Less is more: standard warm-up causes fatigue and less warm-up permits greater cycling power output

Elias K. Tomaras and Brian R. MacIntosh

Human Performance Laboratory, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada

Submitted 28 February 2011; accepted in final form 3 May 2011

WARM-UP (WU) is a precompetition routine that most, if not all, competitive athletes perform, and this ritual is generally meant to enhance the immediately following athletic performance. Although WU is a common practice, little is known about how an athlete should warm up (3). Although there are several potential benefits of a WU, little is known of the optimal procedure that would allow the best preparation for a given event. Some of the proposed benefits of WU are as follows: increased muscle temperature (25), accelerated oxygen uptake kinetics (11), increased anaerobic metabolism (9), and postactivation potentiation (PAP) of the muscles (24).

Although WU is a common precompetition routine, little attention has been paid to the potential adverse effects of an improperly designed WU protocol. Specifically, prior activity (i.e., WU) has the potential to result in fatigue, as well as enhanced athletic performance, by any of the previously mentioned mechanisms. The relative magnitude of enhancing and fatiguing mechanisms will dictate the net outcome in terms of contractile response and, possibly, athletic performance.

After any exercise, muscle contractile response can be decreased by fatigue or enhanced by PAP. PAP putatively occurs when the prior exercise includes a high-intensity component (24) and is thought to be a consequence of regulatory light chain phosphorylation (14). A great deal is known about the mechanism of PAP from animal models (15), but there is little conclusive proof that PAP can enhance athletic performance. It has recently been confirmed in an animal model that prior activity can enhance the peak isometric force and isotonic power of very brief contractions obtained with high-frequency stimulation (18). This observation supports the hypothesis put forward by Sale (24) that activity-dependent potentiation can enhance brief maximal-effort contractions. However, this has not been demonstrated for voluntary contractions obtained when PAP was known to be present. PAP occurs after voluntary exertion and can be identified as an enhanced twitch response that dissipates over a 5-min period of relative inactivity.

Previous studies concerned with WU have reported performance enhancements following a WU containing high-intensity exercise and have attributed these enhancements to PAP (7, 8, 10, 12). It is important to note that although a performance enhancement has been observed, these studies have not measured PAP; they only infer that PAP resulted in the differences in performance. Another flaw of this research is that the mere practice of the task in the pretest may be the reason for the enhanced posttest performance. Familiarization sessions to minimize the impact of learning on test performance are also important.

For measurement of PAP, a muscle’s contractile response following some activity must be compared with that obtained prior to the activity. For comparison of a muscle’s “before” and “after” response, a specific electrical stimulation is used to elicit the contractile response (16). This method of eliciting contractile response permits the central nervous system (CNS) to be bypassed and measures the muscle output for a given stimulation. Motivation and CNS drive are removed as modifiers of muscle force output (2).

It is well accepted that an athlete’s ability to generate and maintain a high peak power output (PPO) is critical to sprint performance, and this performance is hindered by muscular fatigue (6). It is therefore tremendously important that the appropriate balance between enhancement and impairment of performance is found. The purpose of this research was to compare a traditional WU for a 200-m sprint in a track cycling competition with an experimental WU that was designed to be shorter and less intense and to examine the fatigue and cycling performance after traditional and experimental WU as measured by electrically elicited twitch contractions and the 30-s
Table 1. Traditional warm-up protocol

