

Effects of a Flywheel-Based Post-Activation Performance Enhancement Warm-Up Versus a Traditional Rowing Ergometer Warm-Up on 500 m Rowing and Neuromuscular Performance

Piyathida Thongchai¹, Nareerat Koedsiri¹, Sasina Johansen¹, Siriwana Manosukhumnon¹,
Adithep Santalunai¹, Rodrigo Zacca^{2,3}, Dang Van Dung⁴, Phornpot Chainok^{1*}

¹ Faculty of Sports Science, Burapha University, Chonburi, Thailand.

² Research Center in Physical Activity, Health and Leisure (CIAFEL), Faculty of Sports, University of Porto (FADEUP), Portugal

³ Laboratory for Integrative and Translational Research in Population Health (ITR), Porto, Portugal

⁴ Bac Ninh Sport University.

* Correspondence: (PC) phornpot@go.buu.ac.th  0000-0003-2605-4181

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Abstract: Post-activation performance enhancement using flywheel exercises offers substantial immediate consequences on neuromuscular responses and mechanical adaptations. The study aimed to verify the effect of two different post-activation performance enhancement (PAPE) protocols on 500 m rowing ergometer and neuromuscular performance in collegiate rowers. Sixteenth healthy collegiate male rowers (age: 20.7 ± 2.1 years; weight: 69.9 ± 14.2 kg; height: 1.7 ± 0.1 m; BMI: 24.4 ± 3.7 kg·m²) participated in this study. Two different PAPE protocols were randomly administered: i) a general warm-up utilizing a rowing machine (control) and ii) a flywheel protocol encompassing 2 sets of 10 repetitions of biceps curl and high-pull at lower inertial loads (0.1176 kg·m² to 0.1568 kg·m²). No changes were observed between the two warm-up protocols concerning rowing performance and physiological variables throughout the 500 m rowing time trial. The 500 m rowing time in the flywheel warm-up showed a variance of 3.70 % compared to the general warm-up, with no differences observed among the protocols ($p = 0.09$; 95 % CI = -0.63, 7.04; $d = 0.60$: medium). The observed mean differences included a peak force of IMTP at 13.2% ($p = 0.03$; $d = -0.81$; large) and an average rate of force development of IMTP at -21.6 % ($p = 0.04$; $d = -0.53$; moderate) after the 500 m rowing time trial. Nonetheless, no substantial correlations were observed between 500 m rowing time and the neuromuscular performance parameters elicited by either warm-up procedure. This study indicated that both general and flywheel warm-ups are equally effective in enhancing PAPE neuromuscular performance, with the 500 m rowing time showing slightly advantage and lead to an acute positive effect after the flywheel warm-up compared to the general rowing machine warm-up. Coaches and sport scientists may use these findings to inform acute effect consisting of flywheel-based warm-up prior to a sport-specific task of 500 m rowing.

Keywords: Post-activation potentiation, rowing ergometer, neuromuscular performance



1. Introduction

Competitive rowers are typically monitored through rigorous rowing ergometer tests (Lawton, Cronin & McGuigan, 2011; Lawton, Cronin & McGuigan, 2013). Time trials test protocols in rowing ergometers range from 500 to 2000 m lying with the extreme-exercise intensity (Nevill, Allen & Ingham, 2011), with relevant contribution of anaerobic and aerobic capacities, explosive strength and muscular endurance (Allen & Ingham, 2011; Lawton, Cronin & McGuigan, 2011; Lawton, Cronin & McGuigan, 2013; Maroto-Izquierdo, Bautista & Rivera, 2020; Simon et al., 2023). Competitive rowing demands fast accelerations at the start and finish parts of the race, especially in 500 m rowing sprints (Nevill, Allen & Ingham, 2011). The 500 m rowing event is part of the world rowing indoor championship, being covered in less than 90 s by top level rowers.

In this regard, the potential for performance improvement obtained through strategies induced by post-activation potentiation enhancement (PAPE) has been investigated (Boullosa, 2021; Fu et al., 2023). In fact, PAPE induced by submaximal and maximal external loads in both isometric and isotonic exercise such as the traditional back squat back, resistive power rack squat and eccentric flywheel could be beneficial to the sports-related tasks performance (Tillin & Bishop, 2009; Cuenca-Fernández et al., 2017; Egan-Shuttler et al., 2017).

Theoretically, in conjunction with evidence from previous studies, PAPE induced by voluntary conditioning contractions can significantly augment muscular power, peak force, rate of force development (RFD), and performance in sports-related tasks, particularly in explosive activities such as jumps, sprints and throws (Tillin & Bishop, 2009; Cuenca-Fernández et

al., 2017; Petré, Wernstål & Mattsson, 2018; Blazeovich & Babault, 2019; Vargas-Molina et al., 2021).

Flywheel devices, offering consistent resistance during both concentric and eccentric phases of movement, have recently gained popularity for their capacity to provide high-intensity eccentric loading and muscle activation (Maroto-Izquierdo, Bautista & Rivera, 2020; Fu et al., 2023). The PAPE of flywheel-based training has been demonstrated effective in improving strength and power through a wider range of motion and continuous resistance, potentially leading to enhanced neuromuscular adaptations compared to traditional resistance training (Petré, Wernstål & Mattsson, 2018; Maroto-Izquierdo, Bautista & Rivera, 2020; Fu et al., 2023). Furthermore, flywheel workouts require substantial motor unit activation, making them an advantageous tool for improving performance in strength and power-focused sports. However, studies on the effectiveness of flywheel-based PAPE programs in endurance sports are limited, particularly in rowing, where the demand for explosive power in conjunction with sustained effort may be advantageous.

Numerous PAPE procedures have been examined across many sports, predominantly incorporating resistance workouts (e.g., squats, plyometrics) preceding the performance assessment (Cuenca-Fernández et al., 2017; Boullosa, 2021). The time, intensity, and type of exercise used in the PAPE protocol can differ significantly, and these elements may affect the degree of performance enhancement (Tillin & Bishop, 2009; Cuenca-Fernández et al., 2017; Boullosa, 2021). Recent research indicates that different PAPE protocols can provide different outcomes, depending upon the specific muscle groups addressed and the recovery duration between the activation

exercise and the subsequent performance assessment (Cuenca-Fernández et al., 2017; Blazevich & Babault, 2019; Boullosa, 2021). The potentiation responses observed for the upper and lower extremities may indicate an improvement in rowing performance; consequently, assessing individual's strength level and the strength associated with these limbs might shed light on potential correlations with performance (Sañudo et al., 2020; Beato & Dello Iacono, 2020).

