The Effects of a Cycling Warm-up Including High-Intensity Heavy-Resistance Conditioning Contractions on Subsequent 4-km Time Trial Performance

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Abstract

Chorley, A and Lamb, KL. The effects of a cycling warm-up including high-intensity heavy-resistance conditioning contractions on subsequent 4-km time trial performance. *J Strength Cond Res* 33(1): 57–65, 2019—Previous exercise has been shown to improve subsequent performance through different mechanisms. Sport-specific conditioning contractions can be used to exploit the "post-activation potentiation" (PAP) phenomenon to enhance performance although this has rarely been investigated in short endurance events. The aim of this study was to compare a cycling warm-up with PAP-inducing conditioning contractions (CW) with a moderate-intensity warm-up (MW) on performance and physiological outcomes of a 4-km time trial. Ten well-trained male endurance cyclists ($\dot{V}O_2$max 65.3 ± 5.6 ml·kg^{-1}·min^{-1}) performed two 4-km cycling time trials after a 5-minute recovery after a warm-up at 60% of $\dot{V}O_2$max for 6.5 minutes (MW), and a warm-up with conditioning contractions (CW) consisting of 5 minutes at 60% of $\dot{V}O_2$max then 3 × 10-second at 70% of peak power interspersed with a 30-second recovery. Blood lactate concentrations were measured before and after time trial. Expired gases were analyzed along with time, power output (PO), and peak forces over each 500 m split. After CW, mean completion time was reduced (1.7 ± 3.5 seconds $p > 0.05$), PO increased (5.1 ± 10.5 W $p > 0.05$) as did peak force per pedal stroke (5.7 ± 11 N $p > 0.05$) when compared with MW. $\dot{V}O_2$ increased (1.4 ± 1.6 ml·kg^{-1}·min^{-1} $p \leq 0.05$) after CW, whereas respiratory exchange ratio (RER) decreased (0.05 ± 0.02 $p \leq 0.05$). Physiological and performance differences after CW were greatest over the first 1,500 m of the trials. The results suggest that a PAP-inducing warm-up alters $\dot{V}O_2$ kinetics and can lead to performance improvements in short endurance cycling but work and recovery durations should be optimized for each athlete.

Key Words potentiation, PAP, power, prior-exercise, track, pursuit

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Introduction

Before athletic events, most competitors will perform a warm-up routine in the expectation that it will enhance their performance (3). Mechanisms found to improve performance include, but are not limited to, the speeding up of oxygen uptake ($\dot{V}O_2$) kinetics (6) and improving efficiency by reducing the oxygen cost of performance (1). Warm-ups also risk negatively affecting performance should they induce fatigue by being too intense (31) having insufficient recovery before the event (24). One contemporary technique undergoing scrutiny in the search for performance gain is post-activation potentiation (PAP).

Post-activation potentiation is a phenomenon where the performance of a muscle is enhanced by its recent contractile history (17) resulting in an increase of peak torque (12), an increased rate of force development (RFD) (12), a decrease in the time to peak torque (12,22), and a change in pennation angle (35). The mechanism most often suggested as the explanation for the phenomenon is the phosphorylation of myosin regulatory light chains (23), which results in the actin-myosin interaction becoming more sensitive to calcium ions released from the sarcoplasmic reticulum (29). This is thought to increase the rate of the cross bridging action, effectively increasing the RFD (17). Post-activation potentiation has been shown to be more pronounced in type II muscle fibers (15) because of their higher levels of myosin light chain kinase (28). Furthermore, Sale (30) proposed that PAP would be beneficial to endurance performance where submaximal forces are repeatedly exerted, invoking the low-frequency tetanic contractions where calcium sensitivity is a factor and has been found to produce an increased RFD (36).

Although previous activation of a muscle beneficially induces PAP, there is also the coexisting effect of fatigue to be considered, which can produce a net negative effect on performance (24,27,31). The balance of PAP and fatigue was evident in the study by Chiu et al. (7), which found that the training status of subjects influenced the overall response to PAP with athletes displaying enhanced performance compared with recreationally trained subjects. Hamada et al. (14) also suggested that endurance-trained subjects had enhanced fatigue resistance and an increased number of myosin light chains in the type I muscle fibers within the trained muscle groups, thereby enhancing the PAP response. These studies (7,14) suggest that endurance-trained athletes would benefit by both an enhanced PAP response and a reduction in fatigue despite having a predominance of type I muscle fibres; however, few studies have investigated PAP in relation to short endurance events (1,11,16).

Typically, PAP-inducing protocols have used heavy resistance exercise (HRE), often in repeated bouts of muscle activity lasting 10 seconds (37). Intermittent conditioning activities have also been shown to induce PAP (2), leading to recent studies using sport-specific conditioning contractions to induce PAP (11,16,33), while maintaining protocols analogous to the typical HRE inducements. A feature of the Barnes et al. (1) study was the investigation into the oxygen cost of exercise after a PAP-inducing protocol, albeit only measured at submaximal levels. $\dot{V}O_2$ is a performance-limiting component of endurance, and as such characterizes many endurance performance–based studies (8,21), but as yet, owing to the lack of research, no inferences can be drawn as to the positive or negative effects of PAP-inducing warm-ups on the oxygen cost at perimaximal and supramaximal intensities.

There have been many studies into the effects of warm-up routines, but not PAP per se (5,13,25,38), demonstrating how they can elicit power and speed improvements in endurance cycling, particularly in the early stages of performance. The 4-km individual track pursuit race is a short endurance event, raced in the manner of an individual time trial, performed at supramaximal intensity in terms of $\dot{V}O_2$, with an estimated 85/15 aerobic/anaerobic energy contribution (20) making it a potential candidate for the positive effects of PAP. In particular, it seems likely that such a benefit would be evident in the early stages of the event before the self-perpetuating component being established, and where a small performance gain, such as 1 second, could be a race-winning margin.

