



Effect of Time of Day on Post-Activation Performance Enhancement in Resistance Trained Individuals

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Abstract

Purpose This study investigates the influence of time of day (TOD) on post-activation performance enhancement (PAPE) on countermovement jump (CMJ) performance.

Methods Fifteen resistance-trained participants (27.1 ± 5.1 years, 11 males and 4 females, 1-repetition-max (1-RM) back squat = $1.81 \times$ BW) were recruited. Using a crossover, counterbalanced study design, CMJ was measured before and after 3 sets of 85% 1-RM barbell squat in the morning and evening. Post-conditioning activity jump height (JH), modified reactive strength index (RSI_{mod}), time to take-off (TTO), peak power (P_{peak}) and mean concentric power (P_{conc}) were recorded at 10 s, 4, 8, 12 and 16 min of recovery.

Results Factorial repeated measures analysis of variance on baseline and best CMJ identified TOD \times time interaction effects in JH ($P = 0.032$, $\eta_p^2 = 0.29$) and RSI_{mod} ($P = 0.029$, $\eta_p^2 = 0.30$). Moreover, baseline CMJ height ($P = 0.008$) and RSI_{mod} ($P = 0.006$) were higher in the evening vs. morning. While similar performance (i.e. number of repetitions and average concentric velocity) and fatigue indicators (i.e. rating of perceived exertion and velocity loss) during squat were reported in both sessions, subjects exhibited CMJ performance decline in JH, RSI_{mod} , P_{peak} and P_{conc} in the evening. Additionally, high inter-individual response in CMJ performance and time course at different TOD were also reported.

Conclusion Results suggested that TOD moderated the magnitude of PAPE, with greater potentiation in the morning despite greater evening baseline performance. Baseline evening superiority in CMJ performance did not translate to enhanced potentiation in subsequent jumps.

Keywords Potentiation · Diurnal variation · Countermovement jump · Training performance · Complex training

Introduction

The pairing of high-load, low-velocity resistance training and ballistic exercises of lower load and higher velocities is a common training practice in the strength and conditioning field [1]. Numerous studies investigating the efficacy of high-load barbell back squat have observed acute (3 – 10

min) improvements in subsequent measures of rate of force development and explosive strength [2, 3], although the phenomenon is inconsistently elicited at the group level [4]. The transient performance enhancement following conditioning activities (CA) is referred to as post-activation performance enhancement (PAPE) [5]. Previous meta-analyses suggested a single set of heavy intensity ($\geq 85\%$ 1-RM) loads with rest intervals between 3 to 7 minutes or multiple sets of moderate-heavy (60%–84% 1-RM) loads with rest intervals between 7 to 10 min to provide favourable conditions for potentiation [4, 6]. High relative strength, movement competency and predominantly type II muscle fibre composition may further moderate rest duration for optimal performance [7–9]. Furthermore, PAPE may exhibit some degree of movement specificity and thus may result in greater potentiation in test activities performed following a CA with a similar movement pattern [10]. Mechanisms underpinning PAPE may be attributed to increases in neural

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drive, muscle temperature, blood flow/cellular water, and muscle-tendon stiffness [7].

Various psychological and physiological functions exhibit fluctuations throughout the day, also known as circadian rhythms, that contribute to athletic performance [11]. It is well-established that exercise performance across a broad range of exercise tasks varies according to the time of day (TOD) [12]. Previous investigations and systematic reviews show evening superiority in lower limb strength [13], barbell velocity [14], and short-duration maximal efforts like squat jump, countermovement jump (CMJ), vertical jump, and sprints [15].

The diurnal variation in core temperature, and neural drive that underpin circadian performance rhythms may also modulate the optimal rest intervals between CA and subsequent performance and could contribute to the heterogeneous outcomes reported in PAPE literature. Limited research has examined diurnal variation in acute performance following extended warm-up protocols designed to elicit PAPE [16–20], warranting further investigation. Among studies employing separate control sessions for baseline comparisons, three reported greater improvements in ballistic performance following high-load conditioning activities in the evening compared to morning [17–19]. Similarly, Arnett [16] observed superior evening performance in an all-out 100-yard swim time trial despite using a prolonged warm-up in the morning and reduced warm-up in the afternoon ($P = 0.0047$, $d = 0.31$). In contrast, Vieira et al. [20] utilized pre-conditioning performance tests within the same session and found CMJ enhancement of 11.6% in experienced runners during morning testing ($P = 0.005$), but not in evening sessions or among novice runners. While separate control sessions allow for examination of circadian performance variations, they introduce additional sources of between-session variability. The within-session approach provides a more direct measurement of post-activation potentiation by minimizing external variables and aligns with established PAPE research methodologies.

This study sought to examine the diurnal variation in performance and time course of CMJ performance. Identifying the effects of TOD may allow practitioners to select appropriate rest intervals for PAPE and adapt training sessions, and standardised athlete testing based on TOD in pursuit to optimise PAPE utilisation [18]. It was hypothesized that the improved strength and power observed at baseline may translate to enhanced performance during the CA, leading to greater potentiation in the evening.