<table>
<thead>
<tr>
<th>Time, min:s</th>
<th>Classification</th>
<th>Gear Ratio</th>
<th>Instruction</th>
</tr>
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<tbody>
<tr>
<td>0:00–4:00</td>
<td>General warm-up</td>
<td>46:16</td>
<td>60% HRmax*</td>
</tr>
<tr>
<td>4:00–8:00</td>
<td></td>
<td></td>
<td>65% HRmax</td>
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<tr>
<td>8:00–12:00</td>
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<td></td>
<td>70% HRmax</td>
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<tr>
<td>12:00–16:00</td>
<td></td>
<td></td>
<td>75% HRmax</td>
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<tr>
<td>16:00–18:00</td>
<td></td>
<td></td>
<td>80% HRmax</td>
</tr>
<tr>
<td>18:00–20:00</td>
<td>Acceleration sprint</td>
<td></td>
<td>Accelerate from 80 to 95% HRmax</td>
</tr>
<tr>
<td>20:00–20:06</td>
<td>Sprint</td>
<td></td>
<td>6-s sprint</td>
</tr>
<tr>
<td>20:06–21:30</td>
<td>Recovery</td>
<td></td>
<td>Cycle lightly, as if preparing to stop on track</td>
</tr>
<tr>
<td>21:30–23:00</td>
<td>Rest</td>
<td>46:16</td>
<td>Sitting comfortably on chair</td>
</tr>
<tr>
<td>23:00–30:00</td>
<td>Acceleration sprint</td>
<td>48:14</td>
<td>Progressively accelerate from 0 to 35 km/h over 600-m distance, followed by 6-s sprint</td>
</tr>
<tr>
<td>30:00–31:30</td>
<td>Recovery</td>
<td></td>
<td>Cycle lightly, as if preparing to stop on track</td>
</tr>
<tr>
<td>31:30–38:00</td>
<td>Rest</td>
<td></td>
<td>Sitting comfortably on chair</td>
</tr>
<tr>
<td>38:00–40:00</td>
<td>Acceleration sprint</td>
<td>48:14</td>
<td>Progressively accelerate from 0 to 35 km/h over 600-m distance, followed by 6-s sprint</td>
</tr>
<tr>
<td>40:00–41:30</td>
<td>Recovery</td>
<td></td>
<td>Cycle lightly, as if preparing to stop on track</td>
</tr>
<tr>
<td>41:30–48:00</td>
<td>Rest</td>
<td></td>
<td>Sitting comfortably on chair</td>
</tr>
<tr>
<td>48:00–50:00</td>
<td>Acceleration sprint</td>
<td>48:14</td>
<td>Progressively accelerate from 0 to 35 km/h over 600-m distance, followed by 6-s sprint</td>
</tr>
<tr>
<td>50:00–51:30</td>
<td>Recovery</td>
<td></td>
<td>Cycle lightly, as if preparing to stop on track</td>
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</table>

*Based on self-reported maximal heart rate (HRmax).

Wingate test, respectively. It was hypothesized that the traditional WU would result in a significant degree of muscular fatigue and impair Wingate test performance compared with the experimental WU. A secondary hypothesis was that PAP would be evident after the experimental WU.

METHODS

Subjects. Ten highly trained male track cyclists (77.9 ± 7.2 kg body wt, 180.6 ± 7.6 cm height, 33.5 ± 9.1 yr old) were recruited from the Calgary Track Cycling League. Subjects self-reported no neuromuscular or musculoskeletal injuries, nor were they consuming performance-enhancing substances. To provide an appropriate fit for the Velotron Dynafit Pro (Racermate, Seattle, WA) and SRM (Schoberer Rad Messtechnik, Jülich, Germany) cycle ergometers, each subject was asked to measure saddle-to-handlebar and saddle-to-pedal distance on his track bike. These settings were recorded and used for all testing sessions. Subjects were asked to refrain from participation in strenuous physical activity for 24 h and consumption of caffeine for 12 h, alcoholic beverages for 24 h, and food for 2 h prior to testing. All subjects provided informed written consent to participate in the experimental procedure, and all procedures were approved by the University of Calgary Conjoint Health Research Ethics Board.

Design. The study was divided into two parts, each evaluating specific consequences of the same two WU procedures, administered in random order. Part 1 allowed evaluation of the twitch active force of the quadriceps muscles before and after the two WU procedures. After each of these sessions, subjects completed a brief acceleration to allow calculation of optimal cadence (OC) and were required to complete a practice all-out 30-s cycling test (Wingate test) to become familiarized with the effort and sensations associated with the test. In part 2, 9 of the 10 subjects completed a Wingate test 12.5 min after each WU in random order; during the test, PPO, total work, and fatigue were measured. A 12.5-min rest period was used, because the coaches and athletes consulted for the design of this project indicated an average of 10–15 min between WU and time of competition.

