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SPORTS PERFORMANCE

# Dynamic post-activation potentiation protocol improves rowing performance in experienced female rowers

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**ABSTRACT**

Post-activation potentiation likely acutely improves power-based performance; however, few studies have demonstrated improved endurance performance. Forty collegiate female rowers performed isometric potentiating (ISO), dynamic potentiating (DYN) and control (CON) warm-up protocols on a rowing ergometer, followed by a three-minute all-out test to evaluate their total distance, peak power, mean power, critical power, anaerobic working capacity (W′) and stroke rate. Fifteen-second splits were also analysed. ISO consisted of 5 × 5-second static muscle actions with the ergometer handle rendered immovable with a nylon strap, while DYN consisted of 2 × 10-second all-out rowing bouts, separated by a 2-minute rest interval. The participants were divided into high and low experience groups by median experience level (3.75 years) for statistical analysis. Significant differences (DYN > CON; $p < 0.05$) were found for distance (+5.6 m), mean power (+5.9 W) and W′ (+1561.6 J) for more experienced rowers ($n = 19$) and no differences for less experienced rowers ($n = 18$). Mean power in DYN was significantly greater than CON and ISO in the 15–30, 30–45, 45–60 and 60–75 second intervals independent of experience level. These results suggest that DYN may benefit experienced female rowers and that these strategies might benefit a greater power output over shorter distances regardless of experience.

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**KEYWORDS**
Potentiation; PAP; rowing; female; endurance; performance

## Introduction

Acutely enhancing exercise performance by performing high-intensity activities of similar biomechanical characteristics several minutes prior is termed post-activation potentiation (PAP). The potentiating exercise, or activity, is termed the conditioning activity (CA) while the outcome variable is the performance measure of interest. Muscular contraction induces both fatigue and potentiation (Rassier & MacIntosh, 2000) and the net balance between the two may translate into either positive or negative changes in performance (Hodgson et al., 2005). When muscle potentiation exceeds contraction-induced fatigue, observable performance will be improved, and vice versa. It is believed that the mechanism behind PAP is the phosphorylation of the regulatory myosin lights chains, which render the myosin head more sensitive to $Ca^{+2}$, and moves the myosin head closer to the actin filament and into its force-generating state (Hodgson et al., 2005; Tillin & Bishop, 2009).

Post-activation potentiation research has concentrated primarily on power-based performance activities (e.g., jumping, sprinting and throwing). The results of these studies are largely equivocal (Hodgson et al., 2005; Tillin & Bishop, 2009) which is likely due to a variety of modulating factors. One of the most important modulating factors is the recovery interval between the CA and the performance, since it directly affects the balance between fatigue and potentiation (Dobbs et al., 2019). Several meta-analyses found rest intervals of 3 to 7 minutes to produce the greatest effect sizes (Dobbs et al., 2019; Seitz & Haff, 2016; Wilson et al., 2013), while others found 8 to 12 minutes to induce superior results (Gouvêa et al., 2013).

Endurance-based activities may also benefit from PAP; however, the research in this area is quite limited and studies investigating PAP with endurance performance as the outcome variable are rare (Boullosa et al., 2018). For example, four sets of 5RM in the leg press exercise have been shown to improve 20 km cycling time by 6.1% (Silva et al., 2014) and five sets of five-second isometric rowing improved 500 m rowing time by 1.9% (Feros et al., 2012). Additionally, it was suggested that if a submaximal pace is to be maintained, PAP can improve the efficiency of the working muscle by increasing the force production of the muscle fibres. This may lead to lower motor unit firing rates or fewer motor units needing to be recruited, resulting in postponed fatigued and greater time to exhaustion (Sale, 2002).

Rowing is a high-intensity sport that requires high levels of strength and aerobic endurance (Hagerman, 1984; Secher, 1983). Given the physiological and metabolic profile of rowing, it has been suggested that rowers can benefit from PAP by performing appropriate CAs (Feros, 2010). While Feros et al. (2012) examined an isometric CA with a 1000 m performance outcome, Doma et al. (2016) investigated a dynamic 10-second all-out rowing bout as both the CA and performance outcome and found improvement in mean power (2.5%) and peak power (1.5%), which could be relevant to the sprint start of the rowing race. The existing PAP studies completed in

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rowers have utilized different PAP protocols and performance measures representing very specific physical qualities relevant to rowing. While providing beneficial information, the heterogeneity of the research methods makes it difficult to assess and compare the efficacy of the two protocols. Therefore, this study aims to use a standardized assessment method to compare isometric (ISO) and dynamic (DYN) PAP protocols in female collegiate rowing athletes. We hypothesized that both ISO and DYN protocols will improve rowing performance compared to the control condition, and that DYN will be superior to ISO.