Methods

A crossover, counterbalanced study design was incorporated in which participants reported to the laboratory on three separate occasions (Fig. 1). In the first session, participants were assessed for anthropometric measurements and back squat 1-RM and interviewed to determine their age and resistance training experience. The CA and tests were then conducted in the morning (8–10 a.m.) or evening (4–6 p.m.) in random order. To limit the attenuating effects of fatigue, each session was separated by minimally 72 hours. Participants performed a standardised warm up consisting of a 3-min jog, low intensity stretching of the lower limbs and three submaximal CMJs. During the CA, participants performed 3 sets of 85% 1-RM until $\geq 5\%$ velocity loss was achieved with an inter-set rest of 5 min to minimise fatigue accumulation. Participants were also asked to move the bar “as quickly as possible on the ascent” [21]. CMJ assessments were conducted at baseline and over a continuous interval of 10-s, 4-, 8-, 12-, and 16-min (Post_{10s}, Post_{4min}, Post_{8min}, Post_{12min}, Post_{16min}) after completion of the CA.

Subjects

Fifteen resistance-trained individuals (11 males and 4 females) of varying habitual training TOD (morning/early afternoon: $n = 7$, afternoon/late afternoon: $n = 5$, evening/night: $n = 3$) volunteered to participate in this study. The inclusion criteria required the participants to be above the age of 18, a minimum of 2 years resistance training experience, currently perform barbell back squats ≥ 1 /week for the past month, and the ability to perform a 1-RM parallel barbell back squat of around 1.75 times body mass for males and 1.5 times body mass for females based on the “strong” criteria by Seitz and Haff [2]. Participants were excluded if they suffered injury to the lower limb or back within the past 6 months or had tested positive for COVID-19 in the past 3 months. Participants were also informed to refrain from high-intensity lower body exercise and caffeine intake 24h prior to each session. All participants were provided written informed consent prior to the study, and all experiments were performed at either the National Institute of Education or Singapore Sport Institute. This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Review Board of Nanyang Technological University (IRB-2022-830). Table 1 shows the physical characteristics of the participants.

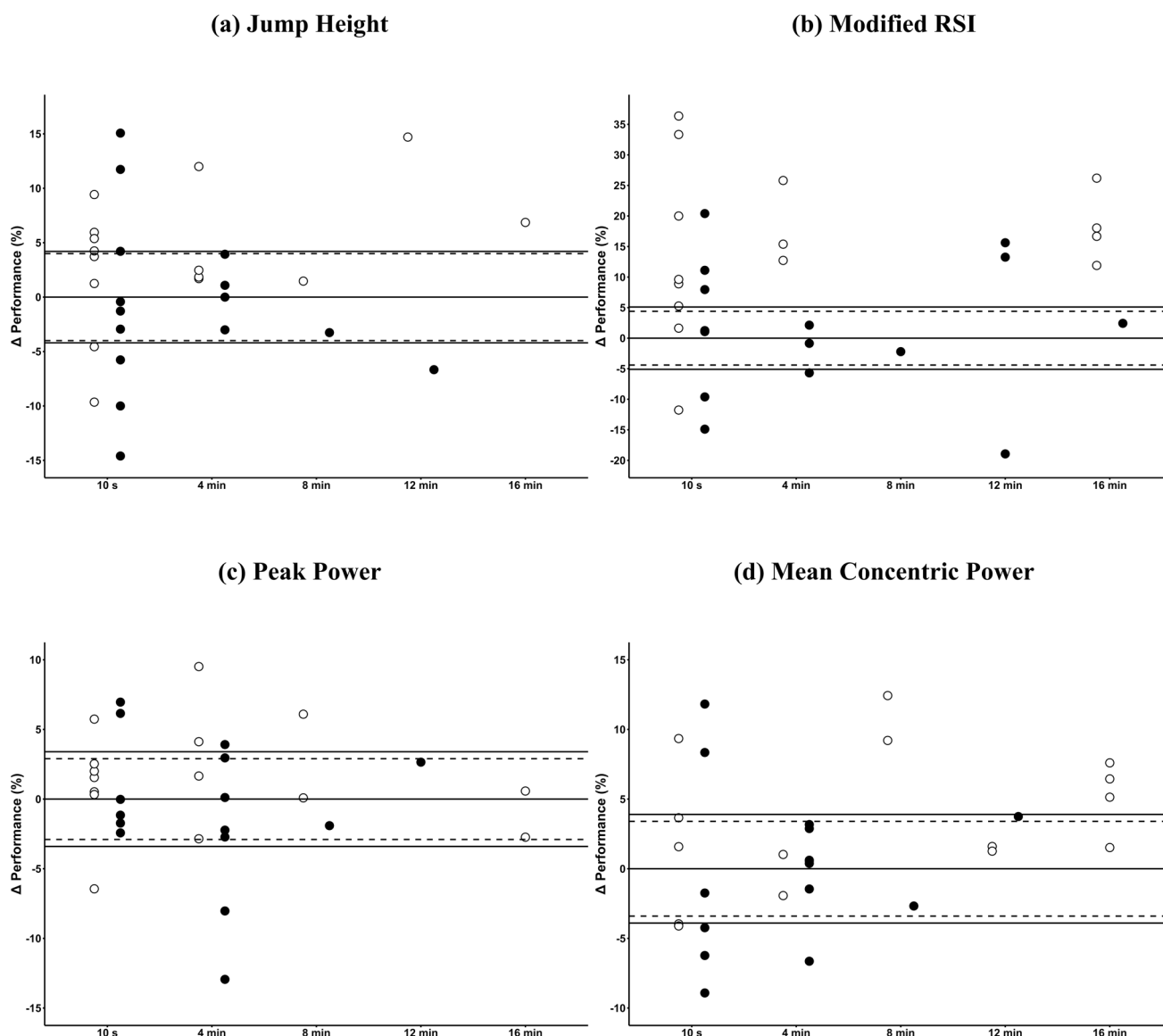


Fig. 1 Overview of study design and performance of Conditioning Activity (CA) and Countermovement Jump (CMJ)