To compare a traditional track cycling WU protocol with an experimental WU that could be utilized in further studies, the traditional and experimental WU needed to be designed in such a way that they were reproducible, quantifiable, and sensitive to individual performance capabilities. To design a traditional WU protocol that accurately reflected current practice in preparation for a flying 200-m time trial, national-level track cycling coaches and athletes were consulted, and consensus was obtained. The traditional WU protocol was therefore assumed to be an accurate representation of a track cyclist’s actual WU. The experimental WU protocol was designed to be similar to the traditional WU but shorter in duration and with less overall intensity. Details of the procedures for the traditional and experimental WU are presented in Tables 1 and 2 and briefly described below.

The traditional WU required continuous cycling at a progressively increasing intensity over 20 min. Cyclists were instructed to gradually increase from 60% to 95% of their self-reported maximal heart rate (HRmax). This general WU was followed immediately by a progressive acceleration over 600 m (i.e., equivalent to 1.5 laps of a 400-m velodrome) and a 6-s sprint. After the 6-s sprint, a 1.5-min active recovery was permitted at very low intensity (subjects were instructed to cycle lightly, as if preparing to stop on the track). This active recovery was followed by a 6.5-min rest period, during which the subject sat on a chair. The subject then performed three additional accelerations with 6-s sprints and the same 1.5-min recovery and 6.5-min rest between sprints. The gear ratio was 46:16 for the general WU and the first two of the four 6-s sprints. The last two accelerations and 6-s sprints were performed with a larger (48:14) gear ratio. It was reported by participants that these are typical gear selections for a traditional track cyclist WU.

The experimental WU protocol utilized a general WU similar to the traditional WU, except the subject progressively increased intensity for only 15.5 min and ended at a lower intensity (Table 2). The

Table 2. Experimental warm-up protocol

<table>
<thead>
<tr>
<th>Time, min:s</th>
<th>Classification</th>
<th>Gear Ratio</th>
<th>Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00–5:00</td>
<td>General warm-up</td>
<td>46:16</td>
<td>60% HRmax*</td>
</tr>
<tr>
<td>5:00–10:00</td>
<td></td>
<td></td>
<td>65% HRmax</td>
</tr>
<tr>
<td>10:00–15:00</td>
<td></td>
<td></td>
<td>70% HRmax</td>
</tr>
<tr>
<td>15:00–15:30</td>
<td>Acceleration</td>
<td></td>
<td>Progressively accelerate to 35 km/h</td>
</tr>
<tr>
<td>15:30–15:36</td>
<td>Sprint</td>
<td>48:14</td>
<td>6-s sprint</td>
</tr>
<tr>
<td>15:36–17:00</td>
<td>Recovery</td>
<td></td>
<td>Cycle lightly, as if preparing to stop on track</td>
</tr>
</tbody>
</table>

*Based on self-reported HRmax.
general WU was immediately followed by one acceleration and 6-s sprint identical to those performed in the traditional WU. The gear ratio was 46:16 for the duration of the experimental WU protocol.

Measuring power output. The SRM cycle ergometer was used for the performance measurements (i.e., 30-s Wingate test). SRM cranks (172.5 mm long), containing strain gauges at the hub, were calibrated according to the manufacturer’s instructions prior to each testing session. Data were collected at 10 Hz and downloaded directly from the PowerControl IV unit.