## Methods

### Participants

The study was conducted in collaboration with the university's female rowing team. Forty female rowers gave their consent to participate in the study (age = 20 ± 1.4 years; height = 171.8 ± 5.16 centimetres; body mass 75.38 ± 10.17 kilograms, rowing experience 4.3 ± 3.3 years, $VO_{2peak}$ 46.12 ± 5.25 ml/kg/min). The university's Institutional Review Board approved this study. All participants completed a written form of consent, physical activity readiness questionnaire (PAR-Q+) and medical activity and history questionnaire prior to the beginning of the study. Participants with recent or current injuries or surgeries were excluded from the study. Familiarization and testing sessions were performed in a group setting, in the team's boathouse. Three participants missed one of the testing sessions due to illness or injury; therefore 37 participants were included in the final analysis.

### Study design

Following the consent and medical screening, all participants completed a familiarization process by performing all of the study's protocols, which included an isometric (ISO) and dynamic (DYN) PAP protocols, and a three-minute all-out test (3MT) as the performance outcome. Participants were then randomized into three groups to perform all three conditions (ISO, DYN and control [CON]) in a different order on separate testing days in a cross-over, counter-balanced design. Testing days were separated by 48-hours and the participants were asked to maintain their usual diet and lifestyle.

For the testing days, the first group arrived at the boathouse at 6:00 a.m., the second group at 6:30 a.m., and the third group at 7:00 a.m. The order was kept consistent, so the same participants were tested at the same times on all testing days. The groups then performed a standardized warm-up which included 5 minutes of sub-maximal rowing, a series of dynamic stretches and then another 10 minutes of sub-maximal rowing. The participants were asked not to exceed a power output of 175 watts during the warm-up. Following the warm-up, the group assigned with CON rested for 7 minutes before performing the 3MT. The groups assigned with the PAP conditions performed the PAP protocols, before resting for 7 minutes, and then performed the 3MT. During the recovery interval, the participants remained seated on the ergometers and were not allowed to stretch. The resistance lever was set to elicit a drag factor of 112 for all protocols (between three and four on the flywheel damper).

### Isometric PAP protocol (ISO)

The ISO was originally described by Feros et al. (2012). To allow for an isometric contraction, the handle on the ergometer (Model D with a PM5 monitor, Concept 2, Morrisville, VT, USA) was made immobile by a heavy-duty nylon boat-strap (Vespoli USA Inc., New Haven, CT) that was wrapped around the ergometer's flywheel column. The strap was adjusted for each participant so that the knee angle was approximately 110 degrees (with complete extension referenced as 180 degrees) by assuming a rowing position known to them as "quarter slide". The coaching staff helped to adjust the rowers to the correct position. The protocol consisted of five repetitions, separated by 15-second rest intervals. Each repetition consisted of 2 seconds of submaximal contraction where the force applied to the handle was gradually increased, immediately followed by 3 seconds of maximal isometric contraction. The participants were informed of the steps during the procedure (i.e., "go", "stop",) using recorded audio instructions.

### Dynamic PAP protocol (DYN)

The dynamic PAP protocol was adopted from Doma et al. (2016) with slight modifications. The protocol consisted of two all-out 10-second rowing bouts on the ergometer. The bouts were separated by a 2-minute recovery interval. Doma et al. (2016) used a single bout as the CA; however, in order to better approximate the time under tension of the ISO and DYN protocols, the protocol was extended.

### Three minute test (3MT)

The 3MT was chosen as the main performance test to prevent the participants from pacing themselves, which was likely to happen if the more familiar 2000 m trial had been chosen. In the event of strategic pacing, which has shown to be a factor in competitive rowing (Abbiss & Laursen, 2008; Brown et al., 2010) potential benefits of PAP may have been adversely impacted.

The 3MT is a test designed to find critical power (CP) and was previously used in cycling and rowing (Bergstrom et al., 2012, 2013; Cheng et al., 2012; Vanhatalo et al., 2007, 2008). The test requires the athlete to maintain an all-out effort for the duration of 3 minutes, depleting their anaerobic work capacity (termed W'). The rowing 3MT was shown to have significant test–retest reliability (ICC = 0.788, $p < 0.05$ for end-test power, ICC = 0.903, $p < 0.05$ for distance) and end-test power was not different from CP obtained through three constant-work tests (Cheng et al., 2012). During the 3MT, all ergometers were controlled by a laptop and were set for a 3-min trial using Venue Race software (Concept2, Inc., Morrisville, VT). The participants performed the all-out 3-min effort with strong verbal encouragement of their peer coxswains. Participants were not able to see any of the monitor's information, nor were they informed of the elapsed time. To prevent pacing and ensure a continuous all-out effort, participants were instructed to "row as hard as they can" and maintain their stroke rates and power output as high as possible, for as long as possible throughout the test (Cheng et al., 2012). The coaching staff indicated that the athletes were familiar with this type of effort due to similarities with specific drills included in their training regimen. Total distance (m) and stroke rate (strokes per minute) were recorded during the 3MT, and peak power (PP), mean power (MP), critical power (CP) and anaerobic working capacity (W′) were calculated. CP was calculated as the mean power during the last 30 seconds of the test and W′ (in joules) was calculated as the work done above CP. Distance and mean power were also calculated for 15 seconds splits.