Further, the variability in PAPE expression has been attributed to several interacting factors, including athlete strength level, neuromuscular training background, intensity of conditioning activities, targeted muscle groups, and the balance between fatigue and potentiation (Tillin & Bishop, 2009; Blazevich & Babault, 2019; Boullosa, 2021; Asencio et al., 2025). Research consistently shows that stronger and well-trained athletes demonstrate earlier and more significant PAPE responses, while weaker or less experienced individuals may exhibit delayed potentiation or fatigue-dominant responses, leading to inconsistent performance results across studies (Wilson et al., 2013; Sañudo et al., 2020).

However, despite the potential of PAPE to improve performance, there is a lack of consensus on the most effective protocol for enhancing rowing ergometer performance and it's still unclear whether PAPE might improve 500 m indoor sprint rowing. Therefore, the aim of this study was to compare the acute effects of a flywheel-based post-activation performance enhancement (PAPE) and traditional rowing ergometer warm-up on 500 m rowing ergometer performance and neuromuscular responses in collegiate rowers. The individual's strength levels in the lower, upper extremities, and trunk isokinetic tests together with neuromuscular performance,

were assessed to determine their correlation with rowing performance. We hypothesized that the flywheel-based warm-up would result in greater enhancements in 500 m rowing performance and neuromuscular function compared to the conventional rowing ergometer warm-up, without causing excessive neuromuscular fatigue.

2. Materials and Methods

Participants - A priori power analysis for sample size determination was performed utilizing G*Power software (version 3.1.9.2; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), following current guidelines for sample size estimation in sports and exercise science research (Abt et al., 2025). Considering a predicted large within-subject effect size (Cohen's $d = 0.95$), an alpha level of 0.05, and an acceptable statistical power of 80% ($1 - \beta = 0.80$), the analysis determined that a minimum of 15 participants was required. Sixteen collegiate and highly trained rowing players (20.73 ± 0.59 years; 72.34 ± 10.26 kg; 1.73 ± 0.04 m; 24.17 ± 3.38 kg/m² of BMI; 20.2 ± 16.19 % of body fat) volunteered in this study (Table1). The inclusion criteria were as follows: (i) minimum of three years of indoor rowing of the national competition level experience and (ii) free from current injury in the six-weeks training period before testing. A history of ankle, knee, or back pathology, as well as a poor health status and physical condition, were considered exclusion criteria. Participants were requested to avoid any intense and vigorous exercise and refrain from alcohol and caffeine from the 24 hours prior to the start of the familiarization sessions until the completion of the investigation. The research protocol was approved by the Ethics Committee of the local University (HS113/2567(C1)) and was conducted in accordance with the guidelines of the Declaration of Helsinki.

Experimental Design - A repeated measures crossover design was employed, wherein all participants ($n = 16$) underwent a familiarization and baseline assessment session followed by two testing sessions. Two days after the familiarization and baseline assessment session of general characteristics and physical fitness, individuals were randomly allocated to two

distinct groups. Participants were randomly allocated to either the general ergometer rowing warm-up or the flywheel warm-up for session two, with each group comprising half of the total participants. Session three, during which protocols were exchanged, occurred over the subsequent two days (see to Fig 1).

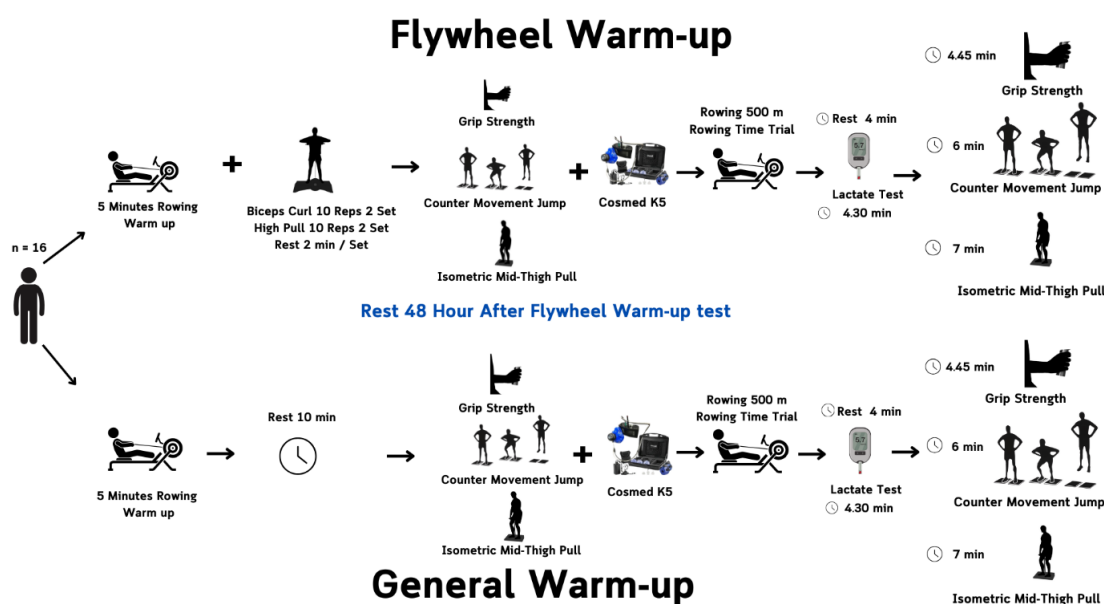


Figure 1. Schematic representation of the experimental design.

Methodology - To minimize the potential for systematic bias due to circadian oscillation, the participants were previously familiarized with the tests, which were conducted at the same time each day. A familiarization session was conducted, providing proper instruction in executing the flywheel biceps curl and high pull. The general characteristics and body composition, isokinetic and aerobic fitness assessments were conducted on two separate days. The evaluation of different PAPE protocols on a 500 m rowing ergometer and neuromuscular performance was randomly assigned to either the general rowing ergometer warm-up or the flywheel warm-up protocols, with a 48-hour interval between sessions.