Optimal cadence. To determine the cadence associated with the highest power output (OC) for each subject, the SRM cycle ergometer was used to perform an acceleration test during part 1 of the study. Each subject was allowed a 1-min lead-in at a cadence of 50 rpm, ensuring that he did not pedal harder than 150 W. At the end of the 1-min lead-in, on the command “Go!”, the subject rapidly accelerated all-out for 8 s against only an inertial load with no limit to cadence. The 8-s duration of the test allowed the subject to pedal from 50 rpm to a cadence corresponding to an angular velocity well above his OC, which was subsequently determined by linear regression (17). The linear torque-angular velocity relationship yields a parabolic power-angular velocity relationship, with the apex of the relationship at a cadence corresponding to half the maximal velocity (half of the intercept on the abscissa). The Wingate tests were conducted at the cadence that was determined to be optimal for each subject.

Temperature. Skin and ambient temperature were measured for the total duration of each testing session in part 2 to see if differences in performance were related to differences in muscle temperature. As mentioned above, muscle temperature can have a significant impact on sprint performance. Skin temperature was measured with a sensor placed on the anterior thigh at the midpoint between the patella and inguinal crease. Neoprene insulation was placed over the sensor to insulate it from the air. It was assumed that this sensor provided an indication of changes in muscle temperature during WU (5). Ambient temperature was recorded 1 m from the subject to ensure that the surrounding temperature was not different between trials. Skin and ambient temperatures were recorded using the NeXus-10/BioTrace+ (version 1.16) Wireless Biofeedback System (Mindmedia, Roermond-Herten, The Netherlands).

Contractile response. A custom-designed dynamometer was used to measure the contractile response of the quadriceps muscle group for electrically elicited isometric knee extension before and after WU. An isokinetic dynamometer (System 3, Biodex Medical Systems, Shirley, NY) was retrofitted with a steel plate attached to the base of the Biodex chair. A force transducer [load cell (model 2150, Vishay Intertechnology, Malvern, PA)] was attached to the steel plate. A cuff and karabiner were used to attach the subject’s ankle to the transducer. The Biodex leg and shoulder straps were used to firmly secure the subject’s chest and legs to the dynamometer chair, limiting mobility and preventing extraneous movements from contributing to the measured twitch responses. The leg was aligned so that the ankle was directly below the knee, and the transducer measured force perpendicular to the Shank. The moment arm was measured from the apparent axis of rotation at the knee to the level of the attachment of the ankle cuff to the force transducer. Twitch torque was calculated as measured force (N) multiplied by moment arm (m).

Rubberized carbon electrodes were taped to the skin over the femoral nerve in the inguinal area and at the gluteal fold, similar to the method described by Kooistra et al. (13). A single pulse (200 μs, 300 V) and supramaximal current (model DSTAFF, Digitimer, Welwyn Garden City, UK) were used for electrical stimulation. For determination of supramaximal current, the current was progressively increased until the twitch amplitude no longer increased. After the determination of supramaximal current, three twitch contractions were electrically elicited with a ≥15-s rest period between twitch. The contractile response of these three twitch contractions was averaged and assumed to be representative of a resting contractile response. This was assumed to be the current necessary to activate all motor units beneath the carbon electrode. Subjects were told they could limit the increase in current if the stimulation became uncomfortable, but no subjects asked for the current to be limited. Resting contractile measurements of an isometric knee extension twitch were recorded prior to any activity done by the subject. After establishing a resting contractile response, the subject performed, in a randomized order, traditional or experimental WU. Twitch contractions were again elicited 30 s after WU and continued every minute for 30 min. Only data measured at rest and 1, 5, 10, 15, 20, 25, and 30 min were statistically analyzed to minimize type II error. The 6.5-min rest periods during the traditional WU allowed assessment of the impact of the added sprints during this WU. Three twitch contractions were elicited at 1-min intervals, beginning 30 s after the active recovery between sprints. Peak active torque (PAT) was measured as the difference between peak torque and resting torque for all twitch contractions.