A performance gain in a race such as the 4-km pursuit is measured in time; however, speed and completion time are a function of the power output (PO) (20), which in turn is derived from the force-angular velocity relationship in pedaling (32). The effects that PAP might have on force, power, and the energy systems at supramaximal intensities warrant further investigation. The principal aim of this study was to compare a cycle specific warm-up including PAP-inducing conditioning contractions with a moderate-intensity warm-up to determine whether there is a performance benefit in well-trained cyclists over a 4-km time trial. Specifically, it was hypothesized that the

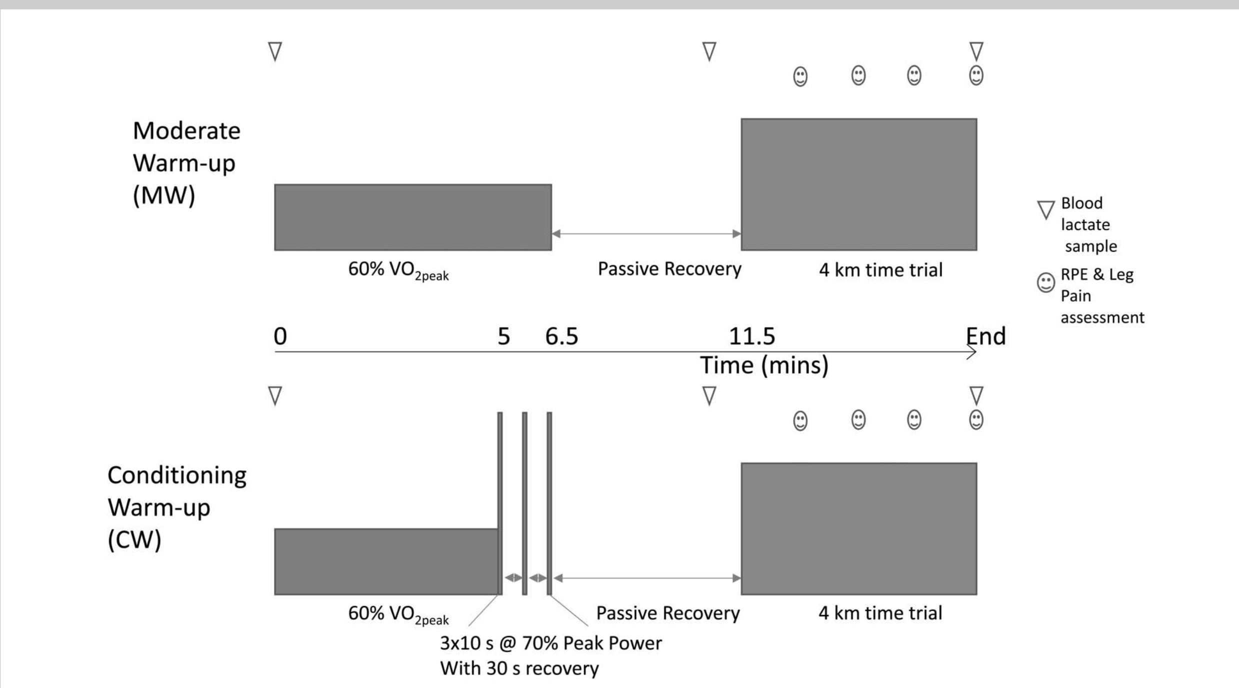

Figure 1. Schematic showing the timeline for both experimental trials.

Table 1. Performance measures for the 4 km after the moderate-intensity warm-up (MW) and the conditioning warm-up (CW).*

	MW, mean ± *SD*	CW, mean ± *SD*	Difference of mean values, 90% (CI: LL to UL)	Effect size 90% (CI: LL to UL)	Effect size Class
Completion time (s)	315.2 ± 6.7	313.5 ± 6.3	−1.7 (−3.7 to 0.4)	0.26 (−0.05 to 0.50)	Small
Power output (W)	356.8 ± 21.7	361.9 ± 21.6	5.1 (−1.0 to 11.2)	0.24 (−0.04 to 0.48)	Small
Peak force per pedal stroke (N)	317.6 ± 28.4	323.3 ± 26.0	5.7 (−0.7 to 12.0)	0.21 (−0.02 to 0.40)	Small

*Power output and peak force per pedal stroke are mean values over the 4-km trials. Effect sizes were determined using the pooled *SD*.

PAP warm-up would enhance force, PO, and time over the 4-km trial, particularly over the early stages. In addition, the study examined the effects of these warm-ups on specific physiological measures that relate to overall performance.

Methods

Experimental Approach to the Problem

In a repeated measures counter-balanced design, subjects visited the laboratory on 3 separate occasions over a maximum of 10 days. During the first visit they undertook a graded incremental cycling test to exhaustion to determine PO intensities relative to $\dot{V}O_2$max and a cycling maximum power test, to determine individual intensities for use in the experimental trials. After a rest period of approximately 30 minutes, subjects then completed a familiarization of the experimental trial conditions. Between 2 and 7 days later the subjects returned for their first experimental trial; 24–96 hours after that they undertook their final and alternate experimental trial. The experimental trials were randomized in order and consisted of either the moderate-intensity warm-up and a 4-km time trial, or the warm-up including