## Statistical analysis

All statistical analyses were conducted via JASP statistical software (JASP Team, Version 0.9, 2018). Results were analysed for the entire sample and by participant's experience level, with the sample split by the median experience (3.75 years) into more ($n = 20$) and less ($n = 20$) experienced groups. An independent samples t-test was used to compare anthropometric and performance measures between the two experience groups. Dependent variables were assessed for normality using the Shapiro–Wilk test. Mann–Whitney tests were used for the variables that were not normally distributed. A three-way [condition (DYN vs. ISO vs. CON) × experience (more experienced vs. less experienced) × 15 s splits (0–15 s vs. 15–30 s vs. 30–45 s … 135–150 s vs. 150–165 s vs. 165–180 s)] repeated-measures analysis of variance (ANOVA) with Holm post-hoc analyses was used to evaluate distance covered, mean power, and stroke rate, while a two-way (condition × experience) ANOVA was used to evaluate CP, W′, and PP. Mauchly's test was used to test for sphericity, and Greenhouse-Geisser corrections were used when the assumption of sphericity was violated. Finally, change in total distance was analysed on an individual basis between CON and ISO and between CON and DYN. A criterion alpha level of $p \leq 0.05$ was used to determine statistical significance. All data are reported as means ± SD and effect sizes are reported as Cohen's d values, with $d < 0.2$ considered trivial, d between 0.2 and 0.5 considered small, 0.5–0.8 considered medium and $d > 0.8$ considered large (Cohen, 1988). For the purpose of clarity, significant findings between conditions are only reported when a difference from the CON was identified; however, specific significant differences between ISO and DYN are indicated in Table 2.

## Results

Descriptive statistics for study participants are provided in Table 1. Years of rowing experience ($p < 0.001$) and 2000 m times reported by the coaching staff ($p = 0.006$) were significantly different between the more and less experienced rowing athletes. No other differences were found between groups. Table 2 presents the findings for all performance-based dependent variables.

A significant main effect for the condition was observed for total distance covered ($p < 0.05$); however, no differences were found between CON and ISO ($p = 0.2$, $d = 0.214$ "small") or DYN ($p = 0.162$, $d = -0.295$ "small"). A significant condition x experience interaction was found ($p < 0.05$) for total distance covered, with the more experienced rowers showing greater values during DYN compared to CON ($p = 0.015$; $d = -0.735$ "medium") and no differences between conditions for the less experienced rowers. Figure 1 displays this finding showing that the more experienced rowers demonstrated improved results [greater distance (~5.6 m) over the three-minute bout] under the DYN condition compared to the CON condition. Individual change in total distance revealed a range between −19.7 and +18 m from CON to ISO, and between −16.4 and +17.1 m from CON to DYN. These are shown in Figure 2.

A significant main effect for the condition was observed for PP ($p < 0.01$); however, no differences were found between CON and DYN ($p = 0.36$, $d = -0.152$ "trivial") or ISO ($p = 0.057$, $d = 0.376$ "small").

A significant main effect for the condition was observed for MP ($p < 0.05$); however, no differences were found between CON and DYN ($p = 0.283$, $d = -0.232$ "small") or ISO ($p = 0.283$, $d = 0.247$ "small"). A significant condition × experience interaction was observed for MP ($p < 0.05$), with DYN being greater than CON ($p = 0.009$, $d = -0.747$ "medium") for more experienced rowers and no differences between conditions for less experienced rowers. Figure 3 displays this finding showing that the more experienced rowers displayed improved results [greater power (~5.9 W) over the three-minute bout] under the DYN condition compared to the CON condition.

A significant condition × 15 s split interaction was observed for MP ($p < 0.001$). Mean power was significantly greater in DYN compared to CON for 15–30 s ($d = -0.588$ "medium"), 30–45 s ($d = -0.809$ "large"), 45–60 s ($d = -0.606$ "medium") and 60–75 s ($d = -0.675$ "medium") seconds splits ($p < 0.05$). Figure 4 displays these findings showing elevated power output following the DYN protocol between 15 and 75 seconds.

Table 1. Descriptive statistics (mean ± SD) for the more experienced (Exp high), less experienced (Exp low), and overall (Combined) groups of female rowing athletes.

| | N | Combined | N | Exp Low | N | Exp High |
|---|---|---|---|---|---|---|
| Height (cm) | 40 | 171.8 ± 5.16 | 20 | 171.6 ± 5.88 | 20 | 172 ± 4.46 |
| Weight (kg) | 40 | 75.38 ± 10.17 | 20 | 74.57 ± 9.76 | 20 | 76.19 ± 10.75 |
| BMI | 40 | 25.26 ± 2.4 | 20 | 25.26 ± 2.4 | 20 | 25.69 ± 2.9 |
| Fat % | 37 | 27.2 ± 4.3 | 18 | 26.34 ± 3.8 | 19 | 28.01 ± 4.7 |
| Age (years) | 40 | 20 ± 1.4 | 20 | 19.9 ± 1.5 | 20 | 20.1 ± 1.3 |
| Experience (years) | 40 | 4.3 ± 3.3 | 20 | 1.5 ± 1.2 | 20 | 7.1 ± 2.1 † |
| 2000 m (sec) | 39 | 464.2 ± 29.5 | 19 | 476.8 ± 34 | 20 | 452.3 ± 18.3 † |
| VO2max (ml\kg\min) | 37 | 46.12 ± 5.25 | 18 | 45.04 ± 4.45 | 19 | 47.14 ± 5.83 |
| VO2max (ml\min) | 37 | 3446 ± 484.5 | 18 | 3335 ± 515.7 | 19 | 3552 ± 440.7 |

Exp Low – experience <3.75 years; Exp High – experience >3.75 years; 2000 m = time in seconds to complete an indoor 2000 m on a rowing ergometer; † different between groups.