Wingate tests. The SRM cycle ergometer was used for the isokinetic 30-s Wingate tests. Subjects were asked to remain seated for the duration of the test. A 1-min lead-in while cycling at 80% of OC was used for all Wingate tests. During the 1-min lead-in, subjects were instructed not to pedal harder than 150 W to limit premature fatigue before the Wingate test. At the end of the 1-min lead-in, on the command “Go!”, the subject rapidly accelerated all-out until they reached their predetermined OC, and cycle ergometer software limited the cadence at this level. The subjects continued to cycle all-out at their OC for the remainder of the 30-s test. Wingate test performance measures included PPO (mean of highest 2.5-s period), total work, and fatigue index (mean of last 5-s period/PPO × 100). The torque-angular velocity relationship during the acceleration phase of the Wingate tests was compared to see if there was evidence of fatigue early in the Wingate test. Fatigue will cause a shift to the left (downward) in this relationship, indicating a lower OC, and lower power at each cadence during the acceleration (6, 17). After the Wingate test, subjects had an active recovery (60 rpm, unloaded) for 20 min.

Blood lactate. Blood lactate concentration was measured using a hand-held analyzer (Lactate Pro LT-1710, Arkray, Kyoto, Japan). The fingertip was cleaned with alcohol and gauze to reduce the risk of infection; then the skin was punctured with a lancet device, and a blood sample was collected. Blood lactate concentration was measured six times for each test session in part 2: at rest, 1 min prior to the Wingate test, and 2, 5, 8, and 20 min after the Wingate test during active recovery. These blood lactate concentrations allowed us to compare the consequences of any differences in intensity during the WU and identify differences resulting from the Wingate tests.

Urine specific gravity. Urine specific gravity (USG) was measured using a clinical hand-held refractometer (SUr-Ne, Atago, Tokyo, Japan) that was calibrated against distilled water prior to each testing session. Urine samples were collected and analyzed immediately prior to testing. USG is a commonly used and reliable measure of hydration status (1). Subjects were told whether their USG indicated that they were hypohydrated (USG <1.020 g/ml) or hyperhydrated (USG >1.020 g/ml). Subjects were encouraged (or not) to consume water accordingly. This was done to limit the influence of hydration status on performance. In part 2, USG was >1.020 g/ml in two subjects in the experimental WU condition and four subjects in the traditional WU condition. In no subject was USG <1.005 g/ml.

Statistics. Values are means ± SE, and all data were analyzed using SPSS analysis software version 15.0. Linear regression was performed on torque-angular velocity data to determine OC. A two-factor repeated-measures ANOVA was used to determine whether there was a significant treatment × time interaction for the following: 1) contractile response measurements at 1, 5, 10, 15, 20, 25, and 30 min, 2) blood lactate measurements at rest, 1 min before the Wingate test, and 2, 5, 8, and 20 min after the Wingate test, and 3) skin temperature at the beginning of WU, the end of WU, immediately prior to the Wingate test lead-in, the time of PPO during the Wingate
test, the end of the Wingate test, and the end of the active recovery. It is important to note that contractile response measurements were obtained every minute from 1 to 30 min, but only measurements obtained at 1, 5, 10, 15, 20, 25, and 30 min were analyzed for significant interaction. Analysis of fewer time points allows greater power in the statistical evaluation. When a significant interaction was indicated by ANOVA, specific differences between treatments were identified with paired t-tests. Such an interaction was found with the skin temperature data, and, as a result, one-a-way ANOVA and Tukey’s post hoc test were used to determine which time points were different from one another within each treatment.

Paired t-tests were used to determine if a difference existed between WU conditions for PPO, total work, fatigue index, and HRmax during the Wingate test. Paired t-tests were also used to determine if a difference existed between reported HRmax and the highest measured heart rate for each individual, as well as between the USG measurements in experimental and traditional WU.