Table 1 Descriptive characteristics of the participants (mean ± SD)

Variables (<i>n</i> = 15, 11M and 4F)	
Age (years)	27.1 ± 5.1
Body mass (kg)	68.1 ± 15.2
Height (cm)	168.9 ± 11.4
Training experience (years)	7.4 ± 3.6
Maximal strength for males (kg)	140.0 ± 24.7
Maximal strength for females (kg)	82.4 ± 3.8
Relative strength for males (kg/kg)	1.91 ± 0.14
Relative strength for females (kg/kg)	1.56 ± 0.16

Procedures

Familiarisation Session and 1-RM Testing

The familiarisation sessions were conducted in the afternoon

(1–3 p.m.) for all participants. A direct 1-RM test was conducted after the warm-up as outlined by Helms et al. [22]. Rating of perceived exertion (RPE), average concentric velocity (ACV) and participants’ input were used to determine subsequent load increments after 90% 1-RM until 1-RM was achieved. Participants rested 3–7 min between each set and 1-RM was determined within 4 attempts. For the criteria of a parallel squat, participants had to reach a depth where the hip crease passed below the top of the knee when viewed from the side. Trials where the attempt did not meet the range of motion criteria were discarded. A FLEX device was magnetically secured onto the left side of the barbell, and the reflective mat was placed below it such that the medial line was aligned to the device when viewed from the posterior aspect and synced to an iPhone via the FLEX

Stronger app (version 2.1.2). The FLEX device (Kinetic, Canberra, Australia) was used to measure the ACV of the barbell squat and has been shown to demonstrate good between-day ($\%CV = 3.77$, $90\%CI = 3.63 - 3.91$) and inter-unit reliability ($\%CV = 3.96$, $90\%CI = 3.83 - 4.12$) when compared to a 3D motion capture system [23]. A resistance training specific RPE scale based on repetitions in reserve (i.e. 10 RPE = 1 repetition in reserve, 9 RPE = 2 repetitions in reserve, and so forth) was used as a subjective indicator of intensity [24]. ACV and RPE were also recorded for each attempt $\geq 70\%$ estimated 1-RM. After 1-RM testing, the participants were given an overview of the subsequent experimental sessions and were given additional CMJ practice.

Countermovement Jump

Participants were instructed to perform CMJs on a Kistler force plate (Kistler Instruments, Hampshire, UK) using a sampling frequency of 500Hz [25]. Each CMJ began with ≥ 3 s of quiet time and was performed with both feet on the force plate at take-off and landing and performed with hands akimbo (Fig. 1.) to reduce the effects of upper body movement on lower body force production. The instructions also included the intent of each jump is to be “explosive” and reach maximal height using a self-selected depth. An encouraging verbal signal was given as the start command for each CMJ. During the rest period, participants were instructed to sit calmly and refrain from re-warming up. Vertical ground reaction force from the force plate was analysed using a Microsoft Excel® template [26]. CMJ jump height (impulse-momentum), time to take-off (TTO), modified reactive strength index (RSI_{mod}), relative peak power (P_{peak}) and relative mean concentric power (P_{conc}) during the concentric phase jump was averaged across multiple jumps at each time interval due to improved sensitivity to neuromuscular fatigue and reliability [27]. To account for inter-individual variability in optimal rest interval for PAPE, the best jump post-CA by JH and RSI were selected as $Post_{best}$.

Conditioning Activity Protocol

Participants were asked to perform 3 sets of 85% 1-RM with a 5-min inter-set rest. The participants were informed to perform the squat with the intent to ascend as quickly as possible and pause after the completion of each repetition. A verbal signal was given for a subsequent repetition until $\geq 5\%$ velocity loss was achieved. To account for the large inter-individual variability that exists for the maximal number of repetitions individuals could do with a given %1-RM, [28], a velocity-loss threshold of 5% was implemented to minimise fatigue and maximise potentiation of CMJ [29].

Percentage of velocity loss (%VL) and RPE were also recorded after each set.

Statistical Analyses

Intraclass correlation coefficient (*ICC*) estimates and coefficient of variance (*CV*) were calculated based on single-measurement, absolute-agreement, 2-way mixed-effects model to determine test-retest reliability of each CMJ performance variable across time intervals. Level of reliability was determined by lower bounds of 95% CI of *ICC* [30].