Table 2. Dependent variables (mean±SD) for the more experienced (Exp high; n = 19), less experienced (Exp low; n = 18), and overall (Combined; n = 37) groups of female rowing athletes.

| | CON | | | ISO | | | DYN | | |
|---|---|---|---|---|---|---|---|---|---|
| | Combined | Exp high | Exp low | Combined | Exp high | Exp low | Combined | Exp high | Exp low |
| Distance (m) | 800.2 ± 44.18 | 813.9 ± 35.7 | 792.2 ± 44.52 | 797.1 ± 45.24 | 813 ± 32.28 | 789.4 ± 46.17 | 804.9 ± 42.4 ‡ | 819.5 ± 34.55 †, ‡ | 791 ± 47.11 |
| Mean Power (W) | 260.7 ± 37.34 | 268.8 ± 35 | 252.2 ± 39.42 | 258.3 ± 36.94 | 267.2 ± 31.38 | 249 ± 40.84 | 263 ± 39.12 ‡ | 274.7 ± 34.17 †, ‡ | 250.6 ± 41.09 |
| Peak Power (W) | 376.8 ± 58.13 | 372.2 ± 53.61 | 381.6 ± 63.76 | 364.8 ± 57.45 | 358.1 ± 49.66 | 371.9 ± 65.39 | 381.9 ± 64.44 ‡ | 383 ± 54.6 | 380.7 ± 75.05 |
| Critical Power (W) | 220.7 ± 39.09 | 234.5 ± 32.89 | 206 ± 40.6 | 219.7 ± 37.31 | 236.4 ± 28.74 | 202.1 ± 37.85 | 217.9 ± 37.21 | 231.7 ± 27.68 | 203.4 ± 41.07 |
| W′ (J) | 7060 ± 2824 | 6084 ± 2709 | 8089 ± 2634 | 6851 ± 3087 | 5455 ± 2824 | 8324 ± 2696 | 7995 ± 2840 ‡ | 7646 ± 2803 †, ‡ | 8364 ± 2913 |
| W′ (m) | 36.46 ± 16.96 | 30.74 ± 15.4 | 42.49 ± 16.82 | 34.17 ± 18.43 | 24.98 ± 16.14 | 43.87 ± 15.78 | 40.70 ± 16.86 ‡ | 36.87 ± 14.9 ‡ | 44.74 ± 18.26 |
| Stroke Rate (s/min) | 35.73 ± 2.86 | 36.47 ± 3.07 | 34.95 ± 2.4 | 36.26 ± 3.18 † | 36.98 ± 3.1 | 35.49 ± 3.1 | 36.75 ± 2.9 †, ‡ | 37.43 ± 2.9 † | 36.03 ± 2.79 † |

CON = control; ISO = isometric protocol; DYN = dynamic protocol; † Different from CON; ‡ Different from ISO; Exp high – rowing experience>3.75 years; Exp low – rowing experience<3.75 years.

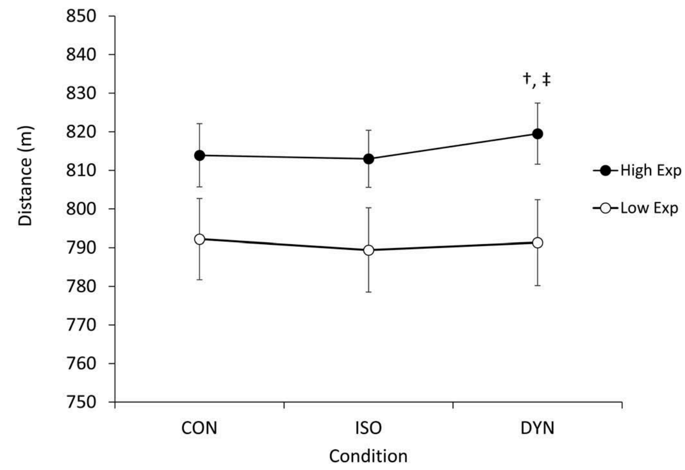


Figure 1. Distance covered in the 3MT by testing condition and by experience levels. Black circles represent high experience, and white circles represent low experience. Error bars represent 95% confidence intervals. † DYN>CON; ‡ DYN>ISO.

A significant main effect for condition ($p < 0.001$) and a condition × 15 s split interaction ($p < 0.001$) was observed for stroke rate. Stroke rate for DYN was greater than CON ($p < 0.001$, $d = -0.868$ "large"), and ISO was also greater than CON ($p = 0.05$, $d = 0.385$ "small"). Stroke rate was significantly higher for DYN compared to CON for every 15 seconds split from 0 to 135 seconds.

