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**Section II – Exercise Physiology and Sports Medicine**

# Acute Neuromuscular and Performance Adaptations to PAPE—Focused Warm-Up Strategies in Rowing

*by*
*Piyathida Thongchai [1], Radomyos Matjiur [1], Rodrigo Zacca [2,3,4,5], Karla de Jesus [6], Jian-Zhi Lin [7], Phornpot Chainok [1,*]*

*Post-activation performance enhancement (PAPE) warm-up practices have received considerable interest due to their potential to acutely enhance neuromuscular output and athletic performance. In this regard, flywheel-based warm-ups have gained recognition as an innovative and effective strategy, particularly relevant in high-intensity sports such as rowing, where explosive power and neuromuscular coordination are key determinants of performance. Through a randomized crossover design, we investigated the acute effects of flywheel-based and general warm-up protocols on neuromuscular performance and 500-m rowing ergometer output in 32 male rowers (16 collegiate and 16 recreational). Post-warm-up assessments included grip strength, the countermovement jump, the isometric mid-thigh pull, the dynamic strength index and 500-m time trials. Collegiate rowers significantly improved 500-m rowing time (diff: 4.06%; p = 0.02, d = 0.84) and the dynamic strength index (diff: 28.44%; p = 0.01, d = −0.98) following the flywheel protocol, despite reductions in isometric mid-thigh pull force (diff: −17.78%; p = 0.03, d = 0.80). Recreational rowers, in contrast, experienced greater strength decline and no performance gains (diff: 1.92%; p = 0.35; d = 0.36). Across all participants, the dynamic strength index increased post-warm-up, indicating enhanced neuromuscular efficiency. These results suggest that flywheel warm-ups can elicit post-activation performance enhancement in trained athletes, while general warm-ups may be more appropriate for less trained individuals. The findings underscore the importance of tailoring warm-up strategies to the athlete's training status to optimize performance outcomes in rowing and other power-endurance sports.*

***Keywords***: *strength; post-activation potentiation; flywheel training*

## Introduction

The warm-up is essential for maximizing subsequent performance by improving neuromuscular activation and readiness for sport-specific activities. Besides basic physiological benefits, specific high-intensity preparatory exercises can induce post-activation performance enhancement (PAPE)—a transient increase in force and power production subsequent to prior muscle activation (Cuenca-Fernández et al., 2017). PAPE involves extensive neuromuscular and metabolic pathways, leading to more enduring performance advantages, in contrast to the temporary and localized effects of post-activation potentiation (PAP) (Blazevich and Babault, 2019; Wallace et al., 2019). Understanding these responses is particularly relevant for rowing, where explosive force generation and effective transmission of force are essential for sprint performance.

[1] *Faculty of Sport Science, Burapha University, Chonburi, Thailand.*
[2] *Research Center in Physical Activity, Health and Leisure (CIAFEL), Faculty of Sports, University of Porto, Porto, Portugal.*
[3] *Laboratory for Integrative and Translational Research in Population Health (ITR), Porto, Portugal.*
[4] *Nucleus of Research in Human Motricity Sciences, Universidad Adventista de Chile, Chillán, Chile.*
[5] *Laboratory of Sport Physiology, Faculty of Sports, University of Porto, Porto, Portugal.*
[6] *Human Performance Laboratory, Faculty of Physical Education and Physiotherapy, Federal University of Amazonas, Manaus, Brazil.*
[7] *Department of Physical Education, National Taiwan University of Sport, Taichung, Taiwan.*
* Correspondence: Phornpot@go.buu.ac.th

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In fact, PAPE seems to involve a wider range of mechanisms and lasts longer (Tillin and Bishop, 2009). Its effectiveness also depends on the balance between performance enhancement and fatigue (Xu et al., 2025). The type, intensity and timing of these exercises disturb this balance (Dobbs et al., 2019; Xu et al., 2025). Recent experimental evidence further demonstrates that diverse conditioning strategies, including blood flow restriction combined with whole-body vibration, maximal eccentric contractions and joint angle-specific isometric exercise, can successfully induce PAPE when appropriately prescribed (Dickey et al., 2025; Fan et al., 2025; Guo et al., 2026). Activating fast-twitch muscle fibers (type II) and exciting the nervous system are central to achieving PAPE, which is also affected by sex, the strength level, training experience and the training method used (Xu et al., 2025). Furthermore, the velocity of eccentric movement has been recently identified as a determining factor in maximizing PAPE outcomes, particularly impacting hip and thigh muscle activation and subsequent power output (Stastny et al., 2024).

Throughout recent years, flywheel resistance training has come to prominence as an innovative and effective approach for eliciting PAPE, primarily due to its capacity to produce eccentric overloading and substantial tension during dynamic movements (Beato et al., 2019, 2020). In contrast to conventional free-weight training, flywheel devices offer varied resistance across the whole range of motion, facilitating enhanced muscle activation and brain stimulation (Maroto-Izquierdo et al., 2017). These characteristics enable flywheel training to be an effective preparation technique for enhancing acute performance, particularly in sports that need both strength and endurance, such as rowing.

Rowing is a sport that necessitates the combination of aerobic capacity, anaerobic power, and neuromuscular coordination. Performance in short-distance rowing sprints (e.g., 500 m) is mostly dependent on power and the effectiveness of technique (Ingham et al., 2002; Ledergerber et al., 2023; Podstawski et al., 2014). The incorporation of a flywheel-based warm-up is especially relevant for rowing, a sport characterized by cyclical concentric-eccentric contractions of the lower limbs, the trunk and the upper body during each stroke. The inertial resistance generated by flywheel devices simulates the force-velocity characteristics encountered throughout the drive and recovery phases of the rowing stroke (Beato et al., 2024; Petré et al., 2018). Furthermore, the controlled eccentric loading characteristic of flywheel exercise could enhance the rate of force development, muscle coordination, and neural drive elements essential for effective stroke execution and quick recovery between strokes (Martín-Rivera et al., 2022; Muñoz-López et al., 2023). Evaluating the efficacy of these particular warm-up protocols provides valuable insights into how various pre-activation strategies might enhance both strength and endurance components of rowing performance (Penichet-Tomas et al., 2021).

The effectiveness of PAPE tends to be affected by individual characteristics, especially training status. Athletes exhibiting higher strength and neuromuscular efficiency, typically observed in collegiate or elite populations, may demonstrate a more favorable response to PAPE protocols due to their enhanced capacity for fatigue recovery and quick motor unit recruitment (Seitz and Haff, 2016). Conversely, recreational athletes may not possess the requisite training experience to endure or gain advantages from high-intensity warm-up techniques, possibly encountering increased fatigue rather than facilitation (Cuenca-Fernández et al., 2017). Recent evidence also indicates that individualized neuromuscular interventions based on athletes' mechanical characteristics produce greater improvements in explosive performance than standardized training approaches (Li et al., 2026). Despite the increasing interest in flywheel training and PAPE, there is a paucity of research investigating the comparative acute effects of flywheel-based vs. conventional warm-up protocols on neuromuscular function and rowing ergometer performance, especially among athletes with varying training backgrounds.

This study aimed to investigate the comparative impacts of flywheel and general warm-up protocols on neuromuscular response and 500-m rowing ergometer performance in collegiate and recreational rowers. Additionally, we aimed to determine whether the competition level and individual physical characteristics would influence the PAPE response, as evidenced by critical neuromuscular and performance indicators following each warm-up protocol. Based on the

current scientific literature, we hypothesized that the flywheel warm-up protocol would result in significant enhancements in dynamic performance metrics (e.g., grip strength, countermovement jump (CMJ), isometric mid-thigh pull (IMTP) and dynamic strength index (DSI)) and rowing ergometer results (e.g., 500-m time, mean power) relative to a general warm-up, while recognizing that transient reductions in maximal isometric force may arise as a consequence of fatigue-potentiation interaction. Moreover, we hypothesized that more experienced and skilled athletes would demonstrate a more significant PAPE response compared to their less-trained peers.