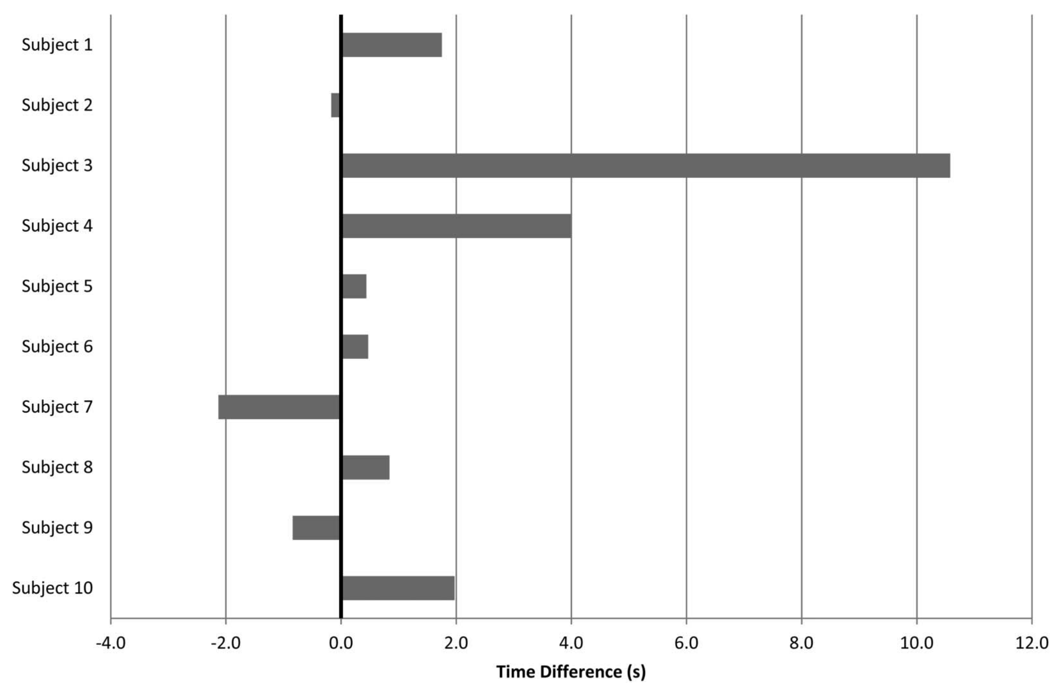

Figure 2. Individual changes in completion time for the 4-km time trial. A positive time difference indicates that the subject was faster after the conditioning warm-up than the moderate warm-up.

high-intensity conditioning contractions and a 4-km time trial.

Subjects were asked to refrain from alcohol and caffeine on the day of any sessions, not to have eaten 2 hours beforehand or undertaken any strenuous exercise in the preceding 24 hours. The 2 experimental sessions were conducted at approximately the same time of day (within 2 hours) for each subject under similar air-conditioned environmental conditions (19–22° C) within the Department of Sport and Exercise Science's Research Laboratory. The 2 ergometers used in the sessions were set up based on measurements the subjects supplied from their own bicycles, which were then replicated in subsequent sessions. Subjects also used their own shoes and preferred pedal type throughout.

The key-dependent variables measured during the 4-km trials were time, PO, and peak force per pedal stroke. Other physiological and perceptual markers of performance measured were $\dot{V}O_2$, volume of carbon dioxide expired ($\dot{V}CO_2$), blood lactate concentration ($[La^-]_b$), heart rate (HR), ratings of perceived exertion (RPE) on a scale of 6–20 (4), and leg pain on a 1–10 scale (9).

Subjects

Ten healthy men aged 18-44 years old from regional cycling and triathlon clubs and teams were invited to participate, and they successfully completed this study, (mean ± *SD*; age 32.2 ± 10.7 years; stature 181.8 ± 7.5 cm; mass 71.7 ± 6.6 kg), which had previous faculty ethics committee approval from the University of Chester. All subjects signed informed consent documents prior to participation in the study. The subjects were well-trained endurance cyclists, experienced at time trials and competing in open regional, national, and international age-group races ($\dot{V}O_2$max 65.3 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$; training volume 8.4 ± 2.6 $h \cdot wk^{-1}$; training experience 8.2 ± 6.0 years). All subjects gave written informed consent before their participation. Before each exercise session subjects completed a health screening questionnaire and received a detailed explanation of the session, along with instruction on how to interpret and use the RPE and leg pain scales.

Procedures

Baseline Test. A graded incremental cycling test was performed on an electronically braked ergometer (Lode Excalibur Sport; Lode BV, Groningen, Netherlands). Cycling commenced at 120 W at a self-selected cadence and was increased by 30 W every 3 minutes until volitional exhaustion. $[La^-]_b$ was measured in the final 30 seconds of each stage using a finger-tip blood sample (Lactate Pro II; Arkay, Kyoto, Japan), together with the subject's RPE. Pulmonary gas exchange was measured using an online gas analysis system (Oxycon Pro; Viasys Healthcare, Hochenberg, Germany), which was calibrated automatically before the test with ambient air, humidity readings, and gases of known concentrations. $\dot{V}O_2$ was measured breath-by-breath and averaged over each 30-second epoch. $\dot{V}O_2$max was determined as the largest of the averaged values recorded and in accordance with the British Association of Sport and Exercise Sciences criteria (40). The $\dot{V}O_2$ for each stage was defined as the average $\dot{V}O_2$ recorded in the final minute. Lactate threshold was determined as the PO when $[La^-]_b$

Table 2. Physiological measures for the 4 km after the moderate-intensity warm-up (MW) and the conditioning warm-up (CW).*

	MW, mean ± *SD*	CW, mean ± *SD*	Difference of mean values, 90% (CI: LL to UL)	Effect size 90% (CI: LL to UL)	Effect size Class
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	57.7 ± 5.3	59.1 ± 5.1†	1.4 (0.5 to 2.4)†	0.28 (0.08 to 0.42)	Small
$\dot{V}CO_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	66.5 ± 6.3	65.3 ± 5.1	−1.2 (−2.6 to 0.3)	0.21 (−0.04 to 0.42)	Small
RER	1.15 ± 0.54	1.11 ± 0.05†	−0.05 (−0.06 to −0.03)†	0.92 (0.59 to 1.08)	Moderate
Heart rate ($b \cdot min^{-1}$)	168.7 ± 10.1	172.7 ± 9.8†	4.0 (2.1 to 5.9)†	0.40 (0.19 to 0.54)	Small
Blood lactate at rest ($mmol \cdot L^{-1}$)	1.3 ± 0.5	1.2 ± 0.4	0.1 (0.2 to 0.4)	0.14 (−0.34 to 0.63)	Trivial
Blood lactate 1 min pre-exercise ($mmol \cdot L^{-1}$)	1.1 ± 0.3	4.9 ± 1.4†	3.7 (3.0 to 4.5)†	3.81 (2.75 to 4.21)	Very large
Blood lactate at completion ($mmol \cdot L^{-1}$)	17.1 ± 3.8	15.6 ± 3.1	−1.5 (−3.1 to 0.1)	0.43 (−0.02 to 0.81)	Small

*Values are mean values over the 4-km trials, unless stated. Effect sizes were determined using the pooled *SD*.
†Statistically significant difference ($p \leq 0.05$).