No significant main effect for condition ($p > 0.05$) or any interactions were found for CP. A significant main effect for experience was found ($p = 0.01$, $d = 0.445$ "small") with the high experience group exhibiting a greater CP compared to the low experience group. A significant main effect for condition ($p < 0.05$) was found for W′; however, no differences were found between CON and DYN ($p = 0.132$, $d = -0.343$ "small") or ISO ($p = 1.000$, $d = 0.089$ "trivial"). A condition × experience interaction ($p < 0.05$) was found for W′ with DYN being greater than CON ($p = 0.032$, $d = -0.611$ "medium") for the more experienced rowers and no differences were found between conditions for the less experienced rowers. Figure 5 displays these findings with the more experienced rowers demonstrating greater W′ (~1562 J) during the DYN protocol compared to the CON condition.

## Discussion

The purpose of this study was to compare the effects of isometric and dynamic PAP protocols on rowing performance, as measured during the three-minute all-out test (3MT), in collegiate female rowers. The primary finding of this investigation was that DYN improved total distance (+5.6 m), mean power (+5.9 W), and anaerobic work capacity (+1562 J) for more experienced rowers, with medium effect sizes, while DYN increased mean stroke rate in the 3MT for all participants.

### *Isometric protocol*

While a previous study has shown improvement in 500 m rowing following the same isometric CA (Feros et al., 2012), the results from the current study did not show such performance

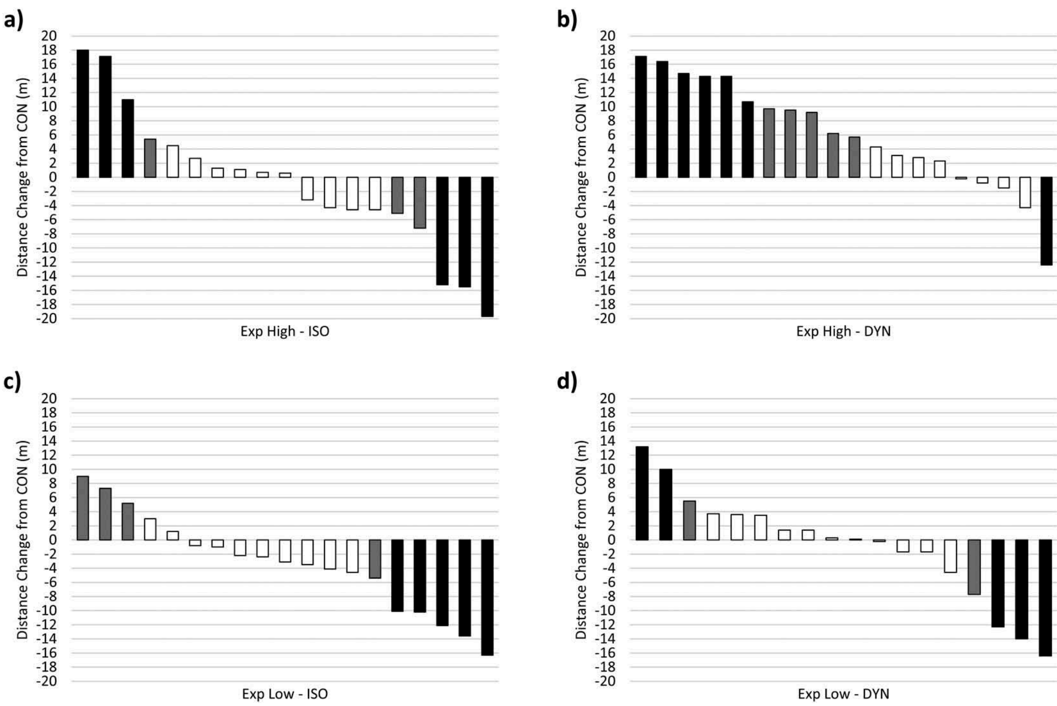


Figure 2. Changes from CON in distance covered during the 3MT for (a) ISO and (b) DYN for the more experienced rowers (Exp High; n = 19), and (c) ISO and (d) DYN for the less experienced rowers (Exp Low; n = 18). Bars in black indicate changes of ≥10 m. Bars in white indicate changes of ≤5.

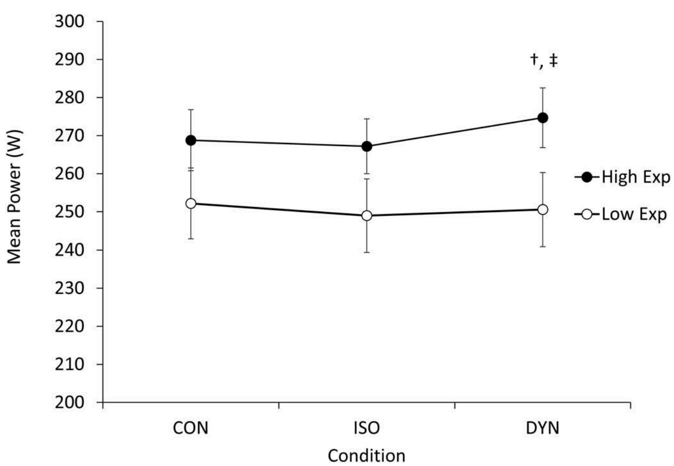


Figure 3. Mean power comparisons of testing conditions by experience level. The black circles represent the high experience group, and the white circles represent the low experience group. Error bars represent 95% confidence intervals. † DYN>CON; ‡ DYN>ISO.