## Methods

### *Participants*

Participants were classified into two groups based on their rowing experience: collegiate rowers (n = 16; age: 23.10 ± 3.70 years, body height: 1.78 ± 0.06 m, body mass: 73.40 ± 6.8 kg) and recreational rowers (n = 16; age: 24.00 ± 5.90 years, body height: 1.76 ± 0.07 m, body mass: 75.10 ± 7.30 kg). Collegiate participants were active members of the university rowing team and had experience of structured strength and endurance training for at least two years, which included resistance-based conditioning (multi-joint free-weight exercises such as squats, deadlifts and interval training on rowing ergometers) as a critical part of their periodized program. Training sessions typically included 2–3 weekly resistance sessions focusing on strength, power, and core stability, along with 4–5 endurance sessions conducted on the water or an ergometer. All collegiate rowers were familiar with flywheel resistance devices from previous supervised strength training sessions, which ensured correct technique and safety during data collection.

Recreational participants engaged in regular exercise at least three times weekly, encompassing a combination of aerobic activities (such as running, cycling or swimming) and resistance training with free weights or machines. All participants had no formal rowing expertise and did not engage in organized rowing programs. However, all individuals were familiar with indoor rowing ergometers for general fitness, ensuring basic technical understanding without specialist rowing training. Recruitment was conducted through university athletic programs, social media announcements and direct referrals. Each participant provided written informed consent after receiving a detailed explanation of the study's procedures, potential risks and benefits. The study protocol was approved by the Ethics Committee of the Burapha University, Chonburi, Thailand (approval code: HS113/2567(C1); approval date: 09 April 2025) and was carried out in compliance with the Declaration of Helsinki criteria.

### *Design and Procedures*

A randomized crossover design was executed over three experimental sessions within a nine-day period, including an initial session for familiarization, anthropometric measurement, and physical fitness assessment, followed by two counterbalanced sessions including flywheel and general warm-ups that were separated by a minimum of 48 h to prevent residual fatigue. Session one consisted of familiarization with all testing procedures and equipment, followed by anthropometric measurements, physical fitness and neuromuscular performance assessments. Sessions two and three involved the implementation of the warm-up protocols in randomized order (counterbalanced across participants), immediately followed by neuromuscular and rowing performance tests. All sessions were conducted in a controlled laboratory setting at the same time of the day (between 08:00 and 11:00 a.m.) for each participant to control for circadian variability.

### *Session One: Familiarization, Anthropometric Measurements and Physical Fitness Evaluation*

For the familiarization procedures, a session was held 48 h before data collection, during which participants practiced the rowing ergometer and flywheel movements, together with all neuromuscular tests, to reduce technical variability and enhance reliability. On the first day, anthropometric characteristics were evaluated utilizing a multi-frequency bioelectrical impedance analyzer (Body Composition Analyzer: X-Contact 357S, Jawon Medical Co., Ltd., Korea). Standing height was measured using an integrated ultrasonic stadiometer, while body mass, the body mass index (BMI; $kg \cdot m^{-2}$), the percentage of body fat, fat-free mass (FFM) and skeletal muscle mass (SMM) were assessed by bioelectrical impedance

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analysis (BIA) (Matjiur et al., 2025). All measurements were performed in compliance with manufacturer specifications. Participants received instructions to refrain from eating, caffeine, alcohol and vigorous activity for a minimum of 12 h prior to testing and to sustain normal hydration levels. Standardized conditions were established to reduce variability related to fluid balance and ensure appropriate body composition evaluation (Kyle et al., 2004).

Isokinetic strength assessments were conducted on the same day as anthropometric and baseline evaluations to ensure consistency in physiological status and minimize inter-day variability. Isokinetic muscular strength was assessed with the Isoforce dynamometer (TUR GmbH, Berlin, Germany). We digitized torque signals at a sampling frequency of 1000 Hz and analyzed them with Isoforce software. Concentric peak torque was evaluated at various angular velocities across two joint complexes: knee extension/flexion at $60°\cdot s^{-1}$ and $180°\cdot s^{-1}$ and trunk flexion/extension at $60°\cdot s^{-1}$ and $120°\cdot s^{-1}$. Each participant executed three maximal repetitions at each velocity following a previously described warm-up protocol (Wilk et al., 2024). Rest intervals of no less than 60 s were provided between trials. The maximum torque value attained at each joint and speed were recorded for further analysis.

On the second day, cardiorespiratory capacity and rowing-specific endurance were assessed using a 6-min maximal rowing ergometer test (Concept 2 Model D, Concept 2 Inc., USA). Participants were instructed to row at a maximal yet sustainable pace to volitional exhaustion, with the maximum heart rate ($HR_{max}$), the rating of perceived effort (RPE), total distance (m), average speed ($m\cdot s^{-1}$), the stroke rate ($strokes\cdot min^{-1}$) and average power output ($W\cdot kg^{-1}$) continuously recorded. Respiratory and pulmonary gas-exchange data were measured breath-by-breath using a telemetric portable gas analyzer K5 wearable metabolic system (COSMED, Rome, Italy), following the calibration procedures recommended by the manufacturer. Respiratory and heart-rate data were processed with Omnia software, individual breath-by-breath $\dot{V}O_2$ responses were time averaged every 10 s and smoothed using a 3-breath moving average. $\dot{V}O_{2peak}$ was determined by visual inspection of the oxygen-uptake curve, following the procedures described by Ojeda and Guerra (2023) and Zacca et al. (2020).

On the third day, participants underwent a series of neuromuscular performance assessments designed to evaluate maximal strength, power, and eccentric control. Testing included hand-grip strength assessment, the CMJ, the IMTP, the DSI and the Nordic Hamstring Exercise (NHE). Hand-grip strength was measured using a K-Grip dynamometer (Kinvent Physio, Montpellier, France). Participants were seated with the elbow flexed at 90°, holding the device vertically without support. Each hand performed two 5-s maximal voluntary contractions separated by 60 s of rest. The highest peak force from each limb was recorded, and inter-limb asymmetry was calculated as the relative percentage difference (Bishop, 2021).

The CMJ and the IMTP were performed on K-Delta dual force plates (Kinvent Physio, Montpellier, France) sampling at 1000 Hz. For the CMJ, participants executed two maximal jumps with hands on hips, emphasizing rapid eccentric-concentric transition. After 60 s of recovery, the IMTP was performed by exerting maximal force against a fixed bar at the mid-thigh position for 5 s. The DSI was calculated as the ratio between CMJ and IMTP peak forces (Thomas et al., 2017). Finally, eccentric hamstring strength was assessed using the NHE, performed on a custom-built device using an ankle brace that was connected to a load cell. Participants lowered their torso under control from a kneeling position until failure to resist the descent. The highest braking force and inter-limb asymmetry were computed for further analysis (Bishop, 2021; Jeanguyot et al., 2023)

### *Sessions Two and Three: Different Warm-Up Protocols in Randomized Order*

In the second and third sessions, participants completed two distinct warm-up protocols in a randomized, crossover sequence: a general warm-up and a flywheel-based warm-up. To ensure rigorous scientific methodology, the general and flywheel warm-up protocols were conducted in randomized, counterbalanced order generated by a computer. This approach was specifically chosen to exclude any systematic order or learning bias. The experimental design was a crossover study, wherein each participant served as their own control, thus minimizing variability

and enhancing the statistical power of the results. A required rest interval of 48 h was implemented between sessions to ensure participants were completely recovered and that no residual effects, such as fatigue or potentiation, influenced their following neuromuscular and rowing performance.

Each testing session started with a standardized 5-min low-intensity rowing warm-up on the ergometer to ensure consistent pre-activation, corresponding to 60–70% of the maximal heart rate ($HR_{max}$) (Blazevich and Babault, 2019). Subsequently, participants were allowed a 10-min passive rest interval before performing the specified warm-up protocol. Under the general warm-up condition, participants performed only the initial ergometer warm-up, while in the flywheel session, this 5-min rowing phase was immediately followed by performance of 10 repetitions of the flywheel high pull and squats employing lower inertial loads in a randomized sequence (0.1176 kg·m² and 0.1568 kg·m²) utilizing a kBox4 system (Exxentric AB, Sweden) (Blazevich and Babault, 2019; Tomiak et al., 2016).

Hand grip strength, the CMJ, the IMTP, and the DSI, calculated as the ratio of CMJ peak force to IMTP peak force derived from the force-time curve, were assessed immediately before and after the 500-m rowing time trial in each experimental session (Thomas et al., 2017). In addition, the unilateral strength asymmetry index was calculated as the percentage difference between the dominant (D) and non-dominant (ND) limbs (Bishop, 2021; Turner et al., 2018). Each neuromuscular performance test comprised two trials and the average value was used for further analysis.