Day one - Anthropometric and body composition - The initial assessment involved

assessing the individual's anthropometric and body composition (physical stature, body weight, body mass index, fat free mass and skeletal muscle mass) and isokinetic test for knee and trunk. Anthropometric and body composition measurements were assessed according to the standards established by the International Society for the Advancement of Kinanthropometry (ISAK). The bioelectrical impedance analysis (BIA) (Body Composition Analyzer: X-CONTACT 357S, Seoul, South Korea) was employed to determine standing height, body weight and body fat percentage.

Isokinetic profiling - The peak torque of knee extensors and flexors were tested concentrically at 60 and 180 deg·s⁻¹ and concentric strength of the shoulder internal and external rotators were measured at 60 and 180 deg·s⁻¹ (Wilk, Arrigo & Davies, 2024). The peak

torque of the trunk flexion and extension was assessed under isokinetic conditions at velocities of 60 and 120 deg·s⁻¹ (Wilk, Arrigo & Davies, 2024). All isokinetic contractions were executed individually for trunk and each leg and arm utilizing the Isoforce dynamometer (TUR GmbH, Berlin, Germany). The torque signals were digitized at a sample frequency of 1000 Hz and evaluated with Isoforce software (TUR GmbH, Berlin, Germany).

Day two - Peak oxygen consumption ($\dot{V}O_{2peak}$) - After the five minute of general rowing ergometer warm-up at low-intensity training (Tomiak et al., 2016) together with five minutes of upper and lower extremity ballistic movements, participants performed a six-minute rowing test with maximal effort (Thomas, Jones & Comfort, 2015). Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured using the K5 wearable metabolic system (Cosmed, Roma, Italy) in breath-by-breath (B × B) mode. Preliminary warm-up and calibration routines were performed for K5 gas analyzers according to the manufacturer's instructions. Data was analyzed with raw data by only excluding errant breaths. Heart rate (HR) was measured continuously by a heart rate monitor (Polar® S810, Finland). $\dot{V}O_{2peak}$ was assessed through visual inspection of each curve of the $\dot{V}O_2$ data from the 6 min rowing ergometer test (6-min_{RT} test) (Tomiak et al., 2016). The final 6 min RT distance, mechanical parameters (average speed, watt, and stroke rate) was measured using rowing ergometers ERGS data.

Day three - Post – activation performance enhancement (PAPE) warm-up protocols

In the subsequent session for comparison of different PAPE protocols, 48 hours later, participants were randomly allocated to either the general ergometer rowing warm-up or the flywheel warm-up protocols. Both interventions took approximately 30 min and started with a uniform standardized general warm-up, which included 5 min of low-intensity rowing ergometer exercise at 60–70%

of HR_{max}, followed by a 10 min passive rest period. Subsequently, neuromuscular performance was evaluated in the general ergometer rowing warm-up condition. On the other hand, 10 repetitions of bicep curls and high pull (2 sets with a 2 min rest period) were performed on a flywheel device (Desmotec D.FULL, Biella, Italy), utilizing lower inertial loads in a random sequence (0.1176 kg·m² and 0.1568 kg·m²) for flywheel warm-up protocols (Blazevich & Babault, 2019; Tomiak et al., 2016). The ergometer rowing warm-up intensity was continuously tracked with a heart rate monitor (Polar® S810, Finland), while the average power during the flywheel warm-up was evaluated throughout the flywheel manufacturer's software.

Neuromuscular performance - Before the 500 m rowing time trial, neuromuscular performance was assessed annually in the following order: grip strength, CMJ), isometric mid-thigh pull (IMTP) and dynamic strength index (DSI) which was derived from the force-time curve data of the ratio between CMJ peak force and their IMTP peak force (Tomiak et al., 2016).

Following completing the 500 m rowing time trial, participants performed grip strength, countermovement jump (CMJ), and isometric mid-thigh pull (IMTP) assessments during the ensuing 4 min 30 s to 7 min of recovery, according to the same protocol as the pre-rowing tests. An initial interval of 4 min 30 s was chosen based on prior PAPE research, which suggests that this duration effectively sustains potentiation while permitting adequate recovery from fatigue, thus enhancing neuromuscular preparedness for subsequent explosive performance (Blazevich & Babault, 2019; Cuenca-Fernández et al., 2017). Each neuromuscular performance test consisted of two trials, and the average of these trials was employed for further analysis.

Grip strength - Each participant was seated comfortably and instructed to hold the

K-grip dynamometer (Kinvent Physio, Montpellier, France) vertically with one hand to perform the maximal voluntary grip-force contraction test for duration of 5 s using a frequency of 500 Hz. The assessments were subsequently repeated with the other hand following a 60 s rest interval for minimizing muscle fatigue (Magni, Olds & McLaine, 2023). From all force-time curves collected during the grip, peak force and average rate of force development were analyzed.

Dynamic strength index (DSI) - The rowing athlete performed CMJ on the commercially available K-deltas dual force platforms (Kinvent Physio, Montpellier, France) at a sampling frequency of 1000 Hz. Data from CMJ, encompassing peak force and average rate of force development, were obtained using the K-deltas dual force platforms (Kin-vent Physio, Montpellier, France), which were connected to an iPad via Bluetooth for real-time measurement of force-time characteristics at a sampling rate of 1000 Hz. After the completion of the CMJ assessment, subjects rested for 60 s before undertaking the IMTP. The test was performed on the K-deltas dual force platforms by applying maximum force by bar pulling and foot pressure on the force platform for duration of 5 s. The force-time curves were recorded at a sampling rate of 1000 Hz, the average rate of force development and peak force were analyzed. Peak forces (N) were utilized for subsequent analysis and DSI was computed by dividing CMJ peak force by IMTP peak force (Tomiak et al., 2016).