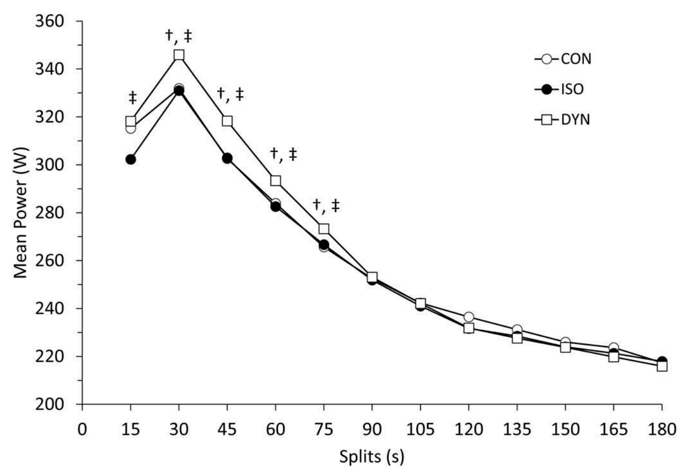


Figure 4. Mean power analysed by 15-second splits and categorized by the condition. † DYN>CON; ‡ DYN>ISO.

enhancements. Some noticeable differences exist between the two investigations, mainly the sex (primarily males vs. females) and experience level (elite vs. collegiate) of the participants. While females have been shown to demonstrate PAP related performance enhancements in several studies (Evetovich et al., 2015; Kontou et al., 2018), the general effect size for females are reportedly lower (ES = 0.42 vs. ES = 0.20) (Wilson et al., 2013), and some studies did not find such effects (Sarramian et al., 2015; Sygulla & Fountaine, 2014). However, it is unclear whether true sex differences in the PAP response exist or if these differences are related to strength levels. The importance of strength levels and training status is emphasized by Seitz & Haff (2016) who reported a larger effect size in stronger individuals and those with more resistance training experience, independent of sex. These findings are in agreement with others (Kontou et al., 2018; Tillin & Bishop, 2009). Although no strength data were reported for the participants in the Feros et al. (2012) study, it was noted that the participants had at least 5 years of resistance training experience. The participants in our study were younger, and while strength was not measured, data from the team's strength and conditioning logs indicated strength levels indicative of limited resistance training experience.

Further support for the importance of strength and sex differences comes from fatigability studies. While some studies have shown no sex differences in fatigability when men and women are matched for strength or power (Hunter et al., 2004a;

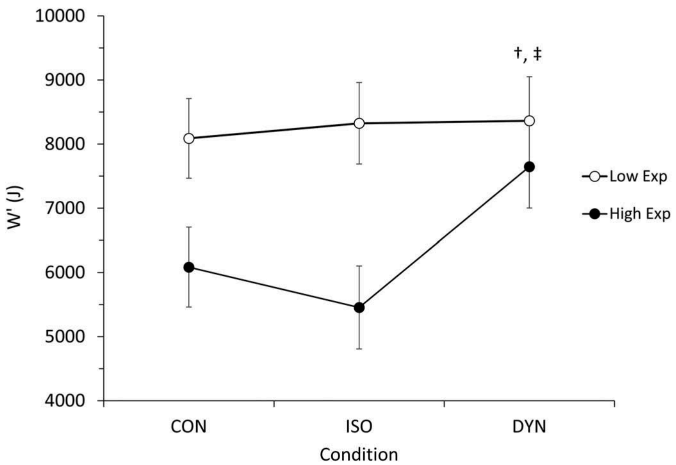


Figure 5. Comparison of W′ (J) by testing condition for experience groups. The black circles represent the high experience group, and the white circles represent the low experience group. Error bars represent 95% confidence intervals. † DYN>CON; ‡ DYN>ISO.

Smith & Billaut, 2012), other studies have found contrasting results (Hunter et al., 2004b). Females have been shown to recover faster and be less fatigable than males (Hunter, 2014, 2016; Hunter et al., 2004b; Laurent et al., 2010). However, this effect is lessened during dynamic contractions compared to isometric contractions, in high-speed contractions compared with lower speed contractions, and in higher intensities compared with medium or low intensities (Hunter, 2014, 2016). If women are less fatigable, then eliciting a meaningful PAP response would require more fatiguing protocols, while a faster recovery response would likely require shorter recovery times. Future studies could use an evoked muscle twitch response before and after the CA to verify the existence of local muscle PAP before performing the performance trial (MacIntosh, 2010).