Following each warm-up protocol, participants were instructed to perform a maximal voluntary isometric grip-force contraction using a K-grip dynamometer (Kinvent Physio, Montpellier, France). The device was held vertically in one hand while the participant remained seated and data were recorded for 5 s at a sampling frequency of 500 Hz. After a 60-s rest interval, the test was repeated using the contralateral hand. From the resulting force-time curves, total peak force, dominant and non-dominant limbs' peak force and the unilateral strength asymmetry index were extracted for subsequent analysis. To assess the DSI, participants performed the CMJ on a pair of K-deltas dual force plates (Kinvent Physio, Montpellier, France), which were wirelessly connected to an iPad for real-time data capture at 1000 Hz. Following a 60-s rest interval, participants performed the IMTP on the same force plates, exerting maximal force against a fixed bar for 5 s. The CMJ was performed bilaterally on dual force plates (K-Delta, Kinvent Physio, Montpellier, France) to evaluate total and limb-specific peak force output. The unilateral strength asymmetry index was calculated using values from the dominant and non-dominant limbs, while the DSI was derived as the ratio of the CMJ peak force to the IMTP peak force.

***500-m Rowing Time Trial***

Each participant executed an indoor rowing assessment on a rowing ergometer (Concept 2, Model D, Morrisville, USA) and was instructed to perform at maximal effort throughout the trial. Peak oxygen uptake ($\dot{V}O_{2peak}$) was assessed utilizing a K5 wearable metabolic system (COSMED, Rome, Italy) operating in the breath-by-breath mode (Ojeda and Guerra, 2023; Zacca et al., 2020). Before each session, the gas analyzer was calibrated in accordance with the manufacturer's recommendations, which involved calibrating the flowmeter with a 3-L syringe and conducting gas calibration using a certified mixture (16.00% $O_2$ and 5.00% $CO_2$ in $N_2$). Respiratory and heart rate data were analyzed utilizing Omnia software (COSMED, Rome, Italy), with invalid breaths automatically eliminated and data averaged over 10-s intervals (Zacca et al., 2020).

$\dot{V}O_{2peak}$ was determined using a visual inspection of the oxygen uptake curve, although the heart rate was continuously recorded and synchronized utilizing a Polar® S810 device (Polar Electro, Kempele, Finland). Capillary blood lactate concentration ($[La^-]$, $mmol \cdot L^{-1}$) was evaluated through earlobe sampling using a CERA-CHEK™ analyzer (GC Medical Science, Gyeonggido, Korea) immediately before and in the fourth minute following the 500-m rowing race. Rowing performance variables, such as time, average speed, power output and the stroke rate, were registered by the ergometer's internal data system (Ojeda and Guerra, 2023; Zacca et al., 2020).

Immediately following completion of the 500-m rowing time trial, participants remained

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seated in a resting position for passive recovery. During the 4 min 30 s of this recovery, a capillary blood sample was collected from the earlobe to assess post-exercise [$La^-$] using the CERA-CHEK™ lactate measurement system (GC Medical Science, Gyeonggido, Korea). Participants also completed grip strength, CMJ and IMTP assessments, conducted in the same manner as pre-rowing measurements using the K-grip dynamometer and dual K-delta force plates (Kinvent Physio, Montpellier, France). All post-500 m rowing time trial tests for neuromuscular performance were supervised by trained researchers to ensure standardization and data integrity. Following each warm-up protocol, a rest period was implemented to balance potentiation and fatigue effects, consistently with previous guidelines of 3–12 min (Beato and Iacono, 2020). Specifically, a 4 min 30 s interval was selected based on previous PAPE studies indicating that this duration effectively maintains potentiation while allowing sufficient recovery, thereby optimizing neuromuscular readiness for subsequent explosive performance (Blazevich and Babault, 2019; Cuenca-Fernández et al., 2017).

### *Statistical Analysis*

All statistical analyses were conducted using IBM SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA), with the significance threshold set at $p < 0.05$. Data are presented as means ± standard deviations (SD), with 95% confidence intervals (CIs) provided where appropriate. The Shapiro-Wilk test verified normality and the Levene's test confirmed homogeneity of variance. Since both assumptions were satisfied, no data transformations were necessary. General characteristics, body composition, isokinetic strength, cardiorespiratory fitness and rowing performance were initially analyzed using a univariate approach with the Student's *t*-test. Cohen's *d* values were calculated and interpreted as follows: <0.20 (trivial), 0.20 to 0.59 (small), 0.60 to 1.19 (moderate), 1.20 to 1.99 (large), 2.0 to 3.9 (very large) and >4.0 (extremely large) (Hopkins et al., 2009).

Sphericity assumptions were verified using the Mauchly's test, and when violations occurred, Greenhouse-Geisser corrections were applied to adjust the degrees of freedom accordingly. A two-way repeated-measures ANOVA was then conducted to examine the effects of the warm-up condition (flywheel vs. general) and time (pre- vs. post-500 m rowing) on neuromuscular (grip strength, CMJ, IMTP, DSI) and physiological ($\dot{V}O_{2peak}$, [$La^-$]) outcomes. In the presence of significant main or interaction effects, Bonferroni-adjusted post hoc comparisons were applied. Effect sizes were expressed as partial eta squared ($\eta^2_p$) and interpreted as small (≥0.01), medium (≥0.06), or large (≥0.14) in accordance with Cohen (1988). A mixed-design ANOVA was employed to assess the moderating influence of training status (collegiate vs. recreational rowers) on performance variations throughout warm-up conditions, with the group as a between-subjects component and the warm-up protocol × time as within-subjects factors.

## Results

A comprehensive comparison of anthropometric profiles, isokinetic strength, neuromuscular capacity and rowing performance between collegiate and recreational rowers is presented in Table 1. Collegiate rowers were significantly taller (1.73 ± 0.04 vs. 1.62 ± 0.05 m, $p < 0.01$, $d = 1.72$) and heavier (73.01 ± 10.27 vs. 64.11 ± 12.16 kg, $p < 0.05$, $d = 0.80$) than their recreational counterparts. While no significant difference was observed in the body mass index (BMI), collegiate rowers exhibited lower body fat content (20.74 ± 6.35 vs. 28.61 ± 6.68%, $p < 0.05$, $d = -1.21$) and greater skeletal muscle mass (31.54 ± 3.49 vs. 24.84 ± 2.75 kg, $p < 0.01$, $d = 2.11$), indicating a more performance-oriented body composition. Isokinetic strength testing showed no significant differences in knee peak torque at either $60°\cdot s^{-1}$ or $180°\cdot s^{-1}$. However, collegiate rowers produced higher trunk peak torque at $60°\cdot s^{-1}$ (125.41 ± 28.21 vs. 101.00 ± 26.21 Nm, $p < 0.05$, $d = 0.89$), indicating superior core strength relevant to rowing-specific force transmission.

Collegiate rowers demonstrated substantially greater performance across all neuromuscular metrics. In the NHE, both dominant and non-dominant limbs exhibited higher peak force values with large effect sizes (ND: 163.24 ± 42.24 vs. 98.81 ± 35.09 N; D: 191.82 ± 48.23 vs. 111.21 ± 38.33 N; both $p < 0.01$, $d > 1.65$). Similarly, the CMJ and IMTP tests showed markedly higher total force output in collegiate rowers (CMJ: 1,805.75 ± 356.87 vs. 1,409.41 ± 252.37

N; IMTP: 1,748.49 ± 417.05 vs. 1,273.46 ± 257.49 N; both $p < 0.01$, $d > 1.27$). Grip strength followed a similar pattern, with very large differences favoring collegiate athletes across both dominant and non-dominant limbs (dominant: 393.51 ± 91.95 N vs. 240.07 ± 40.36 N; non-dominant: 366.68 ± 84.55 N vs. 208.92 ± 33.86 N; both $p < 0.01$, $d > 2.10$). Total grip peak force was significantly higher in collegiate rowers (757.19 ± 175.93 N vs. 448.99 ± 71.55 N; $p < 0.01$, $d = 2.24$), while grip asymmetry was lower, indicating better inter-limb balance. Interestingly, the DSI was slightly lower in collegiate rowers (1.05 ± 0.16 vs. 1.18 ± 0.12, $p < 0.05$, $d = -0.48$).