500 m rowing time trial - The rowing athlete performed indoor tests on a rowing ergometer (Concept 2, Mod. D, Morisville, USA) with verbal encouragement. Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured using the K5 wearable metabolic system (Cosmed, Roma, Italy) in breath-by-breath (B × B) mode. Preliminary warm-up and calibration routines were performed for K5 gas analyzers according

to the manufacturer's instructions. Data was analyzed with raw data by only excluding errant breaths. Heart rate (HR) was measured continuously by a heart rate monitor (Polar® S810, Finland). $\dot{V}O_{2peak}$ was assessed through visual inspection of each curve of the $\dot{V}O_2$ data (Ojeda & Guerra, 2023). Capillary blood samples for [La-] were collected from an earlobe prior to 500 m rowing time trial and at the fourth minutes of the passive recovery using the CERA-CHEK™ lactate measuring system (GC Medical Science, Gyeonggi-do, Korea). The 500 m rowing time trial distance and mechanical parameters (average speed, wattage, and stroke rate) were documented with rowing ergometers ERGS data.

Statistical analysis - Descriptive statistics reported as mean $\pm$ standard deviation and 95% confidence intervals (95% CI). The Shapiro-Wilk test for normalcy was conducted for each variable. Reliability measurements, including absolute reliability (standard error measurement: SEM) and partial reliability (intraclass correlation coefficient model), were computed for baseline conditions. Bivariate Pearson correlation analysis was used to assess the relationship between the individual's strength levels in the lower, upper extremities, and trunk isokinetic neuromuscular performance and 500 m rowing time trial in each PAPE protocol. The relationships were classified as follows: trivial $r < 0.1$, small $0.1 < r < 0.3$, moderate $0.3 < r < 0.5$, large $0.5 < r < 0.7$, very large $0.7 < r < 0.9$, $0.9 < r < 1.0$, nearly perfect (Hopkins et al., 2009). An independent sample t test was applied to determine the effects of PAPE on by comparing the differences between general warm-up and flywheel warm-up. The relative changes (% Δ) were calculated as the percentage difference between conditions. The effect sizes (d) of the obtained differences were calculated and categorized (small if $0 < |d| < 0.5$, medium if $0.5 < |d| < 0.8$, and large if $|d| > 0.8$) (Cohen, 1988). Statistical analysis was performed using JAMOV software (version

0.9, The Jamovi project, 2019) using a significance level of $p < 0.05$.

3. Results

Descriptive data of anthropometric characteristics, isokinetic testing, and physical fitness related to cardiorespiratory performance of the participant are presented in Table 1. Figure 2 depicts relationships between the individual's strength levels in the lower, upper extremities, and trunk isokinetic neuromuscular performance (A) and the neuromuscular performance parameters (B) and 500 m rowing time trial. The most remarkable result to emerge from the data is

that significant correlations between 500 m rowing time trial had large positive correlation with ND_Shoulder_60 ($r = 0.51$, $p=0.04$), D_Shoulder_60 ($r= 0.65$, $p = 0.01$) and ND_Shoulder_180 ($r = 0.63$, $p = 0.01$) after general warm up protocol. For the flywheel protocol, the significant correlations between 500 m rowing time trial had large positive correlation with ND_Shoulder_180 ($r = 0.56$, $p=0.03$). However, there were no significant correlations between 500 m rowing time and the neuromuscular performance parameters induced by both general rowing ergometer warm up and flywheel warm up protocols.

Table 1: General characteristics, anthropometric, isokinetic testing, and physical fitness related to cardiorespiratory performance of the participant.

Variables	Mean $\pm$ SD	95% CI
1.General characteristics and body composition		
Age (yrs)	20.75 $\pm$ 0.68	20.36 – 21.07
Height (m)	1.74 $\pm$ 0.04	1.71 – 1.76
Weight (kg)	75.45 $\pm$ 14.06	66.53 – 83.60
Body mass index ($\text{kg}\cdot\text{m}^{-2}$)	24.56 $\pm$ 3.27	22.48 – 26.35
Body fat (%)	20.24 $\pm$ 5.69	16.59 – 23.63
Fat free mass (kg)	15.81 $\pm$ 6.88	11.45 – 19.45
Skeletal muscle mass (kg)	32.05 $\pm$ 3.71	29.62 – 33.86
2. Isokinetic tests		
Knee non-dominant peak torque at 60 $\text{deg}\cdot\text{s}^{-1}$	52.50 $\pm$ 8.64	47.13 – 57.46
Knee dominant peak torque at 60 $\text{deg}\cdot\text{s}^{-1}$	62.28 $\pm$ 8.26	56.46 – 66.09
Knee non-dominant peak torque at 180 $\text{deg}\cdot\text{s}^{-1}$	60.63 $\pm$ 12.25	52.25 – 67.09
Knee dominant peak torque at 180 $\text{deg}\cdot\text{s}^{-1}$	73.11 $\pm$ 10.54	66.53 – 79.15
Trunk peak torque at 60 $\text{deg}\cdot\text{s}^{-1}$	123.78 $\pm$ 24.83	109.17 – 139.80
Trunk peak torque at 120 $\text{deg}\cdot\text{s}^{-1}$	116.65 $\pm$ 23.62	101.23 – 130.38
Shoulder non-dominant peak torque at 60 $\text{deg}\cdot\text{s}^{-1}$	82.49 $\pm$ 28.18	67.86 – 96.96
Shoulder dominant peak torque at 60 $\text{deg}\cdot\text{s}^{-1}$	103.79 $\pm$ 46.24	79.05 – 126.30
Shoulder non-dominant peak torque at 180 $\text{deg}\cdot\text{s}^{-1}$	54.39 $\pm$ 14.93	48.28 – 64.11
Shoulder dominant peak torque at 180 $\text{deg}\cdot\text{s}^{-1}$	72.62 $\pm$ 15.98	65.81 – 83.12
3.Cardiorespiratory and rowing performance		
$\dot{V}\text{O}_{2\text{peak}}$ ($\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	37.57 $\pm$ 7.61	33.86 – 42.54
HRmax ($\text{beats}\cdot\text{min}^{-1}$)	177.69 $\pm$ 22.17	162.22 – 188.52
RPE	18.69 $\pm$ 1.70	17.49 – 19.51
Total distance (m)	1,434.13 $\pm$ 142.48	1,349.24 – 1,498.19
Average speed ($\text{m}\cdot\text{s}^{-1}$)	3.98 $\pm$ 0.40	3.75 – 4.16
Average watts (watt)	182.00 $\pm$ 55.67	149.03 – 205.40
Stroke rate ($\text{cycles}\cdot\text{min}^{-1}$)	29.00 $\pm$ 5.01	26.23 – 32.35