Shapiro–Wilk test was used to assess the data for normal distribution. If Mauchly’s Test of Sphericity indicated a violation of sphericity, a Greenhouse–Geisser correction was applied. Performance variables in CMJ across each time interval pre- and post-CA were analysed using a 2×6 (TOD \times time) repeated measures ANOVA. An analysis of pre-CA and $Post_{best}$ CMJ performance was also performed using a 2×2 repeated measures ANOVA. In addition, paired t-tests were used to compare absolute and percentage changes in jump performance between TOD.

To explore whether the PAPE response is maintained across time of day, the relationship between change in absolute and percentage change in jump performance between TOD was analysed using Pearson’s correlation.

Given that the variables of each set of the CA were not normally distributed, a Friedman Test was conducted, with separate Wilcoxon signed-rank tests performed in the event of a significant result. For significant main or interaction effects, post hoc pairwise comparisons with Bonferroni correction applied within each dependent variable were performed. The partial eta-squared statistic was reported, where 0.01, 0.06, and 0.14 represent small, medium, and large effect sizes, respectively [31]. Hedge’s *g* effect sizes were calculated to measure the magnitude of between-TOD difference of the post hoc analysis, using Cohen’s effect size threshold values (small: 0.20, medium: 0.50, and large: 0.80). All data were reported as mean \pm SD, and the significance level was set at $P < 0.05$. Data were imported and analysed using IBM SPSS Statistics (Version 29).

Results

Jump Height, Time to Take-off, Modified RSI, Peak Power and Mean Concentric Power

All jumps across both sessions exhibited acceptable reliability ($ICC \geq 0.80$, $CV \leq 11\%$) for JH, RSI_{mod} , P_{peak} , and P_{conc} respectively. However, TTO exhibited poor reliability of 0.58 (95% CI: 0.41 – 0.78). Mauchly’s Test of Sphericity indicated violations of the sphericity on the main effect

of time for JH, $\chi^2(14) = 77.5, P < 0.001$, and $P_{peak}, \chi^2(14) = 28.5, P = 0.013$ and on the interaction effect of TOD \times time for $P_{peak}, \chi^2(14) = 19.0, P = 0.039$. Consequently, Greenhouse-Geisser corrections were applied. Significant baseline differences were identified in favour of PM condition in both JH ($P = 0.008, g = 0.48$) and RSI_{mod} ($P = 0.006, g = 0.59$). Participants on average jumped 2.6 cm higher (95% CI: 0.81 – 4.36) and achieved a greater RSI_{mod} score by 0.05 m/s (95% CI: 0.02 – 0.09) in the evening.

The CMJ performance variables are reported in Table 2. A significant effect of time was found on CMJ JH ($F(2.7, 37.7) = 3.47; P = 0.029; \eta_p^2 = 0.20$), P_{peak} ($F(2.8, 39.7) = 5.52; P = 0.003; \eta_p^2 = 0.28$) and P_{conc} ($F(5, 70) = 2.91; P = 0.019; \eta_p^2 = 0.17$), with RSI_{mod} ($F(5, 70) = 2.33; P = 0.051; \eta_p^2 = 0.14$) approaching significance. Post-hoc analyses showed significant decrease in P_{peak} over time between Pre-Post_{16min} ($P = 0.009$) and Post_{4min}-Post_{16min} ($P = 0.011$). A significant TOD \times time interaction effect was found for JH ($F(5, 70) = 4.81; P = 0.001; \eta_p^2 = 0.26$), RSI_{mod} ($F(5, 70) = 3.93; P = 0.003; \eta_p^2 = 0.22$), P_{conc} ($F(5, 70) = 2.5; P = 0.038; \eta_p^2 = 0.15$), showing greater decrements in the evening. No interaction effect for P_{peak} ($F(2.8, 39.1) = 2.55; P = 0.074; \eta_p^2 = 0.15$) or TTO ($F(5, 70) = 1.41; P = 0.23; \eta_p^2 = 0.09$) were found. However, no effect for TOD was found for any CMJ variables ($P > 0.05$).

When analysed against each individual’s best performance (Post_{best}), a significant main effect of TOD was identified for JH ($F(1, 14) = 8.26; P = 0.012; \eta_p^2 = 0.37$), P_{peak}

($F(1, 14) = 6.30; P = 0.025; \eta_p^2 = 0.31$) and RSI_{mod} ($F(1, 14) = 6.32; P = 0.015; \eta_p^2 = 0.31$), indicating greater performance in PM. Significant interaction effect was found for JH ($F(1, 14) = 5.67; P = 0.032; \eta_p^2 = 0.29$) and RSI_{mod} ($F(1, 14) = 5.95; P = 0.029; \eta_p^2 = 0.30$). No main effect of time was found. Furthermore, performing squats in the morning resulted in significant moderate-to-large differences in magnitude of potentiation when assessed by both absolute and percentage change in JH and RSI_{mod} (Table 3). No significant correlation was observed between absolute and percentage changes in CMJ performance variables between TOD ($P \geq 0.05$), indicating divergent trends in PAPE response to TOD.