Another notable difference from Feros et al. (2012) is the recovery interval which was longer in the present study (4 vs. 7 minutes), which, in conjunction with other parameters such as sex and strength levels, could have led to the observed results. Although the recovery interval in this study was selected based on several meta-analyses, reporting the greatest effect size for rest intervals of 5–7 minutes (Dobbs et al., 2019; Gouvêa et al., 2013; Seitz & Haff, 2016; Wilson et al., 2013), it is possible that the recovery time used was not ideal for the intensity of the CAs, the population, or a combination of both factors. The ideal recovery interval changes between individuals and is probably affected by strength levels and training experience (Seitz et al., 2014; Seitz & Haff, 2016). Considering the variability in responsiveness during the current study, the conclusion from this data is that the PAP protocol should be tailored for each individual according to their own characteristics. If the intensity of the CAs used was not high enough to justify 7 minutes of recovery, then the potentiating effect of the CA might have either dissipated before the beginning of the measured performance (i.e., the 3MT), or the CA may not have generated the intended effect. Since high intensities CAs have been shown to elicit greater PAP than lower intensity Cas (Dobbs et al., 2019; Seitz & Haff, 2016), a maximal effort was expected during this protocol; however, due to limitations with the available instrumentation, such effort was not verified in the current study. Additionally, the participants in this study were not specifically trained in maximal isometric contractions, which could have affected their ability to generate sufficient isometric force to elicit a meaningful PAP response.

### Dynamic protocol

Doma et al. (2016) used a 10-second maximal dynamic rowing bout as both the CA and the performance outcome were separated by 6 minutes. While the performance outcome was different from the current study, the recovery intervals were similar, and the peak power achieved early in the 3MT (usually in the first 10 seconds) can be used for comparison. There was no significant difference in peak power between the CON and DYN in the current study ($p = 0.36$, $d = 0.152$); however, there was approximately a 5 W difference which was equal to 1.3% (of CON peak power). While not significant, the differences in peak power between CON and DYN (+5 watts or 1.3%) resemble the significant results reported by Doma et al. (2016) who found a 6 w or 1.5% difference.

With respect to mean power output, Doma et al. (2016) also found a significant difference of 2.5% between the two 10-seconds bouts. Mean power during the first 15 seconds in the current investigation was not different between CON and DYN; however, these calculations may have been affected by the inability to calculate power for the first ~4 seconds because the software used did not display this information. These results are similar to results reported by Doma et al. (2019) in which a 10-second overloaded cycling sprint improved mean power in a subsequent Wingate anaerobic power test in anaerobically trained males, but not peak power.

### PAP in endurance performance

There is a lack of research examining longer duration, endurance efforts as the performance outcome (Boullosa et al., 2018). Similar to findings of Feros et al. (2012), the results from the current study tend to support the notion that the effect of PAP is more prominent in the earlier stages of the performance. While the more experienced rowers demonstrated improved distance, mean power output, and anaerobic working capacity for the full duration of the test (3 minutes and approximately 800 metres) following DYN, it seems that the majority of the differences in distance and mean power were accumulated in the first part of the test, as differences between the conditions became smaller and smaller for every 15-second interval after peaking, with the largest ES observed at the 30–45 split. Despite providing some support and justification for the use of PAP in longer duration efforts with experienced athletes, further investigations are required to establish whether this method would provide any benefits for longer duration efforts, such as the 2000 m rowing event, which lasts 7–8 minutes for female collegiate rowers. One study examined a longer duration effort with experienced male cyclists and showed potential for such improvements (Silva et al., 2014). The participants performed four sets of 5RM leg press exercises, prior to a 20 km cycling time trial. Results showed a 6.1% ($p < 0.05$)

improvement in time to complete the distance. Interestingly, the authors also reported a trend ($p = 0.06$) of mean power increase in the first 10% of the trial (2 k and approximately 3 minutes) but not over the full distance, similar to the current findings. Further support for the use of PAP in endurance performance comes from a recent study which had trained endurance runners perform either control condition or a 4 x 5RM band-resisted jump squat before a 5 × 1 km time trial (Low et al., 2019). The results showed a faster time to complete the first km in the PAP condition and a better average time to complete each km. Additionally, there was a 3.6% decrease in the aggregate time to complete the 5 km. The authors proposed that increased leg stiffness and reactive power following the intervention improved running economy by allowing for a more effective stretch-shortening cycle. The idea of PAP increasing submaximal exercise economy was suggested previously by Sale (2002); however, in a different context of increased muscle fibre force production, which could lead to a decrease in the number of engaged motor units or motor units firing rates.

