of motor tasks in sports are executed unilaterally, however research on the impact of unilateral conditioning activities (CAs) on both unilateral and bilateral sports tasks remains limited. Therefore, the aim of this study was to evaluate the effects of isometric and plyometric unilateral CAs on unilateral and bilateral jumping performance. The study involved fifteen resistance-trained males who participated in three experimental sessions: 3 sets of 3 s of maximum isometric single-leg quarter-squats or 3 sets of 5 single-leg tuck jumps as CAs, along with a control condition without CA. Measurements of single-leg jump (SLJ) and countermovement jump (CMJ) were taken 5 min before, and at approximately the 3th, 6th and 9th minute after the CA. The analysis did not show any statistically significant interactions nor a main effect of condition or time ($p > 0.05$) for CMJ height and relative peak power. However, a main effect of time ($p = 0.02$) to increase non-dominant SLJ height from baseline to best post-CA time-point was found (+ 0.8 ± 2.5 cm; Cohen's d = 0.22). Neither isometric nor plyometric CAs significantly affected CMJ and SLJ performance. The observed increase in jump height for the non-dominant leg is likely due to motor learning rather than the effects of the applied CAs.

Keywords Post-activation performance enhancement, Power output, Isometric, Overcoming, Plyometric

Post-activation performance enhancement (PAPE) phenomenon has gained increasing interest among the scientific community and sports practitioners. Primarily because it enables a significant acute improvement in power exercises like jumps, sprints and throws[1], as well as chronic adaptation through high-quality training[2,3]. Usually, this effect is achieved by high-intensity resistance or plyometric exercises as a condition activity (CA)[4] that are similar in terms of a movement pattern as well as muscles involved with the subsequent high-velocity task. The main physiological mechanisms underlying the PAPE effect are associated with increased muscle temperature, fiber water content, and muscle activation[4]. The duration of PAPE lasts about 16 to 20 min and reaches peak mostly between 5 and 7 min following the CA[4]. Including a CA in a pre-competition warm-up or a training routine can significantly enhance the athlete's sport performance. However, it should be carefully tailored to the specific demands of the subsequent sport activity[1].

The physical demands of individual and team sports, like sprinting, jumping and changing direction ability, requires generating ground reaction forces unilaterally[5,6]. Therefore, the key element of efficiency in mentioned athletic tasks is the amount of force and power output generated by limbs independently of each other. Despite the fact that the majority of motor tasks in sports are executed unilaterally, most studies aimed to induce PAPE using bilateral CAs[7], even though the movement pattern of CA should be similar to the subsequent exercise[2]. Therefore, it seems to be reasonable to use CA in a unilateral fashion that involves the same muscle groups that will be used in the following task.

Only few studies have investigated the use of unilateral CA on jumping ability, for instance Bishop et al.[8] used 2 sets of 10 repetitions of split squats with body mass or 30 kg weighted vest as a CA to enhance bilateral

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and unilateral countermovement jump (CMJ) and broad jump (BJ). Both protocols improved bilateral CMJ and BJ after 5 minutes post-CA, but there were no changes in unilateral CMJ and BJ, performed on the dominant and non-dominant leg, were reported. Therefore, it seems that the complexity of the post-CA task may affect the magnitude of the PAPE effect. It is also necessary to emphasize that during split squat, force is produced by both limbs with a predominance of the front leg, but still it' s considered as a unilateral exercise[9]. Going further, Kalinowski et al.[10] compared the effects of complex bilateral and unilateral CAs (isometric and plyometric) on bilateral CMJ performance. Participants performed: bilateral or unilateral isometric half back squats followed by bilateral drop jump (DJ) or unilateral isometric half back squats followed by unilateral DJ. Bilateral CA contributed to an increase in CMJ height 6 min post-CA compared to pre-CA. Conversely, unilateral CA did not cause any significant changes in CMJ performance. The training methods used in this study appear to be highly beneficial for sports training. Isometric exercises contribute to minimal exercise-induced muscle damage and soreness while allowing for high levels of force output[11]. Therefore, they seem particularly advantageous for both training and rehabilitation[12]. On the other hand, plyometric training can improve sports activities involving sprinting, jumping and change of direction ability[13]. Dello Iacono et al.[14] found that 3 sets of 10 repetitions of alternate horizontal single-leg DJ led to greater improvement of the change of direction performance in comparison with the vertical single-leg DJ, while the vertical DJ contributed to greater improvement in the bilateral CMJ performance. Despite these studies confirming the effectiveness of plyometric and isometric exercises as a CA, the lack of consensus in the research highlights the need for further studies to optimize PAPE protocols, in which unilateral sports tasks are performed both as the CA and post-CA.