Considering cardiorespiratory and rowing ergometer performance, collegiate rowers outperformed their recreational peers in all rowing performance metrics. $\dot{V}O_{2peak}$ was higher (37.08 ± 7.72 vs. 30.80 ± 6.02 $mL \cdot kg^{-1} \cdot min^{-1}$, $p < 0.05$, $d = 0.90$), and they covered greater distances (1,407.81 ± 132.29 vs. 1,149.36 ± 81.25 m, $p < 0.01$, $d = 2.32$) with higher mean power output (2.36 ± 0.68 vs. 1.31 ± 0.32 $W \cdot kg^{-1}$, $p < 0.01$, $d = 1.98$). Collegiate rowers also demonstrated superior average speed (3.91 ± 0.37 vs. 3.19 ± 0.22 $m \cdot s^{-1}$, $p < 0.01$, $d = 2.32$) with a slightly lower stroke rate (29.00 ± 4.99 vs. 32.93 ± 7.29 $cycles \cdot min^{-1}$, $p > 0.05$, $d = -0.64$).

Table 2 summarizes the differences in 500-m rowing performance following general and flywheel warm-up protocols for both collegiate and recreational rowers. Among collegiate athletes, the flywheel warm-up reduced rowing time (85.12 ± 4.30 s) compared to the general warm-up (89.18 ± 5.34 s), with a 4.60% improvement ($p = 0.02$, $d = 0.84$). In contrast, recreational rowers showed a 1.92% improvement ($p = 0.35$, $d = 0.36$) (Figure 2). However, both groups demonstrated slight increases in average speed and average power (watts) after the flywheel warm-up protocol. Notably, post-exercise [$La^-$] was higher following the flywheel condition in both groups (collegiate: $p = 0.03$, $d = -0.78$; recreational: $p = 0.01$, $d = -1.26$). No changes were observed in subjective effort (RPE), the heart rate, or oxygen uptake across warm-up conditions.

Tables 3 and 4 report the upper and lower limb neuromuscular performance outcomes before and after the two warm-up protocols in both collegiate and recreational rowers. Across all participants, the flywheel warm-up resulted in significant reductions in peak IMTP force for both dominant and non-dominant limbs with moderate to large effect sizes ($p = 0.01$, $d = 0.71–0.78$). This trend was consistent in both subgroups, with particularly large declines observed in the recreational group ($p = 0.03$, $d > 0.89$). Despite the different protocols, the DSI improved across all participant groups following both warm-ups ($p = 0.01$, $d = -0.61$ to $-0.99$). However, no changes were observed in grip strength or CMJ performance (Figure 2).

## Discussion

This study examined the effects of flywheel versus general warm-up protocols on neuromuscular performance and 500-m rowing outcomes, emphasizing how the competitive level influences PAPE. The results indicated that collegiate rowers, characterized by higher skeletal muscle mass and lower body fat content, demonstrated superior baseline performance and a notable 4.60% improvement in the 500-m time trial after the flywheel warm-up, while recreational rowers showed no significant performance enhancements. Although both groups exhibited increased post-exercise blood lactate concentrations, only those who were trained tended to engage with potentiation instead of fatigue. Following the flywheel protocol, the DSI increased across subjects despite a temporary decline in maximal isometric force, signifying improved neuromuscular efficiency during explosive activities. Therefore, although flywheel warm-ups provided particular benefits for trained individuals, other anticipated results such as improvements in the CMJ and overall strength were not validated. These findings partially confirm the proposed PAPE effect, highlighting its dependence on training status and muscle conditioning.

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**Table 1.** Participants' characteristics, body composition, isokinetic strength, neuromuscular performance and cardiorespiratory and rowing performance in collegiate and recreational rowers.

| Variables | Collegiate Mean ± SD | Recreation Mean ± SD | Difference [95% CI] | Effect size (*d*) |
|---|---|---|---|---|
| 1. General characteristics and body composition | | | | |
| Age (yrs) | 20.67 ± 0.60 | 20.64 ± 0.84 | 0.05 [−0.50–0.59] | 0.06 |
| Body height (m) | 1.73 ± 0.04 | 1.62 ± 0.05 | 0.11** [0.08–0.15] | 1.72 |
| Body mass (kg) | 73.01 ± 10.27 | 64.11 ± 12.16 | 8.90* [0.52–17.28] | 0.80 |
| Body mass index (kg·m$^{-2}$) | 24.46 ± 3.45 | 24.26 ± 4.07 | 0.21 [−2.61–3.01] | 0.06 |
| Body fat content (%) | 20.74 ± 6.35 | 28.61 ± 6.68 | −7.87* [−12.75–2.99] | −1.21 |
| Fat free mass (kg) | 16.13 ± 7.40 | 19.86 ± 7.79 | −3.73 [−9.41–1.96] | −0.49 |
| Skeletal muscle mass (kg) | 31.54 ± 3.49 | 24.84 ± 2.75 | 6.70** [4.32–9.07] | 2.11 |
| 2. Isokinetic tests | | | | |
| ND_Knee peak torque at 60°·s$^{-1}$ (Nm) | 55.33 ± 6.92 | 53.23± 7.28 | 2.10 [−3.25–7.45] | 0.29 |
| D_Knee peak torque at 60°·s$^{-1}$ (Nm) | 61.72 ± 8.02 | 61.10 ± 6.79 | 0.62 [−4.98–6.22] | 0.08 |
| Knee asymmetry index at 60°·s$^{-1}$ (%) | 10.10 ± 5.50 | 12.58 ± 10.64 | −2.47 [−8.69–3.75] | −0.30 |
| ND_Knee peak torque at 180°·s$^{-1}$ (Nm) | 66.74 ± 10.17 | 62.61 ± 10.07 | 4.13 [−3.46–11.72] | 0.41 |
| D_Knee peak torque at 180°·s$^{-1}$ (Nm) | 73.53 ± 10.89 | 71.65 ± 7.40 | 1.88 [−5.19–8.95] | 0.20 |
| Knee asymmetry index at 180°·s$^{-1}$ (%) | 9.17 ± 4.89 | 12.74 ± 10.90 | −3.57 [−9.75–2.61] | −0.43 |
| Trunk peak torque at 60°·s$^{-1}$ (Nm) | 125.41 ± 28.21 | 101 ± 26.21 | 24.41* [3.94–44.88] | 0.89 |
| Trunk peak torque at 120°·s$^{-1}$ (Nm) | 116.29 ± 27.43 | 101.88 ± 20.31 | 14.41 [−3.87–32.69] | 0.59 |
| 3. Neuromuscular performance | | | | |
| ND_NHE (N) | 163.24 ± 42.24 | 98.81 ± 35.09 | 64.43** [33.13–93.73] | 1.65 |
| D_NHE (N) | 191.82 ± 48.23 | 111.21 ± 38.33 | 80.61** [47.70–93.73] | 1.83 |
| NHE_total force (N) | 355.01 ± 87.80 | 210.02 ± 72.37 | 145.01** [84.32–205.76] | 1.79 |
| NHE asymmetry index (%) | 14.17 ± 10.54 | 10.86 ± 10.56 | 3.31 [−4.60–11.21] | 0.31 |
| ND_CMJ (N) | 880.43 ± 172.51 | 740.03 ± 122.69 | 176.39** [62.87–289.91] | 1.17 |
| D_CMJ (N) | 925.32 ± 187.71 | 742.26 ± 122.33 | 183.06** [62.60–303.53] | 1.14 |
| CMJ_total force (N) | 1,805.75 ± 356.87 | 1,409.41 ±252.37 | 396.34** [161.91–630.77] | 1.27 |
| CMJ asymmetry index (%) | 4.56 ± 4.88 | 5.18 ± 3.83 | −0.62 [−3.94–2.70] | −0.14 |
| ND_IMTP (N) | 822.92 ± 206.12 | 614.71 ± 133.24 | 208.23** [76.24–340.22] | 1.18 |
| D_IMTP (N) | 925.54 ± 222.94 | 658.75 ± 133.24 | 266.79** [128.63–404.96] | 1.45 |
| IMTP_total force (N) | 1,748.49 ± 417.05 | 1,273.46 ± 257.49 | 475.02** [211.09–738.96] | 1.35 |
| IMTP asymmetry index (%) | 10.64 ± 10.35 | 6.91 ± 5.57 | 3.73 [−2.62–10.08] | 0.44 |
| ND_Grip strength (N) | 366.68 ± 84.55 | 208.92 ± 33.86 | 154.75** [105.24–204.26] | 2.34 |
| D_Grip strength (N) | 393.51 ± 91.95 | 240.07 ± 40.36 | 153.44** [98.94–207.94] | 2.11 |
| Total grip strength force (N) | 757.19 ± 175.93 | 448.99 ± 71.55 | 308.20** [204.98–411.41] | 2.24 |
| Grip strength asymmetry index (%) | 7.48 ± 3.69 | 12.56 ± 7.98 | −5.08* [−9.63–0.53] | -0.84 |
| DSI (%) | 1.05 ± 0.16 | 1.18 ± 0.12 | −0.06* [−0.17–0.04] | -0.45 |
| 4. Cardiorespiratory and rowing performance | | | | |
| $\dot{V}O_{2peak}$ (mL·kg$^{-1}$·min$^{-1}$) | 37.08 ± 7.72 | 30.80 ± 6.02 | 6.28* [1.05–11.52] | 0.90 |
| $HR_{max}$ (beats·min$^{-1}$) | 183.23 ± 8.55 | 181.81 ± 7.24 | 1.41[−4.56–7.38] | 0.18 |
| RPE | 18.31 ± 1.85 | 19.29 ± 0.99 | −0.97 [−2.11–0.16] | −0.64 |
| Total distance (m) | 1,407.81 ± 132.29 | 1,149.36 ± 81.25 | 258.46** [174.85–342.07] | 2.32 |
| Average speed (m·s$^{-1}$) | 3.91 ± 0.37 | 3.19 ± 0.22 | 0.72** [0.47–0.95] | 2.32 |
| Average watts (W·kg$^{-1}$) | 2.36 ± 0.68 | 1.31 ± 0.32 | 1.05** [1.11–2.79] | 1.98 |
| Stroke rate (cycles·min$^{-1}$) | 29.00 ± 4.99 | 32.93 ± 7.29 | −3.93 [−8.55–0.70] | −0.64 |