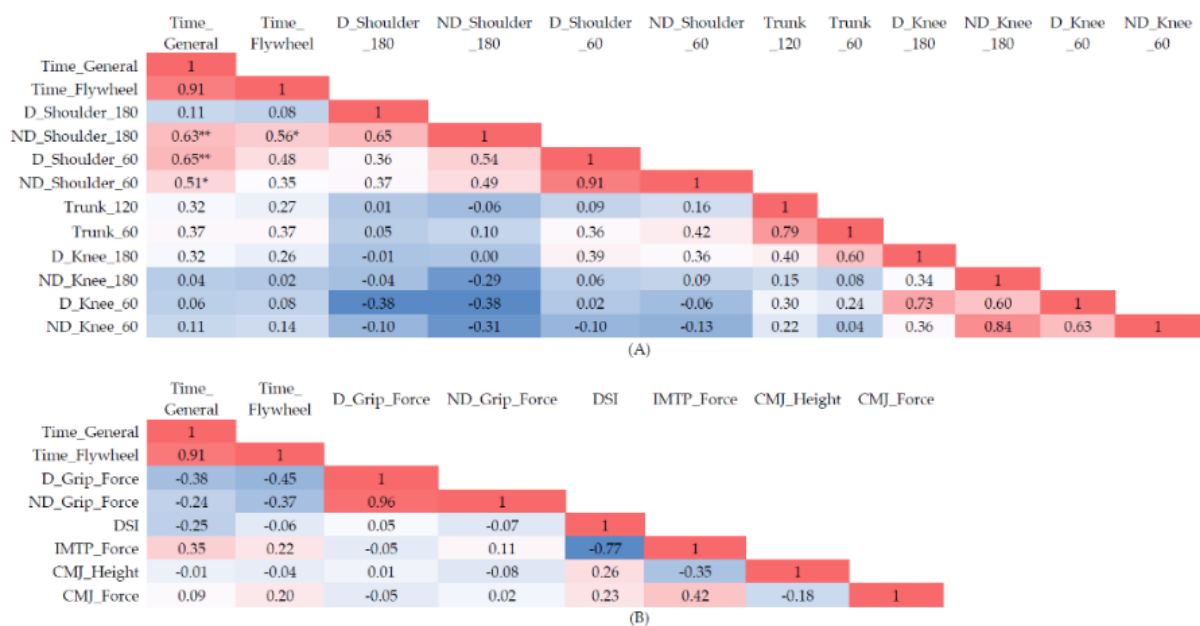


Figure 2. The Pearson correlation between the individual's strength levels in the lower, upper extremities, and trunk isokinetic (A) neuromuscular performance (B) and 500-m rowing time trial in each post – activation performance enhancement (PAPE) protocol. Abbreviations: Time_General–500-m rowing time after general warm up; Time_Flywheel– 500-m rowing time after flywheel warm up Internal training load; D_Shoulder_180–Dominant hand peak torque at 180 deg-s⁻¹; ND_Shoulder_180–Non-dominant hand peak torque at 180 deg-s⁻¹; D_Shoulder_60–Dominant hand peak torque at 60 deg-s⁻¹; ND_Shoulder_60–Non-dominant hand peak torque at 60 deg-s⁻¹; Trunk_120–Trunk peak torque at 120 deg-s⁻¹; Trunk_60 –Trunk peak torque at 60 deg-s⁻¹; D_Knee_180–Dominant leg peak torque at 180 deg-s⁻¹; ND_Knee_180–Non-dominant leg peak torque at 180 deg-s⁻¹; D_Knee_60–Dominant leg peak torque at 60 deg-s⁻¹; ND_Knee_60–Non-dominant knee peak torque at 60 deg-s⁻¹; D_Grip_Force–Dominant dynamometric grip strength peak force; ND_Grip_Force–Non-dominant dynamometric grip strength peak force; DSI– Dynamic strength index; IMTP_Force– Isometric mid-thigh pull peak force; CMJ_Height– Counter movement jump height; CMJ_Force– Counter movement jump peak force. * $p < .05$, ** $p < .01$

Table 2 shows the differences in 500 m rowing and neuromuscular performances before and after the race between the two different warm-up protocols. No differences were observed in all neuromuscular performance variables before the race. The value of grip strength obtained with the flywheel protocol was higher from that obtained with the general warm-up protocol. Counter movement jump height mean (29.00 ± 9.50 vs 28.14 ± 10.52 cm; 95% CI, 6.37 to 8.10) and dynamic strength index mean (1.11 ± 0.14 vs 1.04 ± 0.14 ; 95 % CI, [-0.03 to 0.17]) obtained from general warm-up protocol were higher than flywheel warm-up protocol. For after the race, marked of mean difference were observed on Peak_IMTP (general: $2,204.04 \pm 235.83$ N; flywheel: $2,495.74 \pm 453.68$ N; 13.2 %; $p = 0.03$; $d = -0.81$; large) and RFDavg_IMTP (general: $4,057.63 \pm 1,263.22$ N·s⁻¹; flywheel: $3,182.19 \pm 1,117.68$ N·s⁻¹; -21.6 %; $p =$

0.04 ; $d = -0.53$; medium). The highest percentage changed between two warm-up protocols was observed in RFDavg_NDGrip (general: 634.34 ± 889.88 N; flywheel: 819.65 ± 469.95 N; 22.6 %; $d = -0.33$; small).

When comparing the effects of warm-up protocols with regard to the differences on 500 m rowing time trial, 500 m rowing time differed in 3.70% (general warm-up: 87.17 ± 5.79 s; flywheel warm-up: 83.97 ± 4.78 s) presenting no significant differences between protocol ($p = 0.09$; 95 % CI = -0.63, 7.04; $d = 0.60$; medium). No meaningful differences were found between two warm-up protocols for any rowing performance and physiological variables during 500 m rowing time trial. The highest percentage changed between two warm-up protocols was observed in Post_BLa- (general: 7.28 ± 2.14 Mmol·L⁻¹; flywheel: 8.01 ± 2.25 N; 10.0%; $d = -0.33$; small).

Table 2: Differences in 500-m rowing performance and neuromuscular performance before and after the 500-m rowing time trial between the two different warm-up protocols: General and Flywheel. Mean $\pm$ SD values with the respective level of probabilities (p), mean differences, 95%confidence intervals, relative changes (% Δ), and significant effect sizes.