An important aspect of unilateral activities is their potential to address inter-limb asymmetries[15]. Previous research has revealed that significant inter-limb asymmetries are associated with a greater injury risk and can adversely affect sports performance[15–17]. The commonly accepted threshold for clinically meaningful asymmetries in maximal strength is 10%[18]. However, studies have shown that even differences as small as 5% may impair physical performance in activities like jumping, sprinting, and change of direction tasks[19]. One potential solution may be to perform CA only on the weaker limb[7]. By utilizing the local manner of PAPE demonstrated by the previously cited studies[20–22]. An acute increase ix§n weaker limb strength could potentially produce beneficial effects in reducing inter-limb differences. Andrews et al.[20] observed an increase in CMJ height in the exercised leg and a decrease in CMJ height in the contralateral leg at the 1st, 5th and 10th minute after 3 sets of Bulgarian splits squats, with no differences in DJ performance in either leg. The reported results may be due to underlying PAPE mechanisms which may occur only in the exercised leg, while the lack of improvement in DJ was probably related to the high balance requirements[16]. Outcomes suggest that the unilateral CA can cause an increase in performance only when the same muscle area (limb) is involved in the subsequent task, with negative or no effect on the other limb. In study by Wong et al.[21] performance increased in the exercised upper limb, with no contralateral limb performance changes. Power et al.[22] observed an even decrease in performance by involved limb, without changes in non-exercises limb. Therefore, existing evidence indicates that the PAPE effect may occur mainly locally[21,22]. Moreover, isometric and plyometric CAs could potentially modulate strength differences between limbs while requiring less training equipment than traditional resistance exercises, such as heavy barbell squats.

To the best of the author's knowledge, no study has compared the acute effects of isometric and plyometric unilateral CAs on both unilateral and bilateral vertical jumping performance. Therefore, the aim of this study was to evaluate the impact of isometric and plyometric unilateral CAs performed by the dominant limb on single-leg jumps executed by both the dominant and non-dominant limbs, as well as on bilateral CMJ performance. The following hypotheses were proposed: (1) both of types of CAs would positively affect single leg jump (SLJ) performance in the exercised limb and CMJ performance; (2) CAs would not significantly impact SLJ performance on non-dominant limb; (3) both types of CAs would increase the differences in force generated by the lower limbs during CMJ.

Materials and methods

Experimental approach

The study was conducted using a randomized crossover design, in which each participant completed three experimental sessions to compare the acute effects of maximum isometric and plyometric CAs on the following CMJ and SLJ performance (Fig. 1). Participants were randomly assigned to two different conditions: (i) 3 sets of 3 s of maximum isometric single-leg quarter-squats (ISO), and (ii) 3 sets of 5 single-leg tuck jumps (PLY). Due to logistical reasons, the control condition (CRL) was performed as the last experimental session by each participant. Measurements were performed 5 min before the CA and approximately at the 3rd, 6th and 9th minute following the CA. In the CRL condition, measurements were performed at the same time point, but without CA.

Participants

Fifteen resistance-trained men (age: 23 ± 2 years; body mass: 83 ± 11 kg; height: 179 ± 6 cm; experience in resistance training: 6 ± 3 years; relative back squat one-repetition maximum [1RM]: 1.8 ± 0.3 kg/body mass) participated in the study. The inclusion criteria were: (i) free from neuromuscular and musculoskeletal disorders, (ii) no lower-limb serious injury including tendon or muscle tear (leading to training absence over 4 weeks) for two years prior to the study (iii) have at least two years of experience in resistance training. Participants were instructed to maintain their sleep hygiene and dietary habits throughout the study. Testing was scheduled for the same time of the day for both experimental and control sessions to avoid the effects of the circadian rhythm. Participants were not told of the expected study outcomes and were free to withdraw from the study at any time. They were informed about the benefits and potential risks of the study before providing their written informed consent for participation. The study protocol was approved by the Bioethics Committee for Scientific Research