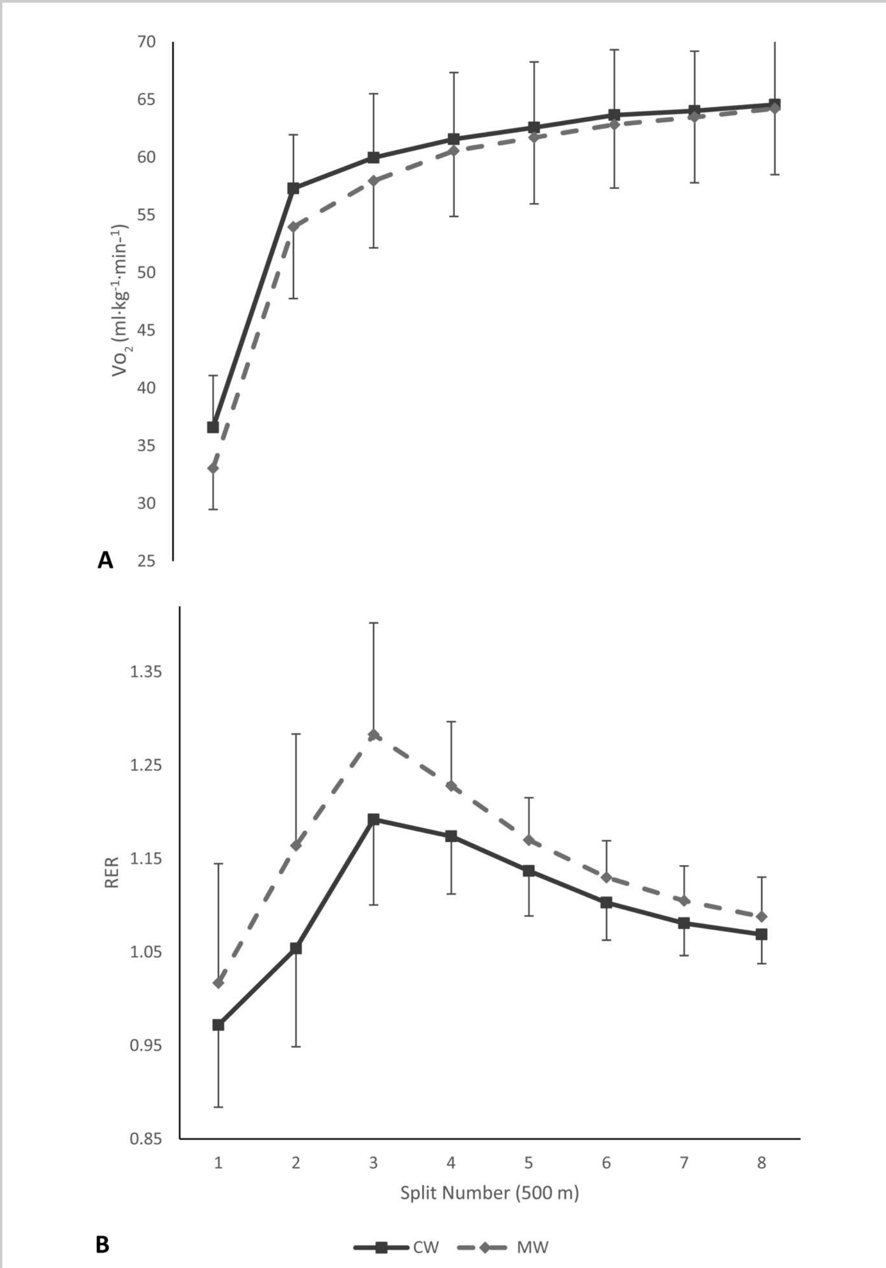

Figure 3. Changes in (A) oxygen uptake and (B) RER for each 500-m split of the 4-km time trials. Differences ($p \leq 0.05$) were due to the main effects of condition, split number, and their interactions. Plot values are mean ± *SD*.

exceeded 1.0 mmol·L^{-1} above baseline values (10). Power output at 60% of $\dot{V}O_2$max was determined using linear interpolation of the PO during of the 2 stages, eliciting $\dot{V}O_2$ closest to 60% of the measured $\dot{V}O_2$max. This was checked to confirm it was below the lactate threshold for each subject and hence in the moderate-intensity domain (26).

After a rest of approximately 30 minutes, 2 maximum power cycling tests were performed on a Wattbike Pro cycle ergometer (Wattbike Ltd., Nottingham, United Kingdom). The Wattbike has been shown to be reliable when used by trained cyclists with a CV of 1.8% at 300 W (18). After a brief warm-up, the subjects performed two 6-second sprints separated by approximately 5 minutes. Peak power (PP) was recorded as the maximum PO reached during the 2 attempts. A value equating to 70% of PP was then recorded for use in the later experimental trials to invoke a PAP-inducing near maximal voluntary contraction (37).

Familiarization Trial. The familiarization trial was conducted after the baseline tests and followed the same procedure as the CW experimental trial (described below), with the exception of allowing the subject to adjust the resistance setting of the Wattbike during the first half of the trial to allow for a self-selected preferred cadence for this duration of trial. The setting used for the second half of the trial was noted and applied for that subject's later experimental trials.