Variables	General Warm-up	Flywheel Warm-up	Difference [95%CI]; % Δ	p-value	Effect size (d)
1.Before race					
Peak_DGrip (N)	392.78 $\pm$ 87.28	396.49 $\pm$ 92.39	-3.71[-68.59,61.18];0.9%	0.91	-0.04
RFDavg_DGrip(N)	2,509.00 $\pm$ 1268.08	2,645.50 $\pm$ 1,076.12	-136.50[-985.73,712.73];5.4%	0.75	-0.12
Peak_NDGrip (N)	375.73 $\pm$ 78.77	363.13 $\pm$ 73.82	12.59[-42.52,67.71];-3.4%	0.64	0.16
RFDavg_NDGrip(N)	481.69 $\pm$ 735.19	819.17 $\pm$ 919.05	-337.49[-938.39,263.14];70.1%	0.26	-0.41
CMJ height (cm)	29.00 $\pm$ 9.50	28.14 $\pm$ 10.52	0.86[-6.37,8.10];-2.9%	0.81	0.09
Peak_CMJ (N)	2,402.38 $\pm$ 291.08	2,449.88 $\pm$ 325.28	-47.50[-270.37,175.37];2.0%	0.67	-0.15
RFDavg_CMJ (N)	750.99 $\pm$ 339.14	792.97 $\pm$ 380.10	-41.98[-302.07,218.10];5.6%	0.74	-0.66
Peak_IMTP (N)	2,219.69 $\pm$ 214.32	2,362.56 $\pm$ 221.03	-142.86[-330.05,37,14.33];6.4%	0.07	-0.66
RFDavg_IMTP (N·s ⁻¹)	3,587.44 $\pm$ 1177.91	2,986.06 $\pm$ 1,488.65	601.38[-367.84,1,570.59];-16.7%	0.22	0.45
DSI (%)	1.11 $\pm$ 0.14	1.04 $\pm$ 0.14	0.07[-0.03,0.17];-6.3%	0.15	0.53
2. 500-m Rowing time trial					
500-m time (s)	87.17 $\pm$ 5.79	83.97 $\pm$ 4.78	3.20 [-0.63,7.04];-3.7%	0.09	0.60
Velocity_avg (m·s ⁻¹)	5.76 $\pm$ 0.40	5.97 $\pm$ 0.34	-0.21 [-0.48,0.06];3.6%	0.12	-0.57
Pre_RPE	6.44 $\pm$ 0.63	6.44 $\pm$ 0.51	0.00 [-0.41,0.41];0.0%	0.67	0.00
Pre_BLa- (Mmol·L ⁻¹)	1.92 $\pm$ 0.15	1.90 $\pm$ 0.15	0.01[-0.10,0.12];-1.0%	0.82	0.08
Watt_avg (watt)	314.19 $\pm$ 103.76	331.94 $\pm$ 124.60	-17.25[-100.04,65.54];5.6%	0.67	-0.15
Stroke rate (cycles·min ⁻¹)	35.56 $\pm$ 6.28	36.50 $\pm$ 4.68	-0.94 [-4.94,3.06];2.8%	0.64	-0.17
$\dot{V}O_{2peak}$ (mL·kg ⁻¹ ·min ⁻¹)	37.29 $\pm$ 6.58	34.09 $\pm$ 8.87	3.20 [-2.44,8.85];-8.58%	0.26	0.41
HRmax (beats·min ⁻¹)	159.81 $\pm$ 9.81	163.08 $\pm$ 14.11	-3.27[-12.05, 5.51];2.1%	0.45	-0.27
Post_RPE	14.50 $\pm$ 2.85	15.25 $\pm$ 3.64	0.75 [-4.11,0.61];5.2%	0.61	-0.53
Post_BLa- (Mmol·L ⁻¹)	7.28 $\pm$ 2.14	8.01 $\pm$ 2.25	-0.73 [-2.32,0.85];10.0%	0.35	-0.33
3.After race					
Peak_DGrip (N)	388.96 $\pm$ 76.63	400.53 $\pm$ 87.92	-11.57[-47.97,71.12];3.0%	0.69	0.14
RFDavg_DGrip(N)	1,716.25 $\pm$ 1288.15	1,912.92 $\pm$ 1,380.66	-196.67[-1,160.76,767.42];11.5%	0.68	-0.15
Peak_NDGrip (N)	358.73 $\pm$ 80.54	368.91 $\pm$ 77.66	-10.18[-67.30,46.95];2.8%	0.72	-0.13
RFDavg_NDGrip(N)	634.34 $\pm$ 489.88	819.65 $\pm$ 469.95	-185.31[-377.04,86.43];22.6%	0.14	-0.33
CMJ height (cm)	27.82 $\pm$ 9.14	26.11 $\pm$ 6.71	1.71[-4.08,7.50];-6.1%	0.55	0.21
Peak_CMJ (N)	2,416.56 $\pm$ 300.50	2,497.81 $\pm$ 326.17	-81.25[-307.69,145.19];3.4%	0.47	-0.25
RFDavg_CMJ(N)	828.46 $\pm$ 339.23	958.08 $\pm$ 394.95	-129.63[-395.45,136.20];15.6%	0.33	-0.35
Peak_IMTP (N)	2,204.04 $\pm$ 235.83	2,495.74 $\pm$ 453.68	-291.71[-552.77,-30.65];13.2%	0.03*	-0.81
RFDavg_IMTP (N·s ⁻¹)	4,057.63 $\pm$ 1,263.22	3,182.19 $\pm$ 1,117.68	875.44[14.26,1,736.61];-21.6%	0.04*	0.73
DSI (%)	1.10 $\pm$ 0.12	1.02 $\pm$ 0.14	0.08[-0.01,0.18];-7.3%	0.08	0.65