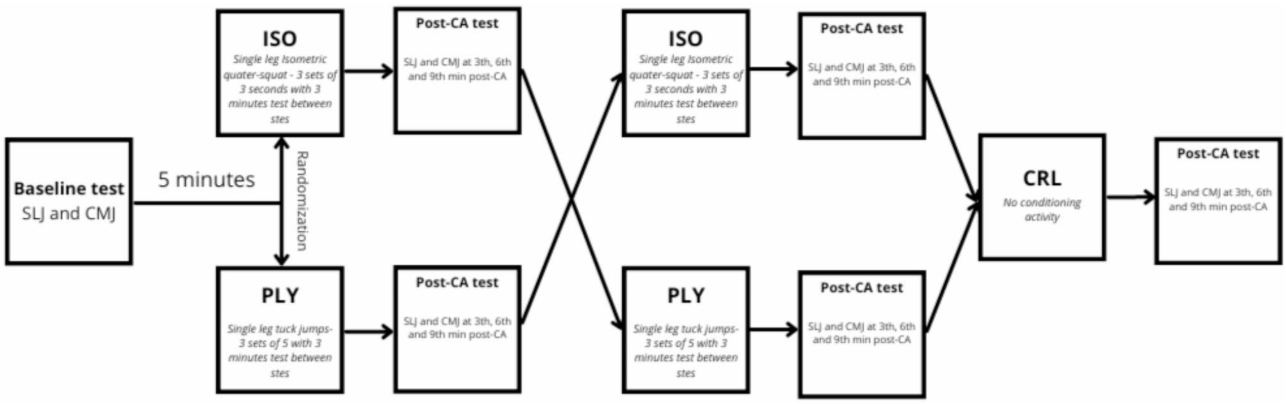

Fig. 1. Schematic representation of the study design. *SLJ* single leg jump, *CMJ* countermovement jump, *ISO* isometric condition, *PLY* plyometric condition, *CA* conditioning activity.

(3/2021) at the Academy of Physical Education in Katowice and performed according to the ethical standards of the Declaration of Helsinki, 2013.

Familiarization session

At least two days before the first experimental session, participants completed a familiarization session that included maximum single-leg tuck jumps, isometric quarter-squats, SLJ and CMJ. The session began with a standardized warm-up consisting of 5 min cycling followed by 10 repetitions of the following bodyweight exercises: bodyweight squats, walking lunges, pulling the knees to the sternum, jumping jacks and submaximal SLJs (5 per leg). Volume of warm up referred to as a "moderate" was shown to be the most optimal for enhancing CMJ height[23]. Immediately after warming up, participants performed one repetition of SLJ with the dominant limb (SLJ_{DOM}), non-dominant limb (SLJ_{N-DOM}) and CMJ (all jumps with upper-limbs placed on the hips). This was followed by a single set of each CA on the dominant lower limb: 5 SL tuck jumps and 3 s SL maximum isometric quarter-squat. The participant identified their dominant leg by answering the question: "Which leg would you use to kick the ball?" (left or right)[24].

Experimental session

After the warm-up (same as during the familiarization session), the participants performed baseline SLJ_{DOM}, SLJ_{N-DOM} and CMJ (30s rest interval between each) performance assessments, always in this order. After 5 min of rest, the participants performed unilateral CA on their dominant lower limb: (i) maximum SL isometric quarter-squat (ISO); or (ii) SL body mass tuck jumps (PLY) in randomized order; or (iii) no CA (CRL) as the last experimental session. The maximum isometric squat was performed on an unmovable barbell placed on a rack, ensuring it could not move and allowing the participant to achieve the proper setup (approximately 120-degree knee extension). Positioned under the barbell, participants were instructed to push the barbell as forcefully and as fast as possible for 3 s. Three sets of 3 maximal attempts were performed, with a 3-min rest interval between sets. Under the PLY condition, participants performed 3 sets of 5 SL tuck jumps with stick between each (jumps were not in a continuous manner). The instruction was to pull the knee as fast and as high as possible before bringing it back down to absorb the landing, with a 3-min rest interval between sets. During the CRL condition, participants walked on a treadmill at 5 km/h for 7 min, which was the time required to complete the entire CA.