Experimental Trials. During each experimental trial, the subject completed either a moderate-intensity warm-up (MW) or CW on the Lode ergometer followed by a 5-minute passive recovery and a 4-km time trial on the Wattbike Pro. Warm-up intensities were fixed using the cadence independent hyperbolic mode of the Lode ergometer. Moderate-intensity warm-up consisted of a 6.5-minute cycle at the PO calculated to elicit 60% $\dot{V}O_2$max. CW consisted of a 5-minute cycle at the same PO eliciting 60% $\dot{V}O_2$max, immediately followed by 3 bouts of 10 seconds at a power equal to 70% PP, with 30 seconds passive recovery between bouts (Figure 1). Subjects were instructed to remain seated and aim for a slow cadence of 60 r·min^{-1} for the 10-second bouts so as to attain a series of near maximal voluntary contractions, and their usual preferred cadence at other times. After 5 minutes of passive recovery, subjects were instructed to perform the 4-km time trial as if it were a race by completing the distance in the shortest possible time, using the drop handlebar position. The resistance setting selected during familiarization was used during the 4-km trials to allow for the subjects who preferred cadence (103.6 ± 2.5 $r \cdot min^{-1}$). No adjustments were allowed during the experimental trials. Subjects were asked not to vary their approach to pacing between the experimental trials. All instantaneous details of speed, power, time, and cadence were withheld from the subjects to minimize self-pacing cues. Subjects were verbally informed of their elapsed distance after each 500 m so as to avoid misjudging the end of the test. Nonspecific verbal encouragement was given throughout. $[La^-]_b$ was taken from finger-tip samples at rest, 60 seconds before the start of, and 15 seconds after completing the trial. After each km of the 4-km trial, the subject was asked to indicate their RPE and leg pain. Heart rates were recorded using a chest strap (Polar Electro Oy, Kempele, Finland) and breath-by-breath pulmonary gas exchange throughout the 4-km trial. The Wattbike Pro calculated distance and recorded time, power, cadence, and force dynamics for each pedal revolution throughout the trials. Split times for each 500 m were computed from the Wattbike Pro data using custom-built spreadsheets in Microsoft Excel 2013 (Microsoft Corp., Redmond, WA, USA) and interpolation of the elapsed times of pedal strokes. Force, PO, $\dot{V}O_2$, $\dot{V}CO_2$, and HR were also computed using custom spreadsheets to extract data for each 500-m split.

Statistical Analyses

Descriptive statistics (mean ± *SD*) were calculated for each dependent variable across each trial. The normality of distributions of the dependent variables was confirmed using the Shapiro-Wilk statistic, and inferential statistics were used to test the main research hypotheses. Specifically, paired sample *t* tests were used to assess differences between the trials because of the condition type (MW/CW) for the following variables: completion time, PO, peak force per pedal stroke, $\dot{V}O_2$, $\dot{V}CO_2$, RER, HR, resting $[La^-]_b$, $[La^-]_b$ 60 seconds before the start of the trials, and $[La^-]_b$ 15 seconds after completion of the trials. Two-way repeated-measures ANOVA were performed to assess the variability of the mean scores because of condition type (MW/CW) and distance (1-km splits over 4 levels for RPE and leg pain, 500-m splits over 8 levels for completion time, PO, peak force per pedal stroke, $\dot{V}O_2$, $\dot{V}CO_2$, RER, HR). Sphericity was checked with Mauchly's test and accounted for where necessary using the Greenhouse-Geisser adjustment. Paired sample *t* tests were used post hoc where appropriate on pair-wise conditions. Statistical significance was set at $p \leq 0.05$ throughout, with Bonferroni corrections where appropriate. Analysis was performed using SPSS v.21 (IBM Corp., Armonk, NY, USA). Effect sizes (ESs) ± 90% confidence intervals were calculated by dividing the mean of the differences due to the conditions by the pooled *SD* from the trials and classified as trivial <0.2; small <0.6; moderate <1.2; large <2.0; very large ≥2.0 (19).

Results

It was observed that CW led to a small but nonsignificant ($p > 0.05$) reduction in completion time of 1.7 ± 3.5 seconds over the 4-km time trial (Table 1), and small but nonsignificant increases in mean PO (5.1 ± 10.5 W) and mean peak force per pedal stroke (5.7 ± 11.0 N). Figure 2 shows the individual responses to the conditioning warm-up in terms of completion times with 7 of 10 subjects completing the 4-km trial faster after CW. The physiological measures taken over the 4-km time trials are shown in Table 2. Mean $\dot{V}O_2$ was significantly elevated after CW compared with MW by 1.4 ± 1.6 $ml \cdot kg^{-1} \cdot min^{-1}$, as was HR by 4.0 ± 3.3 $b \cdot min^{-1}$, while RER decreased significantly by 0.05 ± 0.02. A very

Table 3. Perceptual ratings for each kilometer split after the moderate-intensity warm-up (MW) and the conditioning warm-up (CW).*†

Split	Measure	MW, mean ± *SD*	CW, mean ± *SD*	Difference of mean values, 90% (CI: LL to UL)	Effect size 90% (CI: LL to UL)	Effect size Class
km 1	RPE	15.2 ± 1.3	15.5 ± 1.2	0.3 (−0.4 to 1.0)	0.24 (−0.26 to 0.68)	Small
	Leg pain	5.5 ± 0.8	5.8 ± 0.9	0.3 (−0.4 to 0.9)	0.29 (−0.46 to 1.02)	Small
km 2	RPE	16.4 ± 1.6	17.4 ± 0.5	1.0 (0.2 to 1.8)	0.80 (0.10 to 1.05)	Moderate
	Leg pain	6.3 ± 0.7	6.4 ± 1.1	0.1 (−0.3 to 0.5)	0.11 (−0.47 to 0.74)	Trivial
km 3	RPE	17.9 ± 1.3	18.5 ± 0.7	0.6 (−0.1 to 1.3)	0.57 (−0.09 to 0.95)	Small
	Leg pain	7.1 ± 1.2	7.1 ± 1.2	0.1 (−0.3 to 0.4)	0.04 (−0.24 to 0.32)	Trivial
km 4	RPE	19.5 ± 0.7	19.7 ± 0.5	0.2 (0.0 to 0.4)	0.33 (−0.06 to 0.57)	Small
	Leg pain	7.8 ± 1.5	7.9 ± 1.3	0.1 (−0.3 to 0.4)	0.04 (−0.22 to 0.28)	Trivial

*No statistically significant differences ($p > 0.05$).
†Values are mean values over the each kilometer split during the trials, unless stated. Effect sizes were determined using the pooled *SD*.