Peak_DGrip: dominant grip strength peak force; RFDavg_DGrip: average rate of force development of dominant grip strength; Peak_NDGrip: non-dominant grip strength peak force; RFDavg_NDGrip: average rate of force development of non-dominant grip strength; CMJ height: counter movement jump height; Peak_CMJ: counter movement jump peak force; RFDavg_CMJ: average rate of force development of counter movement jump; Peak_IMTP: isometric mid-thigh pull peak force; RFDavg_IMTP: average rate of force development of isometric mid-thigh pull; DSI: dynamic strength index; Velocity_avg: average velocity; Pre_RPE: Rate of perceived exertion before 500 m rowing; Pre_BLa-: blood lactate concentration before 500 m rowing; Watt_avg: average watts; Max_HR: maximal heart rate; Post_RPE: Rate of perceived exertion after 500 m rowing; Post_BLa-: blood lactate concentration after 500 m rowing. $\dot{V}O_{2peak}$: peak oxygen uptake; HRmax: maximal heart rate

4. Discussion

Since no previous studies have explored the PAPE effects of flywheel and

general rowing ergometer warm-ups on 500 m performance, we aimed to examine the effect of PAPE protocols using either the general rowing

ergometer or flywheel on 500 m rowing ergometer and neuromuscular performance in collegiate rowing players. Initially, it was hypothesized that flywheel warm-up would exhibit greater effects of rowing performance than general rowing ergometer warm-up and do not have any negative fatigue accumulation on neuromuscular performance. Overall, the 500 m rowing performance following flywheel warm-up protocol was greater than that of the general rowing ergometer warm-up protocol. Nevertheless, no significant changes were observed in the neuromuscular performance measures (grip strength, CMJ, IMTP, and DSI) across the entire group. These findings support our hypothesis and as a result, the PAPE of flywheel training yields advantageous acute changes in muscle power, reflex mechanisms to an average RFD facilitating maximum power output over short periods without inducing detrimental fatigue accumulation on neuromuscular performance.

In the current group of collegiate rowers, the flywheel protocol may have induced significant potentiation in particular athletes but yielding neutral or fatigue-dominant effects in others, resulting to moderate group-level results. Research consistently shows that stronger and well-trained athletes display more quickly and greater PAPE responses, while weaker or less experienced individuals may exhibit delayed potentiation or fatigue-dominant responses, leading to inconsistent performance results across studies (Wilson et al., 2013; Sañudo et al., 2020).

Examining the impact of strength level and neuromuscular performance on 500 m rowing after acute PAPE flywheel and general warm-up protocols, moderate to large positive correlations were identified between the isokinetic variables derived from peak torque of the internal and external muscles of maximal strength ($60 \text{ deg}\cdot\text{s}^{-1}$) and muscular endurance ($180 \text{ deg}\cdot\text{s}^{-1}$), which seems to enhance the

efficiency of force transfer to the impulse in the rowing ergometer. This must be recognized when analyzing the relationship between force profile characteristics and performance. Our findings are consistent from a physiological and biomechanical perspective (Loturco et al., 2024; Beato et al., 2024), as it is essential for the rowing stroke to generate high forces within a short period through the upper limbs to optimize force application across the entire muscular chain, which is important for sustained strength and power output during the race.

In contrast to previous studies (Mujika et al., 2012; McGowan et al., 2015), the isokinetic trunk extension and flexion extension strength (60 and $120 \text{ deg}\cdot\text{s}^{-1}$) and maximum lower limbs strength did not correlate with rowing ergometer performance. This study identifies the 500 m rowing ergometer as a power-endurance sport, where upper limb muscle strength primarily facilitates force propulsion and transmission (Beato et al., 2024). Theoretically, maximal trunk extension strength and rapid power production along the kinetic chain are essential (Loturco et al., 2024). Consequently, the potentiation responses observed in neuromuscular performance after PAPE may indicate an enhancement in both static and dynamic performance of the lower and upper limbs; however, this may not correlate with an improvement in the effective 500 m rowing ergometer time. Nevertheless neuromuscular performance, including grip strength, IMTP and DSI, did not exhibit relative contributions or correlations to rowing ergometer performance in collegiate rowers.

In the current study, the implementation of isoinertial exercise utilizing a flywheel warm-up as part of PAPE protocols, through multiple sets of upper extremity activation (bicep curl and high pull), produced an acute enhancement in neuromuscular responses (peak force and average RFD) and mechanical adaptations in the associated

rowing performance. The difference in rowing performance (3.7 %) following flywheel exercises, as opposed to a general warm-up in this study, supports previous studies indicating that multiple sets of flywheel exercises elicit superior PAPE effects compared to single set protocols in team sports (Mujika et al., 2012; Beato & Dello Iacono, 2020), as well as enhancements in neuromuscular performance (jumping performance, sprinting time and change of direction performance) (Miarka et al., 2018). In vigorous sports, particularly rowing ergometer sprints, structured warm-up routines can prime the cardiorespiratory and neuromuscular systems (de Keijzer, Gonzalez & Beato, 2022), resulting in reduced physiological strain and significantly increased power production during rowing time trials (Sabido, Hernández-Davó & Pereyra-Gerber, 2018).

For the perspective of rowing performance, the ability to maintain a substantial proportion of $\dot{V}O_{2peak}$ for an extended duration and rowing economy is evidently crucial (Sabido, Hernández-Davó & Pereyra-Gerber, 2018). In the present study, it was probably the former case; the lower reported value for $\dot{V}O_{2peak}$ in flywheel warm-up indicated that rowers with a good rowing economy use less energy and, therefore, less oxygen uptake with the higher velocity and power output (average watt). Besides, the other physiological and metabolic responses including the maximal heart rate and post-race blood lactate [BLa-] were higher following a flywheel warm-up than a general ergometer warm-up.

The higher [BLa-] may be due to the relatively beneficial effects of flywheel exercises on the acute alterations in reflex mechanisms of muscular rate of force development, consequently enhancing maximal power output. However, the cause for the differences in maximal heart rate following different warm-up protocols is not entirely clear. The

higher maximal heart rates achieved after the race following flywheel warm-up as compared to general warm-up may be due, at least in part, to greater sympathetic nervous system stimulation and perceptual responses to the priming effects of the flywheel warm-up protocol (Lawton, Cronin & McGuigan, 2011; Sañudo et al., 2020).