Measurement of jumping performance and force output during conditioning activities

Each set of jumps and CAs was performed on a force plate (Force Decks, Vald Performance, Australia), which in this study achieved measurement reliability ranging from "good" to "excellent" (intraclass correlation coefficients [two-way mixed effects, absolute agreement, single rate] for jump height were calculated based on pre-CA results from each session: SLJ_{DOM}: 0.616, [coefficient of variation (CV) = 19.1%]; SLJ_{N-DOM}: 0.579, [CV = 19.9%]; CMJ: 0.901, [CV = 16.6]). Peak force output during each set of CA was measured to compare the intensity of the applied CAs. Each participant performed a single trial of SLJ_{DOM}, SLJ_{N-DOM} and CMJ (in the same order, with 30 s of rest between each jump) without arm swing at pre-CA as a baseline and at three time-points post-CA (3rd, 6th, and 9th minute after the CA). For the measurement, participants started in the standing position with their hands placed on the hips. Then they dropped into the countermovement position to a self-selected depth, immediately followed by a maximal effort vertical jump. Participants were instructed to land in the same position as the take-off, in the mid-section of the force plate. After each jump, the participant reset to the starting position, and this procedure was repeated for a total of three jumps. Jump height and relative peak power output were evaluated, with the best jumps after post-CA in terms of height being used for further analysis.

Bilateral strength asymmetry

Bilateral strength asymmetry index 1 (BSA-1) equation was used to assess impact of unilateral CA on each limb's force output during CMJ from pre- to post-CA measures:

$$\frac{dominant\ limb - nondominant\ limb}{dominant\ imb + nondominant\ limb} \times 100$$

The BSA-1 equation has been recognized as a valid and reliable method for calculating strength asymmetries during a bilateral CMJ[25].

Statistical analysis

All statistical analyses were performed using JASP (Version 0.18.3; University of Amsterdam, Netherlands) and the data was shown as means with standard deviations (± SD) with their 95% confidence intervals (CI). Statistical significance was set at $p<0.05$. The normality of data distribution was checked using Shapiro–Wilk tests. To investigate the influence of CA on jump performance two-way ANOVAs (3 conditions × [ISO; PLY; CRL] × 2 time-points [pre-CA; best post-CA]) were used to examine individual peak PAPE responses. When a significant main effect or interaction was found, the post-hoc tests with Bonferroni correction were used to analyze the pairwise comparisons. The paired sample t-test was used to compare peak force output during ISO and PLY CAs. The magnitude of mean differences was expressed with standardized effect sizes. Thresholds for qualitative descriptors of Cohen's d were interpreted as 0.2 "small", 0.5 "medium", and > 0.8 as "large"[26].

Results

Single leg jump performance

The two-way ANOVA did not show statistically significant interaction ($F=1.373$; $p=0.270$; $\eta^2p=0.089$) nor main effect of condition ($F=0.728$; $p=0.492$; $\eta^2p=0.049$) nor main effect of time ($F=0.016$; $p=0.9$; $\eta^2p=0.001$) for SLJ_{DOM} height. Further, no statistically significant interaction ($F=0.313$; $p=0.734$; $\eta^2p=0.022$) nor main effect of condition ($F=0.033$; $p=0.967$; $\eta^2p=0.002$) were observed for SLJ_{N-DOM}. height. However, a main effect of time ($F=6.916$; $p=0.02$; $\eta^2p=0.331$) to increase SLJ_{N-DOM} height from baseline to best post-CA time-point was found ($p_{bonf}=0.02$; mean difference [MD] = + 0.8 ± 2.5 cm; Cohen's d = 0.22) (Table 1).

Moreover, no significant interaction ($F=3.040$; $p=0.064$; $\eta^2p=0.178$) nor main effect of condition ($F=1.811$; $p=0.182$; $\eta^2p=0.115$;) and main effect of time ($F=3.918$; $p=0.068$; $\eta^2p=0.219$;) for SLJ_{DOM} relative peak power output was reported. Further, no significant interaction ($F=0.508$; $p=0.607$; $\eta^2p=0.035$) nor main effect of condition ($F=1.351$; $p=0.275$; $\eta^2p=0.088$;) and main effect of time ($F=0.299$; $p=0.593$; $\eta^2p=0.021$) for SLJ_{N-DOM} relative peak power output was found.

Countermovement jump performance

The two-way ANOVA did not show any statistically significant interactions ($F=1.458$; $p=0.241$; $\eta^2p=0.004$ and $F=0.508$; $p=0.607$; $\eta^2p=0.035$) nor a main effect of condition ($F=0.127$; $p=0.881$; $\eta^2p=0.004$ and $F=0.651$; $p=0.529$; $\eta^2p=0.044$) and also no significant main effect of time ($F=0.052$; $p=0.823$; $\eta^2p=0.001$ and $F=4.212$; $p=0.059$; $\eta^2p=0.231$) was reported for CMJ height and relative peak power output (Table 2).