*ND: non-dominant limb; D: dominant limb; CMJ: counter movement jump; IMTP: isometric mid-thigh pull; NHE: Nordic hamstring exercise; DSI: dynamic strength index; RPE: rate of perceived exertion; $\dot{V}O_{2peak}$: peak oxygen uptake; $HR_{max}$: maximal heart rate. * $p < 0.05$; ** $p < 0.01$*

**Table 2**. Comparison of 500-m rowing performance following the general and flywheel warm-up protocols in collegiate and recreational rowers.

| Variables | Groups | General Warm-up | Flywheel Warm-up | Difference [95%CI]; %Δ | *p*-value | Effect size (*d*) |
|---|---|---|---|---|---|---|
| 500-m time (s) | Collegiate | 89.18 ± 5.34 | 85.12 ± 4.30 | 4.06 [0.67, 7.44]; 4.60% | 0.02 | 0.84 |
| | Recreation | 132.56 ± 7.23 | 130.02 ± 7.02 | 2.54 [−3.01, 8.09]; 1.92% | 0.35 | 0.36 |
| Average speed ($m \cdot s^{-1}$) | Collegiate | 5.40 ± 0.77 | 5.61 ± 0.77 | −0.20 [−0.76, 0.35]; −3.70% | 0.46 | −0.57 |
| | Recreation | 3.78 ± 0.21 | 3.86 ± 0.21 | −0.20 [−0.76, 0.35]; −3.70% | 0.35 | −0.36 |
| Pre_RPE | Collegiate | 6.44 ± 0.63 | 6.44 ± 0.51 | −0.07 [−0.24, 0.09]; 0.0% | 0.36 | 0.00 |
| | Recreation | 6.45 ± 0.64 | 6.45 ± 0.61 | −0.08 [−0.24, 0.09]; 0.0% | 0.35 | 0.00 |
| Pre [$La^-$] ($mmol \cdot L^{-1}$) | Collegiate | 1.92 ± 0.15 | 1.90 ± 0.15 | 0.01[−0.10, 0.12];1.0% | 0.82 | 0.08 |
| | Recreation | 1.90 ± 0.14 | 1.90 ± 0.16 | 0.01[−0.10, 0.12]; −0.0% | 0.81 | 0.08 |
| Avg_Watt (watt) | Collegiate | 277.69 ± 97.43 | 310.38 ± 113.13 | −32.69[−108.92, 43.54];−11.77% | 0.39 | −0.31 |
| | Recreation | 129.00 ± 32.79 | 144.00 ± 42.52 | −15.00[−44.50, 14.50]; −11.63% | 0.31 | −0.40 |
| Stroke rate ($cycles \cdot min^{-1}$) | Collegiate | 34.00 ± 6.04 | 36.03 ± 4.36 | −2.06 [−5.87, 1.74]; −5.97% | 0.28 | −0.39 |
| | Recreation | 31.43 ± 4.35 | 33.43 ± 5.64 | −2.00 [−5.91, 1.91]; −6.36% | 0.30 | −0.40 |
| $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) | Collegiate | 35.57 ± 7.30 | 33.72 ± 8.69 | 2.84 [−3.91, 7.65]; 5.20% | 0.23 | −0.40 |
| | Recreation | 26.64 ± 5.24 | 30.20 ± 4.43 | −3.57 [−7.33, 0.20]; −13.36% | 0.23 | −0.74 |
| HRmax ($beats \cdot min^{-1}$) | Collegiate | 164.25 ± 11.12 | 169.93 ± 15.51 | −5.68[−15.42, 4.07]; −10.35% | 0.24 | −0.42 |
| | Recreation | 162.58 ± 9.99 | 166.61 ± 14.15 | −4.04[−13.55, 5.48]; −2.48% | 0.39 | −0.33 |
| Post_RPE | Collegiate | 16.44 ± 0.63 | 16.44 ± 0.53 | −0.08 [−0.23, 0.10]; 0.00% | 0.41 | 0.00 |
| | Recreation | 16.67 ± 0.33 | 16.74 ± 0.43 | −0.07 [−0.21, 0.11]; 0.00% | 0.42 | 0.00 |
| Post [$La^-$] ($mmol \cdot L^{-1}$) | Collegiate | 6.53 ± 2.91 | 8.18 ± 2.09 | −1.65 [−3.16, −0.14]; −25.27% | 0.03 | −0.78 |
| | Recreation | 5.62 ± 1.17 | 7.40 ± 1.63 | −1.78 [−2.88, −0.68]; −31.67% | 0.01 | −1.26 |

*Pre_RPE: rate of perceived exertion before 500-m rowing; Pre [$La^-$]: blood lactate concentration before 500-m rowing; Avg_Watt: average watts; $\dot{V}O_{2peak}$: peak oxygen uptake; Post_RPE: rate of perceived exertion after 500-m rowing; Post [$La^-$]: blood lactate concentration after 500-m rowing. Values are presented as mean ± SD. MD = mean difference; 95% CI = 95% confidence interval; %Δ = relative change; ES = effect size*