RESULTS

In parts 1 and 2, subjects were instructed to follow strict intensity targets for a portion of the WU protocol, and this was monitored by measurement of heart rate and power output (Fig. 1). Heart rates during experimental and traditional WU were close to targets during testing. Subjects reached $74 \pm 0.8\%$ HRmax during the experimental WU and $94 \pm 0.8\%$ HRmax during the traditional WU prior to the acceleration and first sprint. There was no significant difference ($P = 0.197$) between heart rate reached during the Wingate test after experimental and traditional WU ($184 \pm 2.5$ and $181 \pm 3.6$ beats/min, respectively). In part 1, the twitch contractile responses were measured before and after experimental and traditional WU. Prior to WU, there was no difference ($P = 0.806$) in electrically elicited twitch contractile response between experimental and traditional WU ($53.6 \pm 4.7$ and $52.2 \pm 5.2$ N-m, respectively).

In the traditional WU protocol, there were a total of four 6-s sprints. Twitch contractions were obtained at 1-min intervals after each sprint (for just 3 min after the first 3 sprints). Figure 2 presents the PAT of these postsprint twitch contractions. PAT was significantly depressed relative to control measures after the first sprint (to 85.9%) and did not change significantly with the next three sprints (to 85.1% and 83.6% of resting values).

PAT during the recovery period following each WU is shown in Fig. 3. There was a significant treatment $\times$ time interaction ($P = 0.047$) in PAT. PAT after experimental WU was significantly different from that after traditional WU at 1, 10, and 15 min. PAT after traditional WU was significantly less than that before WU at all times, but only at 5, 25, and 30 min after experimental WU. PAT at 12 min (30 s prior to the beginning of the Wingate test in part 2) was $85.8 \pm 3.4\%$ and $95.7 \pm 2.6\%$ of PAT measured prior to traditional and experimental WU, respectively. In no case was there direct evidence of PAP (PAT greater than that prior to WU), but the decreasing PAT immediately following each vigorous effort (Figs. 2 and 3) is consistent with relative PAP. This is a time when PAT

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Fig. 1. Mean percent maximal heart rate (HRmax) and power output. HRmax and power output can be used as measures of intensity of exercise. Note differences in duration between experimental warm-up (EWU) and traditional WU (TWU). Exercise intensity is clearly higher during the general phase of the traditional warm-up (WU). %HRmax at the time of the Wingate test was not significantly different between WU conditions ($P = 0.197$).

Fig. 2. Peak active torque relative to pre-WU peak active torque during the traditional WU. Peak active torque was measured at 1-min intervals after each 6-s sprint. Time 0 represents the end of each sprint. Values are means $\pm$ SE ($n = 10$ subjects).

Fig. 3. Peak active torque relative to pre-WU peak active torque after experimental and traditional WU. Peak active torque was measured at 1-min intervals after the final sprint of each WU. *Significant difference between traditional and experimental WU ($P < 0.05$). $\xi$Significantly different from pre-WU ($P < 0.05$). Horizontal dashed line represents pre-WU active torque.
Results for PPO, total work, and fatigue index are presented in Table 3. PPO was significantly greater after experimental than traditional WU ($P < 0.01$). Total work was also significantly greater after experimental WU ($P < 0.01$). There was no significant difference in fatigue index ($P = 0.728$) between experimental and traditional WU, reflecting a similar relative decrease in power output from PPO to the end of the test for both WU conditions. Figure 5 illustrates Wingate test performance for experimental and traditional WU.

There were no significant differences in resting blood lactate concentration between experimental and traditional WU ($1.4 \pm 0.1$ and $1.1 \pm 0.1$ mmol/L, respectively). Blood lactate values obtained after the WU and during the recovery period after the Wingate tests are shown in Figure 6. Blood lactate concentration increased as a consequence of the WU and increased further during the Wingate tests. A significant treatment × time interaction ($P < 0.01$) in blood lactate concentration was observed, indicating that the pattern of change over time was different between treatments. Blood lactate concentration was higher after traditional than experimental WU.

At 1 min prior to initiation of the lead-in to the Wingate test, there was still a significant difference in blood lactate concentration between WU conditions ($P < 0.01$). After each Wingate test, blood lactate concentration reached the highest value, then decreased toward the resting value. Other than the 5-min measurement (Fig. 6), there were no significant differences in blood lactate concentration between conditions during this recovery period.