Peak force output during conditioning activities

T-test showed statistically higher mean peak force output during ISO compared to PLY CA ($p<0.01$, ES = 2.69, 2677 ± 320 N vs. 1858 ± 288 N) (Fig. 2).

Bilateral strength asymmetry

The two-way ANOVA did not show a statistically significant interaction ($F=0.128$; $p=0.88$; $\eta^2p=0.009$), nor main effect of condition ($F=1.817$; $p=0.181$; $\eta^2p=0.115$) and there was no significant main effect of time ($F=0.282$; $p=0.604$; $\eta^2p=0.02$) observed for BSA-1 during CMJ (Table 3).

	Pre-CA	3 min post-CA	6 min post-CA	9 min post-CA	Best
Dominant leg [cm] (95%CI)					
ISO	19.9 ± 3.3 (18.1 to 21.8)	18 ± 4.2 (15.6 to 20.3)	18.3 ± 4.1 (16 to 20.5)	18.6 ± 4.6 (16.1 to 21.1)	19.2 ± 4.3 (16.9 to 21.6)
PLY	19 ± 3.6 (16.9 to 21)	19 ± 4.3 (16.6 to 21.4)	18.4 ± 3.8 (16.3 to 20.6)	18.5 ± 3.8 (16.4 to 20.6)	19.7 ± 3.9 (17.5 to 21.8)
CRL	18.9 ± 3 (17.3 to 20.6)	18 ± 4.2 (15.6 to 20.3)	18.6 ± 3.7 (16.5 to 20.6)	18.1 ± 3.9 (15.9 to 20.2	19.1 ± 4 (16.9 to 21.3)
Non-dominant leg [cm] (95%CI)					
ISO	17.5 ± 5.2 (14.7 to 20.4)	16.5 ± 4.7 (13.9 to 19.1)	17.5 ± 3.6 (15.5 to 19.4)	17.8 ± 3.1 (16.1 to 19.6)	18.8 ± 3.2 (17 to 20.5)
PLY	17.8 ± 2.6 (16.4 to 19.2)	17.3 ± 3.4 (15.4 to 19.1)	17 ± 3.8 (14.9 to 19.1)	17.6 ± 3.9 (15.4 to 19.8)	18.2 ± 3.8 (16.2 to 20.3)
CRL	17.8 ± 3.6 (15.8 to 19.8)	17.7 ± 3.5 (15.7 to 19.6)	17 ± 3.6 (15 to 19)	17.2 ± 3.3 (15.3 to 19.1)	18.5 ± 3.3 (16.7 to 20.3)

Table 1. Changes in single leg jump height. *CA* conditioning activity, *CI* confidence interval, *ISO* isometric condition, *PLY* plyometric condition, *CRL* control condition, *Pre* baseline measurement, *Best* the best jump height post-CA.

	Pre-CA	3 min post-CA	6 min post-CA	9 min post-CA	Best
Jump height [cm] (95%CI)					
ISO	39.6 ± 5.9 (36.4 to 42.9)	39.6 ± 7.1 (35.6 to 43.6)	38.3 ± 7.4 (34.3 to 42.4)	39.3 ± 7.6 (35.1 to 43.5)	40.3 ± 7.1 (36.3 to 44.2)
PLY	40.1 ± 6.1 (36.7 to 43.4)	39.4 ± 7 (35.6 to 43.3)	39.1 ± 7.6 (34.9 to 43.3)	38.8 ± 7.5 (34.7 to 43)	40.3 ± 7.1 (36.3 to 44.2)
CRL	40.2 ± 6.5 (36.6 to 43.8)	38.2 ± 7.4 (34.1 to 42.3)	38.3 ± 7.7 (34.1 to 42.6)	38.9 ± 6.9 (35.1 to 42.7)	39.7 ± 7.1 (35.7 to 43.4)
Relative peak power [N/kg] (95%CI)					
ISO	57.9 ± 6.3 (54.4 to 61.4)	57.5 ± 7.2 (57.5 to 61.4)	56.3 ± 7.7 (52.1 to 60.6)	56.3 ± 6.8 (52.5 to 60.1)	57.5 ± 6.8 (53.8 to 61.3)
PLY	57.8 ± 6.3 (54.4 to 61.3)	56.5 ± 6.3 (52.9 to 60)	56.5 ± 6.9 (52.7 to 60.3)	55.5 ± 6.8 (51.7 to 59.2)	57.2 ± 6.6 (53.5 to 60.9)
CRL	57.7 ± 6.6 (54 to 61.3)	56.2 ± 6.7 (52.5 to 60)	56.1 ± 7.2 (52.1 to 60.1)	55.8 ± 6.4 (52.2 to 59.3)	56.6 ± 6.8 (52.8 to 60.3)

Table 2. Changes in countermovement jump variables. *CA* conditioning activity, *CI* confidence interval, *ISO* isometric condition, *PLY* plyometric condition, *CRL* control condition.