**Table 3.** Upper limb neuromuscular performance before and after the two conditioning activities.

| Variables | Groups | Flywheel warm-up | | | General warm-up | | | Between group comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pre | Post | *d* | Pre | Post | *d* | F | *p* | $\eta^2_p$ |
| Peak_D Grip (N) | All | 332.02 ± 100.40 | 326.13 ± 96.07 | 0.06 | 324.88 ± 97.23 | 335.10 ± 97.05 | −0.10 | 0.27 | 0.61 | 0.00 |
| | CG | 397.47 ± 88.11 | 396.03 ± 76.24 | 0.02 | 386.49 ± 89.39 | 405.44 ± 77.61 | −0.23 | 3.67 | 0.06 | 0.01 |
| | RG | 252.54 ± 36.04 | 246.26 ± 31.62 | 0.19 | 250.06 ± 31.44 | 254.71 ± 31.78 | −0.15 | 0.03 | 0.95 | 0.01 |
| Peak_ND Grip (N) | All | 293.64 ± 94.49 | 294.96 ± 95.58 | −0.01 | 294.88 ± 95.08 | 294.50 ± 91.86 | 0.01 | 0.22 | 0.64 | 0.01 |
| | CG | 355.38 ± 82.78 | 364.91 ± 76.20 | −0.12 | 355.72 ± 86.41 | 359.59 ± 75.97 | −0.05 | 0.22 | 0.64 | 0.01 |
| | RG | 218.66 ± 33.62 | 215.02 ± 27.83 | 0.12 | 221.00 ± 30.87 | 220.11 ± 31.48 | 0.03 | 0.04 | 0.84 | 0.01 |
| Peak_Total Grip (N) | All | 625.65 ± 193.20 | 621.09 ± 190.37 | 0.02 | 619.76 ± 190.98 | 629.60 ± 187.56 | −0.05 | 0.16 | 0.69 | 0.01 |
| | CG | 752.85 ± 168.94 | 760.93 ± 150.39 | −0.05 | 742.24 ± 174.61 | 765.03 ± 151.70 | −0.14 | 0.46 | 0.50 | 0.02 |
| | RG | 471.19 ± 64.50 | 461.28 ± 56.31 | 0.16 | 471.06 ± 56.76 | 474.82 ± 59.59 | −0.07 | 0.14 | 0.71 | 0.01 |
| Grip_ASI (%) | All | 11.65 ± 8.34 | 10.05 ± 6.82 | 0.21 | 9.44 ± 7.34 | 12.32 ± 6.96 | −0.40 | 2.60 | 0.11 | 0.04 |
| | CG | 10.55 ± 7.17 | 7.97 ± 6.28 | 0.38 | 7.93 ± 5.16 | 11.34 ± 6.28 | −0.60 | 4.86 | 0.04 | 0.14 |
| | RG | 12.99 ± 9.71 | 12.42 ± 6.84 | 0.07 | 11.26 ± 9.23 | 13.44 ± 7.74 | −0.26 | 0.47 | 0.50 | 0.02 |

*CG: collegiate rowers; RG: recreational rowers; All: combined sample of collegiate and recreational rowers; D: dominant limb; ND: non-dominant limb; ASI: Asymmetry index. Values are presented as mean ± SD. * and ** different from pre-warm-up values for p < 0.05 and <0.01, respectively*

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**Table 4.** Lower limb neuromuscular performance before and after the two conditioning activities.

| Variables | Groups | Flywheel warm-up | | | General warm-up | | | Between group comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Pre | Post | *d* | Pre | Post | *d* | F | *p* | $\eta^2_p$ |
| CMJ height (cm) | All | 22.89 ± 9.97 | 23.28 ± 8.22 | −0.04 | 22.76 ± 9.98 | 23.82 ± 9.33 | −0.11 | 0.20 | 0.66 | 0.01 |
| | CG | 27.49 ± 11.26 | 27.50 ± 8.94 | −0.00 | 28.65 ± 9.61 | 29.52 ± 8.99 | −0.09 | 0.13 | 0.72 | 0.01 |
| | RG | 17.30 ± 3.50 | 18.45 ± 3.38 | −0.34 | 15.60 ± 3.99 | 17.31 ± 3.93 | −0.43 | 0.07 | 0.80 | 0.01 |
| Peak_D_ CMJ (N) | All | 841.80 ± 170.58 | 850.69 ± 176.46 | −0.05 | 831.48 ± 146.92 | 839.03 ± 167.08 | −0.05 | 0.02 | 0.97 | 0.00 |
| | CG | 882.13 ± 130.91 | 910.34 ± 155.43 | −0.20 | 915.09 ± 144.72 | 925.46 ± 148.46 | −0.07 | 0.85 | 0.36 | 0.03 |
| | RG | 752.81 ± 160.69 | 762.25 ± 170.95 | −0.08 | 769.98 ± 130.91 | 757.54 ± 144.87 | 0.09 | 0.06 | 0.81 | 0.00 |
| Peak_ND_ CMJ(N) | All | 798.08 ± 168.97 | 806.65 ± 159.33 | −0.05 | 791.95 ± 148.09 | 788.63 ± 152.74 | 0.02 | 0.05 | 0.83 | 0.01 |
| | CG | 864.88 ± 153.24 | 872.82 ± 123.63 | −0.06 | 843.46 ± 132.99 | 846.42 ± 146.44 | −0.02 | 0.01 | 0.98 | 0.00 |
| | RG | 729.39 ± 145.44 | 722.59 ± 135.99 | 0.05 | 716.96 ± 155.11 | 731.02 ± 165.66 | −0.09 | 0.05 | 0.83 | 0.01 |
| Peak_Total CMJ (N) | All | 1,623.43 ± 293.65 | 1,627.66 ± 317.91 | −0.01 | 1,639.88 ± 337.70 | 1,657.34 ± 334.89 | −0.05 | 0.01 | 0.93 | 0.00 |
| | CG | 1,779.97 ± 295.91 | 1,798.28 ± 270.78 | −0.06 | 1,725.90 ± 262.23 | 1,756.76 ± 298.97 | −0.11 | 0.29 | 0.60 | 0.01 |
| | RG | 1,469.77 ± 313.98 | 1,496.37 ± 336.45 | −0.08 | 1,499.37 ± 290.07 | 1,480.12 ± 279.93 | 0.07 | 0.05 | 0.82 | 0.02 |
| CMJ_ ASI (%) | All | 5.21 ± 4.01 | 4.97 ± 2.72 | 0.07 | 4.85 ± 3.33 | 5.81 ± 4.03 | −0.26 | 1.64 | 0.21 | 0.03 |
| | CG | 5.66 ± 4.09 | 5.39 ± 3.43 | 0.07 | 4.42 ± 3.24 | 6.95 ± 4.55 | −0.64 | 3.20 | 0.08 | 0.10 |
| | RG | 4.67 ± 4.13 | 4.49 ± 1.56 | 0.06 | 5.36 ± 3.49 | 4.50 ± 3.98 | 0.27 | 0.16 | 0.69 | 0.01 |
| Peak_D_ IMTP (N) | All | 775.76 ± 186.85 | 643.13 ± 185.55** | 0.71 | 790.69 ± 194.59 | 699.12 ± 171.35 | 0.50 | 0.89 | 0.35 | 0.02 |
| | CG | 864.62 ± 173.31 | 720.30 ± 210.50* | 0.75 | 899.47 ± 178.31 | 789.64 ± 171.58 | 0.63 | 0.30 | 0.59 | 0.01 |
| | RG | 667.87 ± 144.02 | 554.93 ± 99.84* | 0.91 | 658.61 ± 118.27 | 595.67 ± 99.60 | 0.57 | 0.59 | 0.45 | 0.02 |
| Peak_ND_ IMTP (N) | All | 726.03 ± 177.85 | 592.02 ± 166.72** | 0.78 | 743.70 ± 187.20 | 645.73 ± 162.99* | 0.56 | 0.75 | 0.39 | 0.01 |
| | CG | 804.92 ± 165.39 | 652.68 ± 196.01* | 0.84 | 833.72 ± 189.05 | 721.38 ± 174.25 | 0.62 | 0.49 | 0.49 | 0.02 |
| | RG | 630.24 ± 145.98 | 522.70 ± 89.29* | 0.89 | 634.40 ± 115.87 | 559.29 ± 95.61 | 0.71 | 0.28 | 0.60 | 0.01 |
| Peak_Total IMTP(N) | All | 1,501.79 ± 363.02 | 1,235.15 ±347.73** | 0.75 | 1,534.40 ± 378.72 | 1,344.85 ± 332.11* | 0.53 | 0.85 | 0.36 | 0.01 |
| | CG | 1,669.54 ± 336.96 | 1,372.98 ± 400.02* | 0.80 | 1,733.19 ± 362.87 | 1,511.01 ± 344.07 | 0.63 | 0.41 | 0.53 | 0.01 |
| | RG | 1,298.11 ± 287.93 | 1,077.63.08 ± 187* | 0.91 | 1,293.01 ± 233.47 | 1,154.96 ± 191.39 | 0.65 | 0.43 | 0.52 | 0.01 |
| IMTP_ ASI (%) | All | 6.40 ± 4.38 | 7.51 ± 6.84 | −0.18 | 5.81 ± 5.69 | 7.58 ± 5.82 | −0.31 | 0.14 | 0.71 | 0.01 |
| | CG | 6.91 ± 3.76 | 9.22 ± 8.61 | −0.32 | 7.56 ± 6.92 | 9.01 ± 5.47 | −0.23 | 0.05 | 0.83 | 0.01 |
| | RG | 5.78 ± 5.11 | 5.55 ± 4.80 | 0.05 | 3.68 ± 2.62 | 5.94 ± 4.96 | −0.49 | 1.10 | 0.30 | 0.04 |
| DSI | All | 1.12 ± 0.22 | 1.40 ± 0.36** | −0.94 | 1.09 ± 0.81 | 1.24 ± 0.20** | −0.79 | 2.11 | 0.15 | 0.04 |
| | CG | 1.09 ± 0.18 | 1.40 ± 0.42** | −0.98 | 1.02 ± 0.18 | 1.19 ± 0.21** | −0.99 | 1.69 | 0.20 | 0.05 |
| | RG | 1.16 ± 0.27 | 1.41 ± 0.30* | −0.87 | 1.17 ± 0.19 | 1.29 ± 0.19 | −0.61 | 0.69 | 0.41 | 0.03 |