Individual response to PAPE

Individual participants attained maximal kinetic and kinematic values for CMJ at different time intervals (Table 3). However, this did not necessarily result in potentiation (Fig. 2). Seven and three individuals improved CMJ height greater than smallest worthwhile change (SWC) ($\pm 4\%$ vs. $\pm 4.2\%$) in AM and PM respectively (Fig. 2a). Thirteen and five individuals improved RSI_{mod} greater than SWC ($\pm 4.4\%$ vs. $\pm 5.1\%$) in AM and PM respectively (Fig. 2b). Four and three individuals improved P_{peak} greater than SWC ($\pm 2.9\%$ vs. $\pm 3.4\%$) in AM and PM respectively (Fig. 2c). Six and two individuals improved P_{conc} greater than SWC ($\pm 2.9\%$ vs. $\pm 3.4\%$) in AM and PM respectively (Fig. 2d).

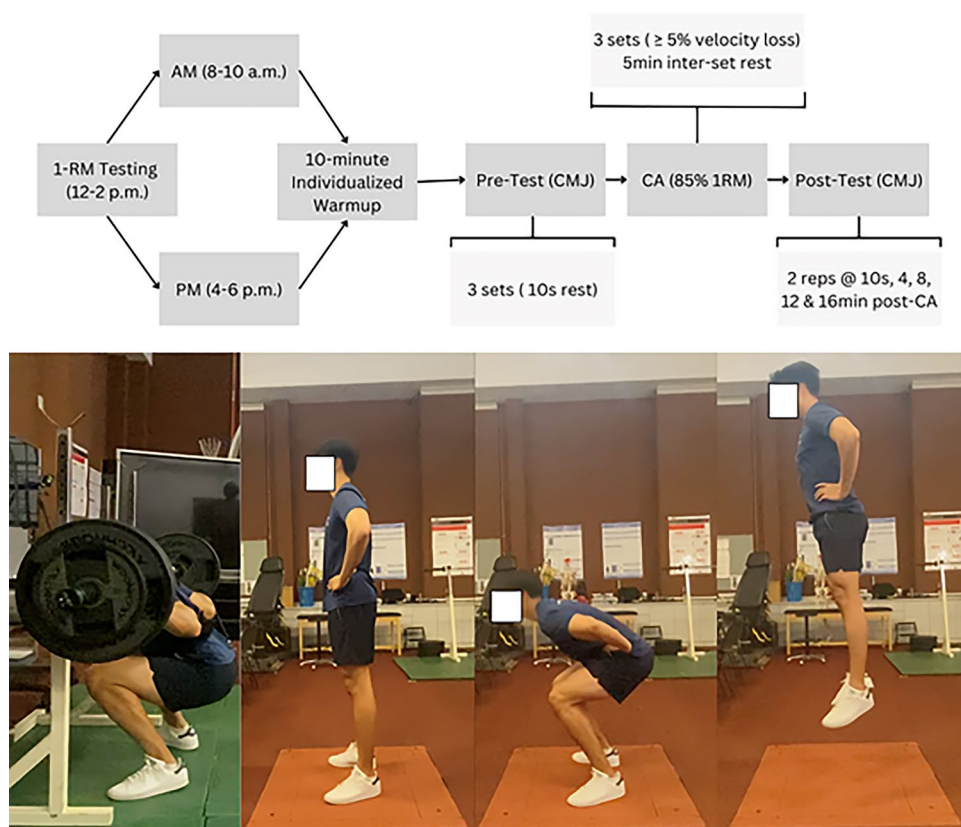
Table 2 Countermovement jump performance variables in the morning (AM: 8–10 a.m.) and evening (PM: 4– 6 p.m.) (mean \pm SD, 95%CI [LL,UL])