![Fig. 4. Individual peak active torque samples after experimental and traditional WU. Data for subjects 4 and 6 are presented relative to pre-WU peak active torque to illustrate individual variability in response to experimental and traditional WU. In experimental WU, subject 6 demonstrated a small postactivation potentiation (PAP) followed by a decline in twitch amplitude to the pre-WU value. This was followed by an interesting rebound (delayed PAP). While subject 4 demonstrates a similar trend in contractile response to experimental WU (decline followed by rebound), the values are depressed throughout the recovery period. However, in both cases, peak active torque following traditional WU was more depressed than that following experimental WU. These observations highlight individual differences in reaction to WU. Horizontal dashed line represents pre-WU active torque.](http://jap.physiology.org/)

![Fig. 5. Mean power for 30-s Wingate tests after experimental and traditional WU. Peak power output and total work were greater after experimental than traditional WU. Fatigue indexes were not significantly different between experimental and traditional WU because of a similar decrease in power output from peak to the end of the test. Values are means ± SE ($n = 9$ subjects).](http://jap.physiology.org/)

![Fig. 6. Blood lactate after WU and after the Wingate test. Data are presented for rest (prior to WU), 1 min prior to the Wingate test, and 2, 5, 8, and 20 min after the Wingate test during the active recovery. There was significant interaction ($P < 0.01$) and a significant difference ($*P < 0.01$) between experimental and traditional WU at 1 min before and 5 min after the Wingate test. Values are means ± SE ($n = 9$ subjects).](http://jap.physiology.org/)
Skin temperature was monitored throughout the trials in part 2 (Fig. 7). Statistical comparison between treatments was limited to the following times: prior to and after the WU, immediately prior to the Wingate test, and immediately after the Wingate test. There was no significant treatment × time interaction ($P = 0.264$) and no treatment effect ($P = 0.261$). There was a significant time effect ($P < 0.001$). Skin temperature at the beginning of the WU was significantly different ($P < 0.01$) from that at the other time points. Although there was a difference in the time course of change in temperature, there was no difference between treatments at the times analyzed. This would indicate that any differences in performance could not be attributed to temperature effects.

**DISCUSSION**

The intent of this study was to examine the contractile response and performance in a Wingate test following a traditional WU for a 200-m sprint in a track cycling competition and a shorter, lower-intensity experimental WU. With WU, we would expect to see an increase in PAT as a result of elevated muscle temperature and, possibly, PAP. However, fatigue encountered during the WU could negate these positive influences. It was hypothesized that the traditional WU would elicit a significant degree of fatigue, given its long duration and multiple all-out efforts. It was also hypothesized that the experimental WU would permit better performance in a Wingate test and would elicit PAP.

The first hypothesis was confirmed by contractile response measurements of electrically elicited twitch contractions in part 1; PAT significantly decreased from pre-WU values to the time when measurements were obtained after traditional WU. The lower values for PAT, indicating fatigue, were maintained throughout the 30-min recovery, during which most athletes would be performing their competitive event. PAT also decreased after experimental WU, despite the fact that the experimental WU was designed to effect less fatigue than the traditional WU. This indicates that a shorter WU than we have evaluated may be even better than the experimental WU completed in this study. Less is more!

There was some evidence of PAP in these contractile measurements. PAT is expected to be enhanced following high-effort voluntary activity (24) if PAP is present. However, fatigue can mask PAP (16, 23). Our measurements indicate that, over the 3 min immediately following the sprint in the experimental WU, PAT was decreasing. Even after the first sprint of the traditional WU, PAT declines. During this time, active force of muscle contraction should increase due to recovery, if fatigue was the only consequence of the prior activation. The declining PAT is evidence that PAP was present (18) and was dissipating over a time course that is consistent with dephosphorylation of the regulatory light chains of myosin. Regulatory light chain phosphorylation is assumed to be the primary mechanism of PAP (14, 20, 22). Although some recovery would also have occurred over the first few minutes after the sprint effort, the dissipation of PAP, bringing PAT to well below the pre-WU value, reveals that a substantial magnitude of fatigue had resulted from the sprint efforts and, perhaps, also from the relatively high-intensity traditional WU. Surprisingly, this pattern was also evident after the experimental WU. However, in this case, the additional recovery after the dissipation of PAP resulted in less obvious fatigue and, in some cases, a subsequent rebound in PAT to values above the pre-WU level (Fig. 4).