Discussions

The aim of this study was to evaluate the acute effects of ISO and PLY unilateral CAs performed by the dominant lower limb on subsequent single leg jumps executed by both the dominant and non-dominant limbs. Additionally, the study aimed to assess the effects on bilateral CMJ performance and strength asymmetry during bilateral CMJ. The results indicated that maximal isometric quarter-squats and single leg tuck jumps used as a CA performed by the dominant lower limb have no impact on subsequent SLJ_{DOM} and CMJ height or CMJ relative peak power output. However, a significant increase in SLJ_{N-DOM} height was found after both CAs, as well as during CRL condition. Additionally, no significant changes in BSA were reported.

Although previous studies have demonstrated the effectiveness of unilateral and bilateral isometric[27,28] and plyometric[14,16,29] CAs in eliciting the PAPE effect in various sports activities, this study did not confirm these findings. Similarly, it did not support reports of local occurrence of the PAPE effect[20,21]. Wong et al.[21] reported increased strength in the exercised upper limb without changes in the strength of the contralateral arm, indicating a localized character of the PAPE effect. However, the occurrence of the PAPE effect was verified under isokinetic conditions, making these tests independent of the coordination and balance influences. This was also demonstrated in a study by Krzysztofik et al.[16], which suggested that the complexity of the post-CA task may influence the magnitude of the PAPE effect. Their study revealed a significant PAPE effect in CMJ but no effect in CMJ with arm swing. Therefore, it seems that results of this study may be explained by the motor learning phenomenon which can be defined as "any experience-dependent improvement in performance[30]. Improvement in SLJ_{N-DOM} probably refers to increased quality of movement not due to mechanisms related to PAPE. Better movement execution is called "motor acuity" and can be improved mainly through practice. Given that the participants were not professional athletes, this explanation seems reasonable. It may be further reflected by the increased difficulty in controlling balance using non-dominant leg[31], which may subconsciously discourage its use during sports activities. This task demands both motor skill learning and substantial dynamic balance, as well as core and lower limb stability. Therefore, the observed improvements likely result from a combination of motor skill learning and neuromuscular control.

The CAs did not cause the PAPE effect in unilateral or bilateral jumping performance. Previous research supports that isometric and plyometric exercises as CA can be effective in enhancing subsequent jumping ability[10,14,27]. For example, Spieszny et al.[27] noted a significant increase in CMJ height in 4th and 8th minute following 3 sets of 3 s maximum isometric half squat. Similarly in the study by Kalinowski[10] where combined isometric half squat and DJ improved CMJ 6 min after CA. Different results may be due to the differences in strength level and training experience between the groups of participants in the abovementioned studies and those in the present study. Performance enhancement occurs only when potentiation outweighs fatigue[2], and highly trained athletes have the ability to resist fatigue and recover better than recreationally trained individuals[32]. On the other hand, in this study, the level of force generated during the applied CAs was measured, and a significantly higher level was recorded during ISO compared to PLY CA (2677 ± 320 N vs. 1858 ± 288 N, respectively). Although this does not allow us to assess which CA caused greater fatigue, the ISO CA seems to provide a greater stimulus from the perspective of force output, while PLY CA could contribute to increased activity of the nervous system. Moreover, the volume of the CAs was not equalized, which might have influenced the outcomes. Nevertheless, neither of these CAs had a significant impact on the subsequent jumps, so it can be concluded that the CAs applied in this study are not recommended for eliciting the PAPE effect in groups with a similar level of muscle strength and training experience. Additionally, future studies using unilateral CAs should take this into consideration whether they aim to maximize the exercise complexity with higher neuromuscular demands (SL plyometrics) or maximize force output with lower neuromuscular demands (SL isometrics on immovable rack).