Variable	Time of day	Baseline	Post _{max}	Post _{10s}	Post _{4min}	Post _{8min}	Post _{12min}	Post _{16min}
Jump Height (cm)	AM	36.1 \pm 7.3 ^a [32, 40.1]	37.3 \pm 7.2 [33.4, 41.3]	36.3 \pm 7 [32.4, 40.1]	36.2 \pm 7.4 [32.2, 40.3]	36.1 \pm 7.4 [32, 40.2]	35.6 \pm 7.6 [31.4, 39.8]	35.8 \pm 7.2 [31.8, 39.8]
	PM	38.7 \pm 8.1 [34.2, 43.1]	38.1 \pm 6.6 [34.4, 41.7]	36.7 \pm 6.4 [33.2, 40.3]	36.8 \pm 6.6 [33.2, 40.5]	36.2 \pm 6.9 [32.4, 40]	36.0 \pm 6.8 [32.2, 39.8]	35.5 \pm 6.5 [31.9, 39.2]
Time to Take off (s)	AM	0.81 \pm 0.11 [0.74, 0.87]	0.78 \pm 0.14 [0.70, 0.86]	0.76 \pm 0.16 [0.67, 0.85]	0.75 \pm 0.11 [0.69, 0.81]	0.81 \pm 0.09 [0.76, 0.85]	0.77 \pm 0.10 [0.72, 0.82]	0.76 \pm 0.11 [0.7, 0.82]
	PM	0.78 \pm 0.11 [0.72, 0.84]	0.79 \pm 0.12 [0.72, 0.85]	0.79 \pm 0.15 [0.72, 0.85]	0.78 \pm 0.12 [0.72, 0.85]	0.79 \pm 0.11 [0.73, 0.85]	0.78 \pm 0.17 [0.68, 0.87]	0.78 \pm 0.11 [0.72, 0.84]
Modified RSI (m/s)	AM	0.45 \pm 0.10 ^a [0.4, 0.51]	0.49 \pm 0.11 [0.43, 0.55]	0.49 \pm 0.12 [0.42, 0.56]	0.49 \pm 0.11 [0.43, 0.55]	0.45 \pm 0.11 [0.39, 0.51]	0.47 \pm 0.1 [0.41, 0.53]	0.48 \pm 0.11 [0.42, 0.54]
	PM	0.51 \pm 0.13 [0.44, 0.58]	0.49 \pm 0.11 [0.43, 0.55]	0.48 \pm 0.12 [0.42, 0.55]	0.48 \pm 0.11 [0.42, 0.54]	0.46 \pm 0.10 [0.41, 0.52]	0.48 \pm 0.12 [0.41, 0.55]	0.47 \pm 0.11 [0.4, 0.53]
Peak Power (W/kg)	AM	56.3 \pm 8.3 [51.7, 60.9]	56.7 \pm 8.5 [51.9, 61.4]	55.9 \pm 8.5 [51.2, 60.6]	56.1 \pm 8.8 [51.3, 61.0]	55.9 \pm 8.8 [51.0, 60.8]	54.9 \pm 8.4 [50.3, 59.6]	55.3 \pm 8.2 [50.7, 59.8]
	PM	58.2 \pm 10.0 [52.6, 63.7]	57.2 \pm 8.3 [52.6, 61.8]	56.0 \pm 8.1 [51.5, 60.5]	56.6 \pm 8.5 [51.9, 61.3]	55.8 \pm 8.8 [51.0, 60.7]	55.6 \pm 8.5 [50.9, 60.3]	54.9 \pm 8.5 [50.2, 59.6]
Mean Concentric Power (W/kg)	AM	29.2 \pm 5.0 [26.4, 32.0]	30.0 \pm 5.4 [27.0, 33.0]	29.8 \pm 5.4 [26.8, 32.8]	29.7 \pm 5.3 [26.7, 32.6]	29.3 \pm 5.4 [26.3, 32.3]	29.2 \pm 5.5 [26.1, 32.2]	29.4 \pm 5.5 [26.4, 32.5]
	PM	30.5 \pm 5.9 [27.2, 33.7]	30.1 \pm 5.1 [27.3, 32.9]	29.3 \pm 4.8 [26.6, 32.0]	29.8 \pm 5.2 [26.9, 32.6]	29.0 \pm 5.3 [26.1, 32.0]	29.2 \pm 5.2 [26.3, 32.1]	28.7 \pm 5.2 [25.9, 31.6]

^aSignificantly different from PM ($P \leq 0.007$)

Table 3 Absolute and percentage change and mean time course of peak countermovement jump performance variables in the morning (AM: 8–10 a.m.) and evening (PM: 4–6 p.m.)

Measure	AM			PM			P-value	Hedge's g	Power (1 - β)	
	Mean	SD	95% CI	Mean	SD	95% CI				
Jump	Absolute Change	1.25	1.9	[0.26, 2.23]	-0.59	2.86	[-2.07, 0.89]	0.032*	0.661	0.6
Height	Percent Change	3.8	6	[0.68, 6.9]	-0.6	7.6	[-4.5, 3.3]	0.051	0.561	0.51
	Time to Peak	3.55	4.92	[1.06, 6.04]	2.5	3.57	[0.69, 4.3]	0.56	0.239	0.08
Time to Take off	Absolute Change	-0.027	0.077	[-0.067, 0.012]	0.011	0.036	[-0.008, 0.029]	0.147	-0.55	0.3
	Percent Change	-3.4	8.8	[-8, 1.1]	0	0.1	[-0.01, 0]	0.129	-0.583	0.32
Modified RSI	Absolute Change	0.037	0.056	[0.008, 0.066]	1.37	5.08	[-1.26, 3.99]	0.029*	0.83	0.62
	Percent Change	8.5	12.9	[1.8, 15.1]	-1.6	10.1	[-6.8, 3.6]	0.024*	0.761	0.66
Peak Power	Time to Peak	5.15	6.94	[1.64, 8.66]	4.87	5.63	[2.03, 7.72]	0.9	0.043	0.05
	Absolute Change	0.352	1.6	[-0.476, 1.18]	-0.921	3.58	[-2.77, 0.925]	0.221	0.403	0.22
Concentric Power	Percent Change	0.6	3.2	[-1.1, 2.3]	-1.1	5.4	[-3.9, 1.7]	0.287	0.332	0.18
	Time to Peak	4.34	5.49	[1.56, 7.12]	3.62	3.38	[1.55, 4.98]	0.49	0.23	0.1
Average	Absolute Change	0.293	1.21	[-0.333, 0.918]	-0.391	1.8	[-1.32, 0.541]	0.192	0.39	0.25
	Percent Change	1	4.1	[-1.1, 3.1]	-0.8	5.9	[-3.8, 2.3]	0.274	0.301	0.19
Concentric Power	Time to Peak	7.52	6.68	[4.14, 10.9]	3.26	3.38	[1.55, 4.98]	0.02*	0.782	0.66

* $P < 0.05$ **Fig. 2** Percentage difference in performance of individual participants in response to 3 sets of high-load squats (post – pre) at each time interval (10 s, 4, 8, 12, 16 min) for a) jump height, b) modified reactive strength index, c) peak power and d) mean concentric power in the morning (AM: 8–10 a.m.) and evening (PM: 4–6 p.m.) (AM: ○, PM: ●). Smallest worthwhile change in performance for each variable in the morning and evening indicated by *dashed* and *solid line*, respectively

Maximal values of kinetic and kinematic variables were attained with the highest frequency at Post_{10s} and Post_{4min}. Despite substantial potentiation observed for individuals, the average cohort response at each time did not significantly differ from baseline or between TOD (Table 2).