An important finding from part 1 was that the contractile responses at 10 and 15 min after the traditional WU were diminished below that observed prior to WU. This was not the case after the experimental WU. The time of these measurements corresponds to the initiation of the 30-s Wingate test (12.5 min) after WU in part 2. The PPO and total work were lower during the Wingate test after the traditional WU than after the experimental WU. It is reasonable to conclude that the cause of impaired performance following the traditional WU is a greater level of fatigue, as indicated by the contractile measurements in part 1.

The traditional WU resulted in greater fatigue than the experimental WU, presumably as a result of the longer duration and higher intensity of this protocol and the greater number of sprint efforts in the WU. The evidence for this conclusion is that the elevated PAT after the first sprint during the traditional WU was less than PAT at the end of the experimental WU. Furthermore, PAT decreased further as the subjects performed additional sprints, such that there was a substantial deficit by the time the WU was completed. This deficit persists at least until the Wingate test was completed.

Several measures confirm that the traditional WU was more intense than the experimental WU. During the traditional WU, subjects achieved higher average power output at a higher average heart rate than during the experimental WU. Blood lactate concentration at 1 min prior to the Wingate test was higher after traditional than experimental WU. The higher blood lactate concentration indicates that more of the traditional WU was conducted using nonaerobic metabolism. It has been suggested that the amount of work that can be done using nonaerobic energy is finite (4, 19, 21). The recovery time needed to permit full restitution of this energy supply is not known. The change in blood lactate concentration during the Wingate test was greater following the experimental than
traditional WU, suggesting that nonaerobic metabolism contributed more during the Wingate test following the experimental than traditional WU. This greater anaerobic contribution probably accounts for the extra work and higher power output achieved after the experimental WU and may be a consequence of more complete restoration of this energy supply following the WU.

This research provides an argument against the traditional “more is better” WU concept that is adopted by many competitive athletes. A WU that is performed at an intensity that is too high for longer than necessary can result in fatigue and impair subsequent athletic performance. Similarly, the effort to take advantage of PAP might actually cause more fatigue and impair subsequent performance. The reality is that track cycling competition involves multiple performances within the same day. If WU results in fatigue of an athlete and impairs performance in a single subsequent bout of exercise, what impact would it have on multiple performances required on the same day? Furthermore, what are the consequences of the exercise done during the cool-down? These are important questions for future research in the area of WU and cool-down and their effects on athletic performance.

This study highlighted the individual responses of athletes to various WU procedures (Fig. 4). The individual data are from two of the best (and similar) Wingate performances (i.e., highest PPO and total work), yet the responses to WU differed substantially. One athlete demonstrated clear PAP and the other a significant attenuation in contractile response. These observations suggest that competitive athletes require individually customized WU protocols to suit their needs and abilities. While previous studies have intended to elicit PAP (using a high-intensity conditioning exercise) and demonstrate an improved performance as a result, few have actually measured the contractile response prior to and following a standardized WU using electrically elicited twitch contractions. This study demonstrates that to fully understand and quantify the effect of PAP, one must take into consideration that track cycling competition involves multiple efforts within a day and, also, the effects of WU and cool-down on these multiple performances.

**ACKNOWLEDGMENTS**

The authors thank the athletes who reported to the laboratory on several occasions, prepared to follow our instructions, receive repeated stimulation to their thighs, and give their best effort. The authors also thank Mike Patton, Tanya Dubincoff, Kurt Innes, and Laura Milne for assistance in the development of this project.

**GRANTS**

This research was supported by the Natural Sciences and Engineering Research Council.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

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