To the best of the authors' knowledge, an aspect that has not yet been analyzed in the context of PAPE protocols is the effect of CA on inter-limb strength asymmetries. Excessive inter-limb strength asymmetries (> 10%) have been associated with an increased risk of injury[17] and impaired sports performance[32]. A previously

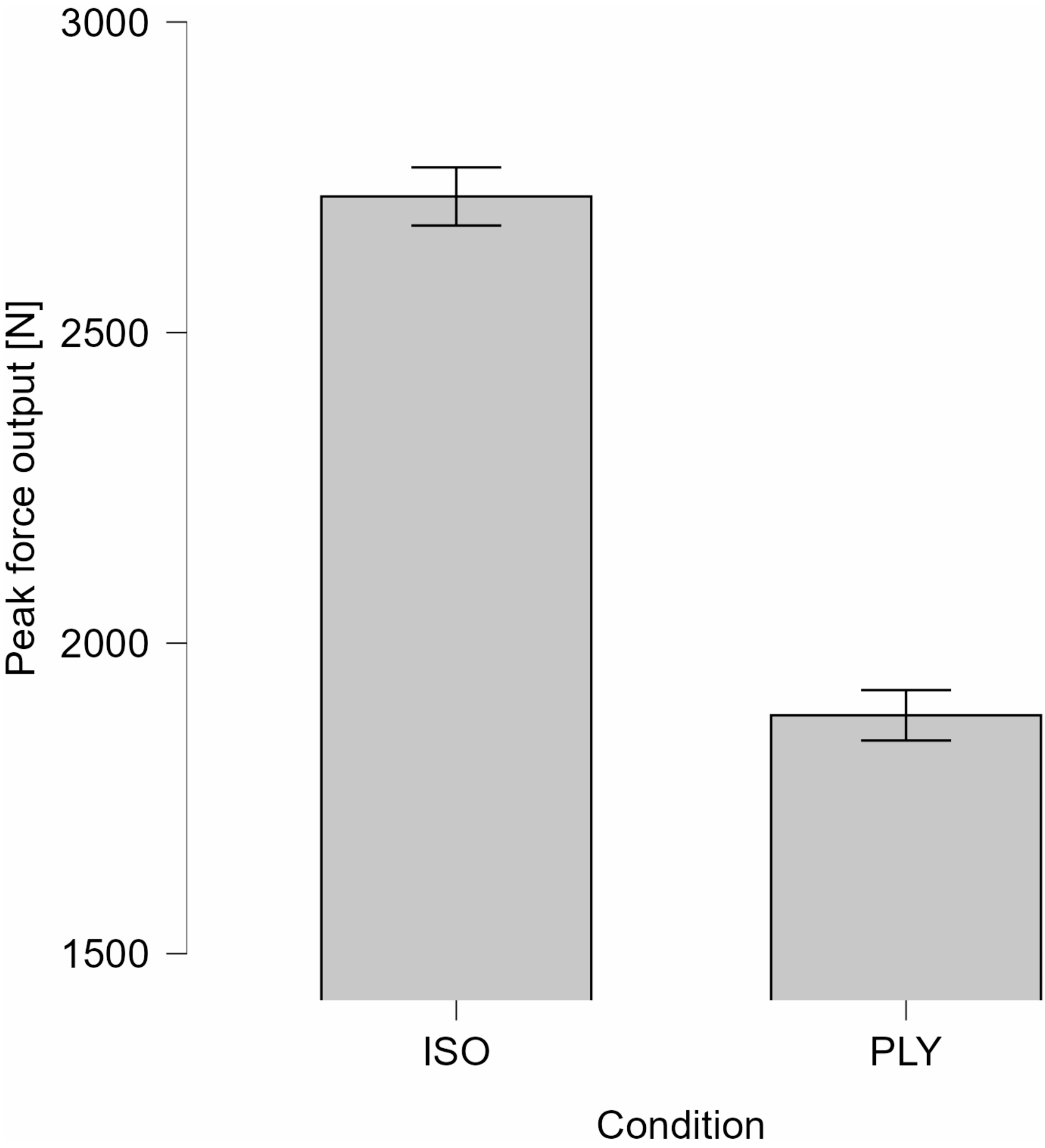

Fig. 2. Difference in force output between CAs. *ISO* isometric conditioning activity, *PLY* plyometric conditioning activity.