Table 4. Differences in performance and physiological variables during the first 1,500 m after the moderate-intensity warm-up (MW) and the conditioning warm-up (CW).*

	MW, mean ± *SD*	CW, mean ± *SD*	Difference of mean values, 90% (CI: LL to UL)	Effect size 90% (CI: LL to UL)	Effect size Class
Time to 1,500 m (s)	114.3 ± 5.1	113.1 ± 4.2	−1.2 (−2.7 to 0.3)	0.26 (−0.1 to 0.5)	Small
Power output (W)	393.6 ± 48.1	404.1 ± 43.9	10.4 (−2.8 to 23.7)	0.23 (−0.1 to 0.5)	Small
Peak force per pedal stroke (N)	335.8 ± 34.5	340.2 ± 30.8	4.4 (−3.9 to 12.7)	0.14 (−0.1 to 0.3)	Trivial
$\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	48.4 ± 5.5	51.7 ± 4.7†	3.3 (1.9 to 4.7)†	0.97 (0.5 to 1.2)	Moderate
RER	1.18 ± 0.11	1.09 ± 0.09†	−0.09 (−0.12 to −0.05)†	0.81 (0.4 to 1.0)	Moderate

*Power output and peak force per pedal stroke are mean values over the initial 1,500 m. Effect sizes were determined using the pooled *SD*.
†Significant difference ($p \leq 0.05$).

large significant increase in $[La^-]_b$ was seen after CW compared with MW of 3.7 ± 1.4 $mmol \cdot L^{-1}$ 60 seconds before the start of the 4-km trials; however, on completion, the difference had been reversed (−1.5 ± 2.7 $mmol \cdot L^{-1}$).

For the 500-m splits no significant ($p > 0.05$) interactions between split and warm-up condition for time, power, peak pedal forces, or HR were observed. ANOVA of expired gases did reveal significant ($p < 0.01$) split × warm-up condition interactions for both $\dot{V}O_2$ and RER but no significant interaction effect including $\dot{V}CO_2$ ($p > 0.05$). As can be seen in Figure 3, $\dot{V}O_2$ rose at a faster rate while RER was suppressed after CW. Post hoc analysis of the first three 500-m splits revealed significant increases in $\dot{V}O_2$ during splits 2 and 3 ($p < 0.017$), and decreases in RER during splits 1, 2, and 3 ($p < 0.017$). Although notable and expected increases in both RPE and leg pain scores were evident as the time trial progressed (Table 3), no significant interactions of condition and 1-km splits were observed.

Post hoc analysis of time, power, peak pedal forces, $\dot{V}O_2$, and RER were undertaken on the first 1,500 m of the trials as the greatest differences in performance were seen during the initial stages after the warm-up conditions (Table 4). Although a small difference in time to 1,500 m (1.2 ± 1.5 seconds), and a small increase in mean power (10.4 ± 13.3 W) between the trials were detected over this initial period, the differences were not significant.

Discussion

The main hypothesis for the study was that the conditioning warm-up would improve completion time, PO, and peak forces during the 4-km time trials. Although mean completion time was reduced by 1.7 seconds, mean PO by 5.1 W, and mean peak force by 5.7 N, the results did not attain statistical significance. The mean increase in PO after CW, however, did exceed the 5-W increase suggested to show a true increase in trained cyclists on a Wattbike (18). Although the ESs of these improvements are small, they are substantial in relation to competition events and surpass the gold medal race winning margins of less than 0.5 seconds in both the 2014 and 2015 4-km individual pursuit World Championships. Similarly, the performance differences due to the warm-ups tended to be greatest over the initial 1,500 m of the trials and accounted for 1.2 seconds of the overall mean reduction in time. However, it is unclear if the peak forces applied to the pedals during each pedal stroke were responsible per se, or whether the increased forces necessary to generate the additional power were distributed through the pedal stroke.

The high-intensity, heavy-resistance conditioning contractions performed in CW were intended to elicit PAP in the muscles used in the pedalling action. Similar to a number of other studies (1,11,16,33) the magnitude of PAP was not directly measured after the complex actions; however, the presence of the potentiating effect is assumed due to the near maximal voluntary contractions undertaken (12,35,37). Notwithstanding the nonsignificance of the improvements found in this study, the effects of CW are similar to the findings of other studies in short endurance events designed to invoke PAP which have shown performance improvements in rowing (11), swimming (16,33), and running (1). Where split times have been considered during the trials (11,16), the improvements in time and power have been more pronounced during the earlier splits, supporting the proposition by Sale (30) that any muscle activity will induce PAP, and that once initiated in an endurance event the effects of PAP would be ongoing owing to the exercise itself. The neuromuscular effects of PAP include increased calcium sensitivity of the myosin light chain (36), possibly explaining increases in power after conditioning contractions. While a small increase in power was found in this study after CW, changes to the peak force per pedal stroke were less clear. As PAP also modifies muscle twitch properties by increasing the

RFD (12,17), reducing time to peak torque (12,22), and reducing half-relaxation time (12), potentially it yields higher forces being generated sooner and distributed over a greater portion of the pedal stroke rather than increasing peak forces.

The effectiveness of the CW in this study seemed to be individualistic despite the subjects being of similar fitness, training background, and standard. While training status (14) and muscle fiber type (15,28) have been shown to influence the effects of PAP and fatigue (7,27), there is no method of accurately quantifying their interaction on the balance of these opposing effects. The magnitude of the PAP effect was not measured by electromyography in this study and doing so in future studies could help maximize the positive effects of PAP on an individual basis, and help control the parameters of the balance of PAP and fatigue. The rest interval between the PAP inducement and exercise trial is critical to this balance and as a number of different rest periods from 2 to 18 minutes have been trialled for different activities with varying results (39), it would seem that optimization on an individual basis by trial and error is needed to ensure performance improvements.