### Critical power and anaerobic work capacity

The 3MT used in this study was previously used to evaluate critical power (CP) and anaerobic working capacity (W′) in cycling (Burnley et al., 2006; Vanhatalo et al., 2007) and rowing (Cheng et al., 2012). While CP is the highest work rate that can be sustained at a steady state without fatigue, it has been suggested that W′ is fixed and finite, indicating inter-individual tolerance to exercise in the severe intensity domain above CP (Jones & Vanhatalo, 2017). Various factors have been proposed to explain the mechanism behind W′. Although the use of the term "anaerobic" suggests that W′ is related to substrate availability, this may be an oversimplification, as other possible explanations exist (Jones et al., 2010). Interestingly, changes in CP are inversely related to changes in W′ and the two seem to be dependent, or at least related, to each other. Therefore, these variables cannot be perceived as independent aerobic and anaerobic entities (Jones et al., 2010). For example, endurance training, as well as hyperoxic exposure, increased CP but at the same time reduced W′ (Jenkins & Quigley, 1992; Vanhatalo et al., 2010), whereas W′ was reduced by glycogen depletion (Miura et al., 2000) and increased after short-term sprint-interval training (Jenkins & Quigley, 1993) and creatine supplementation (Smith et al., 1998). However, the magnitude of W′ might also be related to the accumulation of fatigue-induced metabolites (e.g., $H^+$ and $P_i$) (Fitts, 1994).

The results from this study showed no change in CP and an increase in W′ following DYN, for experienced rowers only. Since CP is a highly related to aerobic capacity, it was not expected to change following the interventions. It can be argued that the magnitude of change in W′ increased due to the increase in mean power in the first stages of the test. Such an increase could originate from the PAP intervention by increasing the rate of force development at the muscular level (Tillin & Bishop, 2009). Since the magnitude of W′ seems to be related to the accumulation of muscle contraction-impairing metabolites (Burnley & Jones, 2007; Fitts, 1994), improving muscle contraction function or efficiency might delay this accumulation, thereby delaying fatigue. Improved muscle efficiency resulting from PAP was suggested by Sale (2002) and explained by a reduced motor units utilization originating from an increased muscle fibres force production. The increased fibres force enables the muscle to use less muscle fibres to perform a given task thus making the muscle contraction more efficient (Sale, 2002).

The use of the 3MT for this study may have limited ecological validity. While the results of this study show some promise, ultimately rowing performance is measured over larger distances (e.g., 2000 m). It remains to be tested if PAP would have a significant effect (statistical and/or practical) over a distance that is used for competition. Additionally, the test was performed on an indoor rowing ergometer and not on the water, which is where rowers compete. Another consideration was the absence of pacing that was required due to the nature of the 3MT. Although this was required to measure the effects of PAP, in real competition rowers do pace themselves. For example, Abbiss & Laursen (2008) noted that performance times of athletes in efforts >2 minutes are optimized if athletes distribute their pace evenly. Similarly, Brown et al. (2010) found that elite level rowers maintained an even pace to regulate their effort, whereas their sub-elite counterparts did not. Therefore, we concluded that if the rowers were given their familiar 2000 m event, they might have been inclined to endorse their usual pacing strategy; however, the impact of such a strategy cannot be concluded from the current findings. Additionally, the effects of an individual improvement due to PAP on a team of rowers competing on a single scull are unknown. Another potential limitation is the absence of local muscle PAP measurement, or another kind of neuromuscular measurements (e.g., muscle twitch potentiation, H-reflex, EMG) that could have provided further information regarding the mechanism of the observed improvements and verify the existence of muscular potentiation.

Power output measured by the Concept 2 performance monitor has been shown to differ from the input power measured using external sensor measurements; however, values between these measurements were correlated for the first 15 strokes ($r = 0.75$, $p < 0.001$) and this relationship improved after removing the first three strokes ($r = 0.93$, $p < 0.001$). (Boyas et al., 2006) While peak power from the Concept 2 rowing ergometer has been found reliable in several studies (Metikos et al., 2015; Nugent et al., 2019), this could raise some concern regarding the power-related findings in the current study. Specifically, an underestimation of the reported power output values at the beginning of the 3MT (i.e., during acceleration or uneven pace) due to limitations in quantifying changes in kinetic energy may have masked any additional effects related to the interventions being examined. However, the cross-over nature of the study likely yielded comparable measurement error across conditions and the use of mean power over 15-second splits may have lessened the potential for spurious findings.

## Practical applications

This investigation found both statistically significant and practical differences for the DYN PAP protocol in improving total distance, mean power output and anaerobic rowing capacity in experienced female rowers. A 5.6 m difference over a 3-minute rowing bout may translate to valuable results throughout a competitive race. Additionally, the DYN PAP protocol could be easily implemented in the natural environment of the rowers by completing short, all-out bouts on rowing ergometers or in the boat on water prior to racing. The use of this equipment reduces the need for heavy and cumbersome resistance training equipment which is commonly used to elicit PAP. This intervention may serve as a simple, low-risk, cost-effective method to improve rowing performance.

## Perspective

Our results showed that DYN increased distance, mean power and W′ for experienced collegiate female rowers. Additionally, stroke rate increased for rowers of all experience levels. This study supports the use of PAP in short-duration endurance-based efforts and adds to the limited body of knowledge in that area, particularly with female athletes. Since rowing experience was shown to be a significant modulator of the PAP response, future studies should attempt to identify the mechanism behind this effect. In that regard, psychological measures (e.g., mental toughness questionnaire) could be used as part of the effort to identify differences between experienced and inexperienced athletes. Finally, future studies should also try to implement a more personalized protocol for each athlete to maximize the effects of PAP and identify modulating factors for PAP in endurance efforts.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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