Repetitions, Ratings of Perceived Exertion, Concentric Velocity and Velocity Loss

Number of repetitions, RPE, ACV and %VL are reported in Table 4. Median total squats repetitions performed across 3 sets were seven at both TOD and not significantly different from one another ($Z = 21.2$, $P = 0.59$). RPE differed

Table 4 Median and interquartile range (IRQ) of number of repetitions, rating of perceived exertion (RPE), average concentric velocity and velocity loss across three sets during the squat protocol in the morning (AM: 8–10 a.m.) and evening (PM: 4–6 p.m.)

Trial	Variable	Set 1		Set 2		Set 3	
		Median	(Interquartile Range)	Median	(Interquartile Range)	Median	(Interquartile Range)
AM	Repetitions	2.4	(2.0 – 3.0)	2.0	(2.0 – 3.0)	2.0	(2.0 – 3.0)
	Rating of Perceived Exertion	7.2	(6.8 – 8.0)	8.0	(8.0 – 8.5)	8.0	(7.5 – 9.0)
	Average Concentric Velocity (m/s)	0.48	(0.42 – 0.53)	0.47	(0.44 – 0.51)	0.49	(0.44 – 0.51)
	Velocity Loss (%)	9.43	(7.5 – 11.0)	9.84	(7.4 – 13.6)	10.3	(7.7 – 13.6)
PM	Repetitions	2.0	(2.0 – 3.0)	2.0	(2.0 – 3.0)	2.0	(2.0 – 2.0)
	Rating of Perceived Exertion	8.0	(6.5 – 8.3)	8.0	(7.3 – 9)	8.5	(8.0 – 9.3)
	Average Concentric Velocity (m/s)	0.47	(0.44 – 0.51)	0.450	(0.43 – 0.50)	0.50	(0.43 – 0.51)
	Velocity Loss (%)	8.5	(6.4 – 13.0)	12.5	(9.3 – 17.7)	13.6	(7.5 – 20.4)

significantly based on the TOD and the sets performed during the CA ($\chi^2(5) = 6.42$, $P < 0.001$), with a significant difference between RPE from AM set one and set three ($P = 0.036$). and PM set one and set three ($P = 0.036$). No significant differences were found in repetitions, ACV or %VL between TOD or sets ($P < 0.05$).

Discussion

The primary aim of this investigation was to compare the magnitude and time course of PAPE induced following a high-load squat CA on CMJ performance assessed at two different times of day (AM and PM). A primary finding of this study was a significant interaction effect of TOD on the time course of CMJ performance in response to a high load squat CA. Consistent with established literature, superiority in baseline CMJ performance was observed in the evening. However, contrary to our initial hypothesis, superior baseline performance did not translate to enhanced potentiation. The magnitude and consistency of PAPE were significantly greater in the morning. The study further demonstrated inter-individual variability in the time-course of PAPE and the direction and magnitude of response to the same CA protocol at different TOD.

Significant interaction effects suggests that the group-level magnitude of PAPE was modulated by TOD. Performing three sets of 85% 1-RM squats till $\geq 5\%$ loss threshold appeared to, on average, elicit potentiation of CMJ height and RSI_{mod} in the morning but not in the evening. Vieira et al., [20] employed a similar study design to the present study. While individual best performances were not described, comparable findings of greater group-level CMJ enhancement were reported in the morning in experienced endurance runners following a 30-min submaximal run despite higher baseline performance in the evening. Previous investigations have compared different warm-up protocols against control sessions at different TOD [16–19]. In contrast to the current study's findings, Eken et al. [17] observed a greater potentiation in basketball players

following five repetitions of 85% 1-RM bench-press CA in seated medicine ball throw but not CMJ when performed in the evening (4–6 p.m.) as compared to the morning (9–11 a.m.). Similarly, [18] observed a greater CMJ and agility performance in judokas following 6 repetitions of 80% 1-RM squat CA in the evening (5–7 p.m.) as compared to the morning (8–12 p.m.). Maaouia et al. [19] found significant time x protocol interaction effects on 30 m sprint performance after various warm-up protocols, with the greatest potentiation observed in the evening after dynamic stretching and 2 sets of 4 half squats. Compared to previous investigations that recruited only male athletes with similar sporting background, participants from the current study are comparably heterogenous. While potential moderating variables such as sex, sporting background, habitual training TOD and chronotype were not controlled for, the complex interaction between time of day and the magnitude of PAPE given the same conditioning stimulus is evident. Elevated core temperature in the evening was suggested to be the primary determinant for the circadian pattern of performance and may be explained by its effects on central and peripheral mechanisms such as nerve conduction properties, muscle contractility, local muscle temperature and blood flow [32]. However, methodological limitations in previous investigations limited inferences related to the interaction between changes in body temperature, PAPE and TOD [19, 20]. Future research should focus on delineating the contributions of muscle temperature to PAPE at different TOD, considering the overlapping mechanism in acute performance enhancements.