While the current performance changes observed after CW were suggestive of PAP, they were accompanied by changes in the physiological measures of $\dot{V}O_2$, HR, RER, and $[La^-]_b$, which also offer a potential explanation for the changes. A moderate elevation of $[La^-]_b$ has been linked with an improvement in subsequent endurance performance (6,21,25,38), possibly inducing a protection against fatigue (21). Despite an increase in $[La^-]_b$, Burnley et al. (6) found a performance reduction after 30 seconds of sprinting before a short cycling time trial. However, while the high-intensity sprint warm-up produced similar metabolic responses, the high cadences are unlikely to have elicited a similar PAP response as this study. The particular early stage increase in $\dot{V}O_2$ in this study mirrors that in many studies exhibiting improved performance after effective prior exercise (5,8,13,25) and would seem to be a highly desirable effect of a high-intensity warm-up. It has also been speculated that increased muscle temperature may be associated with changes in oxygen kinetics (5); however, the measurement of muscle temperature was beyond the scope of this study. This relationship between $\dot{V}O_2$ and PAP is opposite to that reported by Barnes et al. (1) who found a lower oxygen cost after PAP-inducement in submaximal exercise. It is possible that this discrepancy reflects the differences in intensity at which $\dot{V}O_2$ was measured, with the supramaximal exercise in this study eliciting $\dot{V}O_2$ values at or very close to each person's $\dot{V}O_2max$.

Accompanying the elevated $\dot{V}O_2$ after CW was a reduced $\dot{V}CO_2$ and a moderate reduction in RER, both in the first 1,500 m and throughout the 4-km time trial, together with a lower $[La^-]_b$ on completion of the 4-km time trial, suggesting a reduced reliance on energy derived from anaerobic pathways (34). It is somewhat surprising that a more noticeable difference in PO was not evident rather than the apparent sparing of anaerobic resources. Quantifying the anaerobic contribution cannot be done by measurement, and calculations of the anaerobic contribution in supramaximal exercise contain major sources of error (25), hence the inferences about anaerobic contribution in this study are drawn from pulmonary gas exchanges and the $[La^-]_b$ measurements previously mentioned. It is possible that pacing cues and effort perception prevented any uprating of PO during either trial until the final seconds regardless of remaining anaerobic capacity. Adherence to a preferred pacing strategy along with measures of RPE and leg pain that increased throughout each trial may have restricted the raising of PO more so than the availability of anaerobic resources. Instantaneous performance measures were withheld from the subjects; however, the sound from the airbrake of the Wattbike offered continuous feedback of any change of cadence or power. This feedback could also have influenced pacing and consequently the anaerobic contribution, particularly in the latter stages of the trial as the subject's focus may have been on maintaining cadence rather than increasing it.

The effect of this high-intensity heavy-resistance conditioning warm-up is similar to the effects found in other warm-up routines that have included PAP-inducing contractions (11,16,33), and those that have associated performance improvement with metabolic factors after high-intensity warm-ups or repeated sprints (13,21,25). Whether PAP can be used to complement existing routines, in order to enhance both the neuromuscular and metabolic responses, and so compound performance improvements warrants further research. Investigations into complex warm-up routines incorporating PAP should also look at the individual responses to the PAP-fatigue balance and recovery times.

Practical Applications

This study indicates that a warm-up routine that includes PAP-inducing conditioning contractions can have a beneficial and worthwhile effect on cycling performance. The study also emphasizes the need for coaches and athletes to optimize the balance of PAP and fatigue, by variation of recovery and work intervals on an individual basis. As the effects tended to be greatest over the first 1,500 m (or approximately 80 seconds), the inclusion of conditioning contractions alongside a traditional metabolic warm-up would be most beneficial in the short-duration endurance track racing of 4 km or less, such as the individual pursuit or "kilo." The high-intensity, heavy-resistance efforts can be reproduced using readily available turbo-trainers meaning that all athletes can easily implement the protocol immediately after competition.