Theoretically, flywheel exercises, which utilize inertia-based resistance rather than traditional weightlifting resistance, have emerged as an effective tool for eliciting PAPE effects (Sabido, Hernández-Davó & Pereyra-Gerber, 2018; Beato & Dello Iacono, 2020). Implementation of acute flywheel exercise protocols and practical recommendations can be offered for the appropriate methodology by considering various inertial intensities (training intensity), sets of flywheel exercises (training volume), duration of the flywheel exercise (rest interval), training specificity, familiarization (Maroto-Izquierdo, García-López & de Paz, 2017; Wallace et al., 2019; Beato & Dello Iacono, 2020) and conditioning activity or the athlete's strength level (Wallace et al., 2019). Since the scientific evidence on the PAPE effects of flywheel exercises to rowing ergometer performance is relatively limited, the selection of inertial intensities (0.1176 kg·m² and 0.1568 kg·m²), two multiple sets of biceps curl and high pull was selected based on the exercise specificity and subsequent of muscles rowing-specific tasks (Sabido, Hernández-Davó & Pereyra-Gerber, 2018; Beato & Dello Iacono, 2020).

Considering rest interval, the rest intervals typically range from 3 to 12 min (Beato & Dello Iacono, 2020). This range is determined upon a variety of factors, such as the individual's training status, the intensity of the conditioning exercise, and the muscular and neural contributions outcome (e.g., CMJ height, lower-limb muscle strength and power, sprinting and change of direction performance, and RFD) (Suchomel, Nimphius & Stone, 2016;

Beato et al., 2021; Beato, Stiff & Coratella, 2021; Tseng et al., 2021). Research suggests that an optimal rest interval allows for the decay of fatigue while preserving the potentiation effect (Beato, Stiff & Coratella, 2021; Tseng et al., 2021). The present study utilized moderate rest intervals of approximately 4-5 min post-race to assess and optimize neuromuscular performance, depending upon the conditioning intensity, which typically lasts about 1.5 to 2 min, with the maintenance of high-power output being necessary (Tseng et al., 2021).

A 500 m rowing effort is a high-intensity, rigorous anaerobic activity that can induce fatigue and decrease power output in succeeding endeavors. Therefore, the potentiating effects of flywheel PAPE, which can facilitate neuromuscular priming, counteract muscle fatigue, enhance explosive strength and power in both upper and lower extremities, and augment RFD-specific parameters from selected neuromuscular performance, must be evaluated to determine the variations generated by different warm-up protocols. Interestingly, we recognized no alterations in muscle fatigue, peak force, or RFD between the two warm-up protocols through isometric grip strength, CMJ and DSI. This means that multiple sets of upper extremity activation directly improve rowing performance acutely, without potentiating or adversely affecting neuromuscular responses, as evidenced by peak force and average rate of force development in comparison to a general warm-up. The current results of CMJ height align with prior findings utilizing a single set of flywheel (Beato et al., 2024), although contradict other studies that indicated flywheel treatments enhance jumping height (Beato & Dello Iacono, 2020; Vargas-Molina et al., 2021; Tseng et al., 2021; McErlain-Naylor & Beato, 2021).

The neuromuscular responses and mechanical adjustments in rowing performance exhibit potentiating effects entirely on IMTP. A series of flywheel warm-up PAPE protocols involving

multiple sets of upper extremity activation (bicep curl and high pull) have potentiating effects exclusively through peak force and average RFD. Besides, the results point to the probability and suggest that there may exist a specificity of transfer from the force-velocity region occupied during the pre-load flywheel inertia exercise to the subsequent kinetic PAPE response. The results of the present study are in line with those suggested by Tseng et al. (Tseng et al. 2021), indicating that intensified eccentric loading exercises can induce a higher PAPE and improve subsequent jumping performance, force production, and RFD in IMTP (Morin & Samozino, 2016). The key mechanism that may elucidate the underlying PAPE is the enhanced recruitment of motor units, which is closely linked to improved force-time characteristics that facilitate greater force production and may account for these temporary performance enhancements (Wilson et al., 2013; Maroto-Izquierdo, García-López & de Paz, 2017).

It is necessary to recognize specific shortcomings and possible limitations of our study. Firstly, it should be noted that the results of the current study are only appropriate for collegiate rower players' level and should not be generalized to other performance levels. This means that the players who have different performance levels from the collegiate rower of the current study, such as young and elite rower player, might show different results. Secondly, it should be noted that an effectiveness of PAPE may vary between individuals, depending on their training status, individual muscular strength, and familiarity with explosive movements (Cuenca-Fernández et al., 2019; Asencio et al., 2025), future studies should replicate these procedures with a higher number of participants with the variations competitive level and physical performance. Finally, it is essential to incorporate a control group in future studies to minimize random effects and enhance the robustness of experimental study designs.

5. Practical Applications.

The present findings offer significant practical insights for sport scientist and strength and conditioning coaches engaged with competitive rowers. Despite several performance outcomes failing to achieve statistical significance, the reported amount of change during the flywheel warm-up requires practical attention. The 3.7 % decrease in 500 m rowing time, surpasses the minimal significant change generally observed in short-duration rowing and sprint activities, where performance variations of approximately 1–2 % might be competitively significant. The noticeable enhancements in IMTP peak force and rate of force development (RFD) indicate improved neuromuscular readiness without signs of undesirable fatigue. In the context of PAPE literature, such effect magnitudes are considered practically significant, especially when implemented just before high-intensity exercise. Thus, including upper-body flywheel workouts (e.g., bicep curls and high pulls) into pre-competition warm-ups may effectively enhance force generation and explosive capacity in sprint rowing events.

6. Conclusions

Flywheel exercise provides a conditioning stimulus that aligns with established post-activation performance enhancement (PAPE) mechanisms, such as eccentric loading, increased neuromuscular activation, and metabolic stimulation. The current study demonstrated that both general rowing ergometer and flywheel-based warm-ups were equally effective in preserving neuromuscular performance, with a small-to-moderate improvement in 500 m rowing times observed after the flywheel warm-up relative to the general rowing machine warm-up. Responses to the flywheel protocol, however, varied among athletes, suggesting that PAPE effects were not consistent at the group level. The findings indicate that, when properly

organized and individualized, flywheel-based warm-ups could function as an effective option for preparing rowers for short-duration in 500 m rowing effort. Coaches and sports scientists should thus take into account athlete-specific characteristics and the fatigue–potentiation balance when applying flywheel-based PAPE techniques in realistic scenarios.

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