*CG: collegiate rower; RG: recreational rower; All: collegiate and recreation rower; ND: non-dominant limb; D: dominant limb; CMJ: counter movement jump; IMTP: isometric mid-thigh pull; NHE: Nordic hamstring exercise; DSI: dynamic strength index; ASI: Asymmetry index; RPE: rate of perceived exertion; $\dot{V}O_{2peak}$: peak oxygen uptake; $HR_{max}$: maximal heart rate. * and ** different from pre-warm-up values for p < 0.05 and <0.01, respectively*

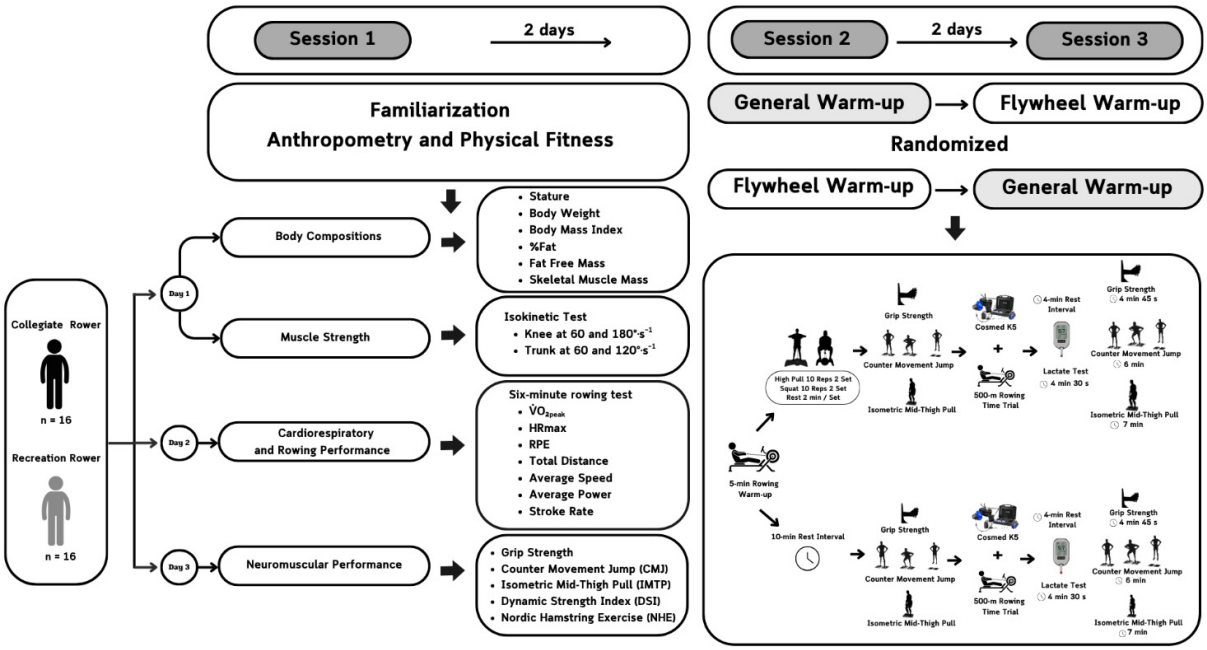



**Figure 1.** Schematic of the research design.

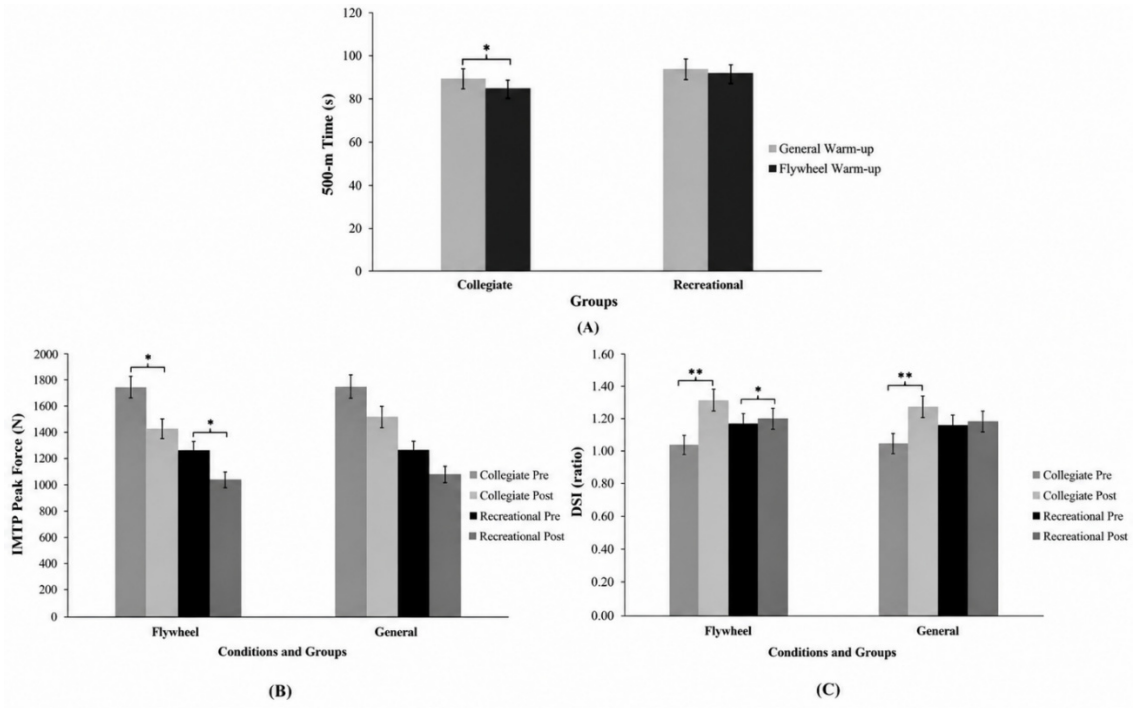



**Figure 2.** Comparison of 500-m rowing time after the general and flywheel warm-up protocols (A) and isometric mid-thigh pull (IMTP) peak force (B) and dynamic strength index (DSI) (C) before and after each warm-up protocol in collegiate and recreational rowers.

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From the perspective of anthropometric and neuromuscular distinctions, the disparities between collegiate and recreational rowers offer crucial insights into the role of training status in physical preparedness and potential for rowing performance. Collegiate rowers were taller and heavier, with significantly increased skeletal muscle mass, and notably lower body fat content, aligning with the characteristics of elite athletes as detailed by Ingham et al. (2002). Consistently with these anthropometric advantages, collegiate rowers produced greater force during the CMJ, IMTP, NHE and grip strength assessments, indicating superior neuromuscular capacity that supported effective force production during rowing (Tomiak et al., 2016). The greater peak trunk torque in the collegiate group aligns with Beato et al. (2020) who emphasized the significance of core strength for efficient kinetic chain force transmission in rowing.