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References

1. Barnes, KR, Hopkins, WG, McGuigan, MR, and Kilding, AE. Warm-up with a weighted vest improves running performance via leg stiffness and running economy. *J Sci Med Sport* 18: 103–108, 2015.
2. Batista, MA, Ugrinowitsch, C, Roschel, H, Lotufo, R, Ricard, MD, and Tricoli, VA. Intermittent exercise as a conditioning activity to induce postactivation potentiation. *J Strength Cond Res* 21: 837–840, 2007.
3. Bishop, D. Warm up II: Performance changes following active warm up and how to structure the warm up. *Sports Med* 33: 483–498, 2003.
4. Borg, G. The Borg RPE Scale. In: *Borg's Perceived Exertion and Pain Scales.* Champaign, IL: Human Kinetics, 1998. pp. 29–31.
5. Burnley, M, Doust, JH, Carter, H, and Jones, AM. Effects of prior exercise and recovery duration on oxygen uptake kinetics during heavy exercise in humans. *Exp Physiol* 86: 417–425, 2001.
6. Burnley, M, Doust, JH, and Jones, AM. Effects of prior warm-up regime on severe-intensity cycling performance. *Med Sci Sports Exerc* 37: 838–845, 2005.
7. Chiu, LZ, Fry, AC, Weiss, LW, Schilling, BK, Brown, LE, and Smith, SL. Postactivation potentiation response in athletic and recreationally trained individuals. *J Strength Cond Res* 17: 671–677, 2003.
8. Christensen, PM and Bangsbo, J. Warm-up strategy and high-intensity endurance performance in trained cyclists. *Int J Sports Physiol Perform* 10: 353–360, 2015.
9. Cook, DB, O'Connor, PJ, Oliver, SE, and Lee, Y. Sex differences in naturally occurring leg muscle pain and exertion during maximal cycle ergometry. *Int J Neurosci* 95: 183–202, 1998.
10. Coyle, EF, Coggan, AR, Hemmert, MK, and Walters, TJ. Glycogen usage and performance relative to lactate threshold. *Med Sci Sports Exerc* 16: 120–121, 1984.
11. Feros, SA, Young, WB, Rice, AJ, and Talpey, SW. The effect of including a series of isometric conditioning contractions to the rowing warm-up on 1,000-m rowing ergometer time trial performance. *J Strength Cond Res* 26: 3326–3334, 2012.
12. Gago, P, Arndt, A, Tarassova, O, and Ekblom, MM. Post activation potentiation can be induced without impairing tendon stiffness. *Eur J Appl Physiol* 114: 2299–2308, 2014.
13. Hajoglou, A, Foster, C, De Koning, JJ, Lucia, A, Kernozek, TW, and Porcari, JP. Effect of warm-up on cycle time trial performance. *Med Sci Sports Exerc* 37: 1608–1614, 2005.
14. Hamada, T, Sale, DG, and Macdougall, JD. Postactivation potentiation in endurance-trained male athletes. *Med Sci Sports Exerc* 32: 403–411, 2000.
15. Hamada, T, Sale, DG, MacDougall, JD, and Tarnopolsky, MA. Interaction of fibre type, potentiation and fatigue in human knee extensor muscles. *Acta Physiol Scand* 178: 165–173, 2003.
16. Hancock, AP, Sparks, KE, and Kullman, EL. Postactivation potentiation enhances swim performance in collegiate swimmers. *J Strength Cond Res* 29: 912–917, 2015.
17. Hodgson, M, Docherty, D, and Robbins, D. Post-activation potentiation: Underlying physiology and implications for motor performance. *Sports Med* 35: 585–595, 2005.
18. Hopker, J, Myers, S, Jobson, SA, Bruce, W, and Passfield, L. Validity and reliability of the Wattbike cycle ergometer. *Int J Sports Med* 31: 731–736, 2010.
19. Hopkins, WG, Marshall, SW, Batterham, AM, and Hanin, J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.
20. Jeukendrup, AE, Craig, NP, and Hawley, JA. The bioenergetics of world class cycling. *J Sci Med Sport* 3: 414–433, 2000.
21. Jones, AM, Wilkerson, DP, Burnley, M, and Koppo, K. Prior heavy exercise enhances performance during subsequent perimaximal exercise. *Med Sci Sports Exerc* 35: 2085–2092, 2003.
22. Jubeau, M, Gondin, J, Martin, A, Van Hoecke, J, and Maffiuletti, NA. Differences in twitch potentiation between voluntary and stimulated quadriceps contractions of equal intensity. *Scand J Med Sci Sports* 20: e56–e62, 2010.
23. Levine, RJ, Kensler, RW, Yang, Z, Stull, JT, and Sweeney, HL. Myosin light chain phosphorylation affects the structure of rabbit skeletal muscle thick filaments. *Biophys J* 71: 898–907, 1996.
24. Needham, RA, Morse, CI, and Degens, H. The acute effect of different warm-up protocols on anaerobic performance in elite youth soccer players. *J Strength Cond Res* 23: 2614–2620, 2009.
25. Palmer, CD, Jones, AM, Kennedy, GJ, and Cotter, JD. Effects of prior heavy exercise on energy supply and 4000-m cycling performance. *Med Sci Sports Exerc* 41: 221–229, 2009.
26. Poole, DC and Richardson, RS. Determinants of oxygen uptake. Implications for exercise testing. *Sports Med* 24: 308–320, 1997.
27. Rassier, DE and Macintosh, BR. Coexistence of potentiation and fatigue in skeletal muscle. *Braz J Med Biol Res* 33: 499–508, 2000.
28. Ryder, JW, Lau, KS, Kamm, KE, and Stull, JT. Enhanced skeletal muscle contraction with myosin light chain phosphorylation by a calmodulin-sensing kinase. *J Biol Chem* 282: 20447–20454, 2007.
29. Sale, DG. Postactivation potentiation: Role in human performance. *Exerc Sport Sci Rev* 30: 138–143, 2002.
30. Sale, D. Postactivation potentiation: Role in performance. *Br J Sports Med* 38: 386–387, 2004.
31. Sargeant, AJ and Dolan, P. Effect of prior exercise on maximal short-term power output in humans. *J Appl Physiol (1985)* 63: 1475–1480, 1987.
32. Sargeant, AJ, Hoinville, E, and Young, A. Maximum leg force and power output during short-term dynamic exercise. *J Appl Physiol Respir Environ Exerc Physiol* 51: 1175–1182, 1981.
33. Sarramian, VG, Turner, AN, and Greenhalgh, AK. Effect of postactivation potentiation on fifty-meter freestyle in national swimmers. *J Strength Cond Res* 29: 1003–1009, 2015.
34. Spriet, LL, Howlett, RA, and Heigenhauser, GJ. An enzymatic approach to lactate production in human skeletal muscle during exercise. *Med Sci Sports Exerc* 32: 756–763, 2000.
35. Tillin, NA and Bishop, D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med* 39: 147–166, 2009.
36. Vandenboom, R, Grange, RW, and Houston, ME. Threshold for force potentiation associated with skeletal myosin phosphorylation. *Am J Physiol* 265: C1456–C1462, 1993.
37. Vandervoort, AA, Quinlan, J, and McComas, AJ. Twitch potentiation after voluntary contraction. *Exp Neurol* 81: 141–152, 1983.
38. Wilkerson, DP, Koppo, K, Barstow, TJ, and Jones, AM. Effect of prior multiple-sprint exercise on pulmonary O2 uptake kinetics following the onset of perimaximal exercise. *J Appl Physiol (1985)* 97: 1227–1236, 2004.
39. Wilson, JM, Duncan, NM, Marin, PJ, Brown, LE, Loenneke, JP, Wilson, SM, Jo, E, Lowery, RP, and Ugrinowitsch, C. Meta-analysis of postactivation potentiation and power: Effects of conditioning activity, volume, gender, rest periods, and training status. *J Strength Cond Res* 27: 854–859, 2013.
40. Winter, EM, British Association of Sport, and Exercise Sciences. Part Three: General Procedures. In: *Sport and Exercise Physiology Testing Guidelines: The British Association of Sport and Exercise Sciences Guide.* London, United Kingdom: Routledge, 2007. pp. 61–138.