hypothesized solution to address these imbalances involves performing CA on only one limb—the weaker one[7], based on the localized nature of the PAPE effect[21]. The protocol in our study aimed to determine whether the PAPE effect would occur exclusively in the exercised limb. However, the results of this study indicate that ISO and PLY conditions performed by the dominant leg did not have any meaningful impact on inter-limb force output asymmetries during bilateral CMJ performance. Moreover, it did not affect the subsequent performance of the SLJ_{DOM}. On the other hand, an increase in SLJ_{N-DOM} height was observed. Although there are some studies that suggest the existence of a remote PAPE effect, they are primarily related to upper-body exercises potentiating lower-body performance[33]. However, to the best of the authors' knowledge, there is a lack of studies that directly examine the utilization of PAPE protocols for addressing inter-limb asymmetries[22]. While Wong et al.[21] study did not directly address this, it did show an increase in isokinetic strength in the ipsilateral arm. Moreover, this

	Bilateral strength asymmetry				
	Pre-CA	3 min post-CA	6 min post-CA	9 min post-CA	Best
ISO	1.52 ± 3.81 (− 0.59 to 3.63)	2.06 ± 3.85 (− 0.07 to 4.2)	2.28 ± 4.26 (− 0.07 to 4.64)	3.27 ± 4.79 (0.62 to 5.92)	1.91 ± 4.16 (− 0.4 to 4.21)
PLY	2.56 ± 4.63 (− 0.01 to 5.13)	3.39 ± 4.2 (1.06 to 5.71)	1.76 ± 3.74 (− 0.31 to 3.83	1.57 ± 4.82 (− 1.1 to 4.24)	3.08 ± 4.4 (0.65 to 5.52)
CRL	1.52 ± 3.84 (− 0.6 to 3.65)	2.16 ± 3.8 (0.05 to 4.26)	1.44 ± 3.18 (− 0.33 to 3.2	1.27 ± 3.28 (− 0.55 to 3.08)	1.39 ± 3.64 (− 0.63 to 3.4)

Table 3. Changes in bilateral strength asymmetry during countermovement jump. *CA* conditioning activity, *CI* confidence interval, *ISO* isometric condition, *PLY* plyometric condition, *CRL* control condition.

result was only observed in participants trained in resistance exercises, but not in untrained individuals. This may indicate that the occurrence of a localized PAPE effect, and consequently the significant impact of CA on inter-limb force asymmetries, is mediated by the experience level of the participants. Therefore, further studies are needed that include groups with different training experience levels. Since the results of this study suggest that the applied CAs were not able to significantly affect inter-limb force asymmetries in the studied group, it is suggested that this approach should not be used as a potential method for preventing asymmetries until more data on unilateral CA's ability to induce the PAPE effect becomes available.

This study had several limitations: (i) the measurements of jumping performance were taken only up to the 9th minute post-CA, although the PAPE effect may have occurred within a different time frame; (ii) the CA was performed only by the dominant limb, without comparison to the contralateral limb; (iii) only a single setting of isometric and plyometric CAs was compared, without the use of other intensities or volumes, and the effectiveness of high-intensity resistance exercises was not investigated; (iv) the CRL condition was performed last by all participants, which may have significantly influenced the results; (v) based on inconsistent ICC and CV values between CMJ and SLJ, it was likely too challenging for physically active individuals who were not specialized in jumping to perform the SLJ in a repeatable manner. Future research should focus on highly trained athletes or adjust the protocol to include less complex tasks to accommodate individuals with lower skill levels, allowing for a better understand the effects of unilateral CAs in sport and rehabilitation settings. Another valuable addition would be integration of force and kinematic data, including kinematic analysis to track joint angles and movement patterns, thereby providing a deeper understanding in the biomechanics of jumps.

Conclusion

Three sets of 3-second isometric maximal quarter-squats or 5 tuck jumps performed by the dominant limb did not significantly impact CMJ and SLJ height or relative power output for either the dominant or non-dominant limb, nor did they affect the bilateral symmetry index. Additionally, the protocol did not contribute to an increase in jump height for the non-dominant leg, which is likely attributed to motor learning rather than the applied CAs. Therefore, it can be concluded that the CAs applied in this study are not recommended for eliciting the PAPE effect in groups with a similar level of muscle strength (1RM in back squat: 1.8 ± 0.3 kg/body mass) and resistance training experience (6 ± 3 years).

Data availability

We declare that all research data generated and/or analyzed during this study are included in the manuscript. Raw data files are available from the corresponding author upon reasonable request.

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Study design, J.H. and M.K.; data collection, J.H., A.L.; statistical analysis, J.H.; data interpretation, J.H. and M.S.; manuscript preparation, J.H. and M.K.; literature search, J.H., P.E., and M.S.; supervision, M.S., P.E. and M.W. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

Informed consent
Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patients to publish this paper.

Additional information
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