The present study observed a moderate-to-large effect size for TOD on JH and RSI_{mod} when comparing baseline and baseline-Post_{best} changes in CMJ performance in favour of PM. However, evening superiority in CMJ performance was not sustained when comparing the average time-course response between TOD (Table 2). Critically, the velocity-based CA with 5% velocity-loss threshold revealed no significant differences between squat performance (i.e. number of repetitions, ACV) and fatigue indicators (i.e. RPE, %VL) at different TOD. This suggests that participants experienced

comparable stimulus during both sessions yet demonstrated divergent CMJ responses. Physiologically, PAPE on athletic performance is underscored by the net balance of fatigue and potentiation induced concurrently by the CA [9]. A review by Chtourou et al. [33] suggested that in addition to neuromuscular performance, neuromuscular fatigue in discrete short-term maximal efforts is also affected by TOD, with higher power decrements in the evening. The authors argued that the phenomenon is more likely due to higher initial power output, rather than inherent muscle fatigability in the evening. Multiple sets of high load squats ($\geq 85\%$ 1-RM) have previously been shown to elicit PAPE in some studies compared to a single set [34, 35] but not in others [36]. Given the comparable conditioning stimulus between TOD in the present study, our findings suggested that the potentiation-fatigue profile may be more favourable for PAPE expression in morning sessions despite lower absolute performance capacity.

When considering the individual optimal time for attaining maximal values in CMJ variables, participants achieved maximal CMJ performance at different time intervals (Fig. 2). The optimal time for attaining maximal values were also different between variables, consistent with reports of high inter-individual response to the time-course of potentiation [37, 38]. Furthermore, the non-significant correlation between absolute and percent changes in CMJ performance variables indicate a limited predictability of individual response to the same PAPE protocol at different TOD. While descriptive patterns suggest potential difference in the timing of peak performance between morning and evening sessions, the present investigation was not adequately powered to detect statistically significant differences in optimal recovery intervals between TOD. In concordance with group-level trends, a higher frequency of potentiation ($\geq \text{SWC}$) in kinetic and kinematic CMJ variables were observed in the morning. While trends suggest peak performance occurred most frequently between 10 s and 4 min with minor differences between TOD, our limited sample size and trials prevent definitive conclusions. A recent study by Stuart et al., [39] analysed the repeatability of PAPE within individuals across multiple sessions. The findings suggested that enhanced jump performance and the time course of CMJ height in response to CA may not be determinative or repeatable across multiple experimental sessions. The day-to-day variation in PAPE response and optimal recovery duration further highlights the difficulty in parsing the effects of TOD on PAPE.

Several limitations of the present study warrant discussion. While participants were given additional practice of CMJ, poor reliability in TTO suggests a broad variance in movement competency among participants. A lower number of female participants ($n = 4/15$) and participants who

habitually train in the evening/night ($n = 3/15$) make it difficult to establish comparisons between these groups. Participants who habitually train in the evening may demonstrate greater differences in baseline CMJ at different TOD and thus exhibit greater capacity for potentiation in the morning. Furthermore, individual chronotype, sleep quality, core temperature (resting, post-warm-up, post-CA), were not collected during this trial. Data regarding these variables would prove valuable for better characterisation of PAPE responses. Repeating the experimental protocol across multiple sessions and an addition of control arm (e.g., no CA) would allow for a more robust analysis of TOD effects on the magnitude and time course of PAPE.

The influence of TOD on athlete performance and PAPE should be considered in athlete monitoring during training and testing. Pairing high-load and high-velocity movements in a complex or contrast set remain a useful tool in training athletes to express force production along a load-velocity continuum. Athlete testing should be performed at similar TOD, preferably in the morning, due to diurnal variation and lower variability of performance in the morning. Furthermore, divergent PAPE responses warrant testing of priming protocols at different TOD to optimise performance during competition.

Conclusion

The present study investigated the diurnal effects on CMJ performance and enhancement following three sets of high-load squats with 5%VL in a heterogeneous group of resistance-trained individuals. The findings demonstrated superior CMJ performance in kinetic and kinematic variables at baseline in the evening. However, contrary to the initial hypothesis, morning session elicited significantly greater and more consistent potentiation in JH, RSI_{mod} and P_{peak} . Moreover, the absence of differences in squat performance suggests that the divergent PAPE response reflects genuine altered PAPE potential rather than differential fatigue. However, the high degree of inter-individual variability in both the magnitude and optimal timing of peak performance enhancements highlights the complex nature of PAPE expression. Athletes may benefit more from training complexes meant to induce PAPE in the morning, though individual monitoring is warranted.

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Data Availability The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at Nanyang Technological University.

Declarations

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Consent to Publish The authors affirm that human research participants provided informed consent for publication of the images in Figure 1.

Ethics Approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Review Board of Nanyang Technological University (IRB-2022-830).

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