At baseline, collegiate rowers demonstrated slightly lower DSI values compared to recreational rowers, likely indicative of their superior absolute force-generating capacity and the maintenance of maximal strength potential, consistent with post-activation performance enhancement (PAPE) mechanisms described by Blazevich and Babault (2019) and Seitz and Haff (2016). These differences likely point to enduring neuromuscular conditioning, enabling trained rowers to utilize short, high-intensity stimuli such as flywheel warm-ups for instant performance enhancement (Lawton et al., 2011, 2013).

This study's most significant finding was the considerable enhancement in 500-m rowing time among collegiate rowers after the flywheel warm-up, indicating a post-activation performance enhancement (PAPE) response. The 4.06-s reduction (about 4.60%) represents a meaningful improvement in short-distance rowing performance. The observed enhancement, exceeding the typical 1–3% range associated with PAPE-related improvements (Cuenca-Fernández et al., 2017; Seitz and Haff, 2016), possibly indicates the higher training status, strength reserves, and neuromuscular conditioning of collegiate rowers.

Importantly, the observed performance enhancement should be interpreted as an acute PAPE response rather than an increase in neuromuscular capacity, as IMTP peak force decreased following the flywheel warm-up. This pattern aligns with PAPE mechanisms that enhance the neuronal drive, optimize motor unit recruitment efficiency and the rate of force development, despite temporary declines in maximal strength (Blazevich and Babault, 2019; Stastny et al., 2024). Consequently, the flywheel warm-up results in optimizing the utilization of task-specific explosive force rather than enhancing maximal force production, thereby supporting its effectiveness for short-duration rowing performance in highly trained athletes (Guo et al., 2026).

In contrast, recreational rowers in this study demonstrated no significant enhancements in ergometer performance after the flywheel warm-up (1.92%), probably because of diminished neuromuscular efficiency, inadequate strength reserves, and an unfavorable fatigue-to-potentiation ratio. In contrast to trained athletes, they did not possess the requisite neuronal and muscular adaptations to gain from high-intensity eccentric stimuli, frequently leading to exhaustion that eclipsed any potentiation effects (Dobbs et al., 2019; Seitz and Haff, 2016; Wilson et al., 2013). The reduction in IMTP force and constrained power production indicate that general or submaximal warm-ups may be more suitable for this group, which is consistent with studies advocating for tailored warm-up strategies based on training status (Beato et al., 2020; Sañudo et al., 2020). Similar neuromuscular responses have also been reported following maximal multi-joint eccentric conditioning activities, where transient reductions in maximal force coexisted with improvements in explosive performance because of enhanced neural activation and motor-unit recruitment (Dickey et al., 2025).

In addition, while the IMTP peak force decreased after the flywheel condition, the increased DSI values may suggest the PAPE effect, a phenomenon where stimulation quickly enhances central drive and muscle contractility (Blazevich and Babault, 2019; Fu et al., 2023; McErlain-Naylor and Beato, 2021). Additionally, the increased blood lactate concentration during the flywheel warm-up indicates heightened metabolic activity which, when well managed by trained systems, may improve acute power production (Dobbs et al., 2019; Wallace et al., 2019). This heightened metabolic activity could improve PAPE by elevating muscle temperature, calcium

kinetics, and motor unit excitability (Blazevich and Babault, 2019; Cuenca-Fernández et al., 2017). Nonetheless, higher [$La^-$] concentration is not always beneficial, as excessive accumulation could indicate excessive anaerobic stress or insufficient recovery, particularly in less-trained individuals (Seitz and Haff, 2016; Wallace et al., 2019). In well-trained rowers, moderate lactate elevation likely reflects efficient metabolic priming that facilitates power output, whereas in recreational participants, it may induce early fatigue. Accordingly, the metabolic response to the flywheel warm-up appears dependent on training status, distinguishing potentiation from fatigue-associated deterioration.

Considering the neuromuscular responses to warm-up modalities, particularly emphasizing the role of training status and task-specific readiness, the flywheel warm-up induced a significant decrease in IMTP peak force across both groups, with larger declines in the group of recreational rowers. Despite these slight decreases in maximal isometric strength, both collegiate and recreational rowers demonstrated similar neuromuscular adaptations post-flywheel protocol, evidenced by minimal and statistically non-significant intergroup differences in the DSI, the CMJ, grip strength and the IMTP. This indicates that the flywheel intervention effectively induced acute activation but might have simultaneously induced fatigue, particularly in less-trained individuals. The 10-repetition, 2-set procedure likely induced excessive mechanical and physiological stress in recreational participants, thereby offsetting possible potentiation benefits.

This is in line with earlier studies showing that insufficient strength levels can reduce the efficacy of PAPE protocols due to low fatigue tolerance and undeveloped neuromuscular capacity, especially in less trained individuals (Dobbs et al., 2019; Seitz and Haff, 2016). On the other hand, stronger individuals, such as collegiate rowers, tend to have a higher tolerance for neuromuscular stress, which allows them to recover faster and make better use of mechanisms that increase performance (Blazevich and Babault, 2019; Sañudo et al., 2020).

This suggests that the flywheel intervention successfully elicited acute activation but may have concurrently introduced fatigue, especially among less-trained individuals. It is plausible that the 10-repetition, 2-set protocol generated excessive mechanical and metabolic stress for recreational participants, thereby offsetting potential potentiation effects. This interpretation aligns with prior findings that lower strength capacity and reduced fatigue tolerance can diminish PAPE efficacy (Dobbs et al., 2019; Seitz and Haff, 2016). Conversely, stronger and more experienced rowers likely possessed greater neuromuscular resilience and recovery kinetics, allowing them to harness the potentiating effects of the flywheel protocol (Blazevich and Babault, 2019; Sañudo et al., 2020).

Notably, despite the observed reductions in peak strength, the DSI markedly increased in all groups after both warm-up strategies. This indicates greater neuromuscular efficiency, characterized by the higher capacity to produce explosive force in relation to peak strength production (Beato et al., 2020). The disconnection between reduced maximum isometric force and increased DSI values suggests that explosive performance potential may enhance even when absolute strength is momentarily diminished probably due to acute alterations in motor unit recruitment patterns and central nervous system activation (Tillin and Bishop, 2009). Although no significant enhancement in CMJ performance was observed, the current pattern corresponds with previous findings that eccentric overloading and stretch-shortening cycle (SSC) dynamics can improve subsequent concentric readiness by enhancing muscle spindle sensitivity and elastic energy utilization (Beato et al., 2020; Maroto-Izquierdo et al., 2017). In addition, Sañudo et al. (2020) highlighted that stronger individuals exhibited enhancements in CMJ and sprint performance following flywheel procedures, underscoring that training status influences the extent of PAPE.

## Conclusions

This study provides novel insights into the immediate impact of flywheel versus general warm-up procedures on neuromuscular function and 500-m rowing performance in collegiate and recreational male rowers. The findings indicate that only collegiate rowers who were characterized by greater muscle mass, more training experience and greater fatigue resilience, derived significant

benefits from the flywheel warm-up, showing a 4.60% enhancement in 500-m performance despite temporary reductions in maximum isometric force (IMTP). The concurrent increase in the DSI indicates improved neuromuscular efficiency and the rate of force development, rather than increases in absolute strength, reflecting acute preparedness rather than structural adaptation.

Conversely, recreational rowers exhibited no significant enhancements in ergometer performance, suggesting that the 10-repetition, 2-set eccentric flywheel protocol likely surpassed their ideal potentiation threshold, resulting in residual fatigue that inhibited performance enhancement. Thus, flywheel-based warm-ups may function as an efficient pre-activation method for highly skilled athletes, although they should be implemented cautiously or modified for less-trained individuals. Future research should (1) incorporate rowing-specific or lower-body flywheel exercises to enhance movement specificity; (2) analyze various post-activation time intervals to determine individualized PAPE response windows; (3) evaluate dose-response relationships by varying inertial load and training volume; and (4) explore sex-specific adaptations for extending applicability across athletic populations.

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***ORCID ID:***

Piyathida Thongchai: https://orcid.org/0009-0008-0655-4182

Radomyos Matjiur: https://orcid.org/0009-0000-9835-6192

Karla de Jesus: https://orcid.org/0000-0002-7710-9843

Rodrigo Zacca: https://orcid.org/0000-0003-0494-0000

Jian-Zhi Lin: https://orcid.org/0000-0003-1564-8136

Phornpot Chainok: https://orcid.org/0000-0003-2605-4181

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