Less is More: Standard Warm-up Causes Fatigue and Less Warm-up Permits Greater Cycling Power Output

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Running title: Standard Warm-up Impairs Cycling Power Output
Abstract

The traditional warm-up (WU) athletes use to prepare for a sprint track cycling event involves a general WU followed by a series of brief sprints lasting at least 50 min in total. A WU of this duration and intensity could cause significant fatigue and impair subsequent performance. The purpose of this research was to compare a traditional WU to an experimental WU and examine the consequences of these on the 30 s Wingate test and electrically elicited twitch contractions. The traditional WU began with 20 min of cycling with a gradual intensity increase from 60% to 95% of maximal heart rate (HRmax). Following this, there were 4 sprints at 8 min intervals. The experimental WU was shorter with less high intensity exercise. Intensity increased from 60% to 70% HRmax over 15 min, and this was followed with just 1 sprint. The Wingate test was conducted with a 1 min lead-in at 80% of optimal cadence (OC), followed by a Wingate test at OC. Peak active twitch torque, after the traditional WU (86.5 ± 3.3 %) was significantly lower (p<0.05) than that after experimental WU (94.6 ± 2.4 %) when expressed as % of preWU amplitude. Wingate performance after experimental WU (PPO=1390 ± 80 W; Work=29.1 ± 1.2 kJ) was significantly better (p<0.01) than after traditional WU (PPO=1303 ± 89 W; Work=27.7 ± 1.2 kJ). The traditional track cyclists’ WU results in significant fatigue which corresponds with impaired peak power output. A shorter and lower intensity WU permits a better performance.

Keywords: muscle fatigue, postactivation potentiation, human performance, optimal cadence
Introduction

Warm-up (WU) is a pre-competition routine that most, if not all competitive athletes perform, and this ritual is generally meant to enhance the immediately following athletic performance. Despite how common a practice WU is, little is known about how an athlete should WU (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: 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 pre-competition 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 to enhance 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.

Following 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 about whether or not 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
This observation supports the hypothesis put forward by Sale (24) that activity dependent potentiation can enhance brief maximal effort contractions. However, to date this has not been demonstrated for voluntary contractions obtained during a time 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 five 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 observed differences in performance. Another flaw of this research is that the mere practice of the task in the pretest may be the reason the posttest performance was enhanced. It is also important to have familiarization sessions to minimize the impact of learning on test performance.

In order to measure PAP, a muscle’s contractile response following some activity must be compared to that obtained prior to the activity. To compare 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 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 to an experimental WU, designed to be shorter and less intense, and examine the fatigue and cycling performance after both as measured by electrically elicited twitch contractions and the 30 s Wingate test, respectively. It was hypothesized that traditional WU would result in a significant degree of muscular fatigue and impair Wingate test performance compared to experimental WU. A secondary hypothesis was that PAP would be evident after the experimental WU.

Methods

Subjects

Ten highly-trained male track cyclists (weight 77.9±7.2 kg, height 180.6±7.6 cm, age 33.5±9.1 years) were recruited from the Calgary Track Cycling League. Subjects self-reported that they had no neuromuscular or musculoskeletal injuries nor were they consuming performance-enhancing substances. To provide an appropriate fit for the Velotron Dynafit Pro (Racermate Inc, Seattle, WA, USA) and SRM (Schoberer Rad Messtechnik, Jülich, Germany) cycle ergometers, subjects were asked to measure saddle to handlebar and saddle to pedal distance on their track bike. These settings were recorded and were used for all testing sessions. Subjects were asked to refrain from the following: strenuous physical activity for 24 hours, consuming caffeine for 12 hours, consuming alcoholic beverages for 24 hours, and eating for 2 hours 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

This 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 prior to 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 this test. In Part 2, nine of the ten subjects completed a Wingate test 12.5 min after each WU in random order, during which 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 time of 10-15 min between warm-up and time of competition.

In order to compare a traditional track cycling WU protocol to an experimental WU that could be utilized in further studies, the traditional WU 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 each of these are presented in Table 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 where the subject sat on a chair. The subject then performed 3 additional accelerations with 6 s sprints and the same 1.5 min recovery and 6.5 min rest between sprints. The gearing 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 that the subject progressively increased intensity for only 15.5 min and ended at a lower intensity (see Table 2). The general WU was immediately followed by one acceleration and 6 s sprint identical to those performed in the traditional WU. The gearing was 46/16 for the entire duration of the experimental WU protocol.

Measuring Power Output

The SRM cycle ergometer was used for the performance measurements in this study (i.e., 30 s Wingate test). SRM cranks (172.5 mm length), containing strain gauges at the hub, were calibrated according to manufacturer 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, an acceleration test was performed, during Part 1 of this study, using the SRM cycle ergometer. Each subject was allowed a 1 min lead-in at a cadence of 50 rpm ensuring not to pedal any 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 their 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 earlier, muscle temperature can have a significant impact on sprint performance. Skin temperature was measured, with a sensor placed on the anterior thigh at the mid-point, between the patella and inguinal crease. Neoprene insulation was placed over the sensor to insulate 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+ (V1.16) Wireless Biofeedback System (Mindmedia BV, Roermond-Herten, 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. A Biodex system 3 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA) was retrofitted with a steel plate attached to the base of the Biodex chair. A force transducer (Load Cell - Model 2150; Vishay Intertechnology Inc, Malvern, PA, USA) was attached to the steel plate. The subject’s ankle was attached to the transducer using a cuff and karabiner. The subject’s chest and legs were then firmly secured to the dynamometer chair using the Biodex leg and shoulder straps, limiting mobility and preventing extraneous movements from contributing to the measured twitch responses. Their 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 Kooistra et al. (13). Electrical stimulation was with single pulse (200 µs, 300 V) and supramaximal current (Digitimer model DS7AH, Digitimer Ltd, Welvyn Garden City, UK). Supramaximal current was determined by progressively increasing the current until the twitch amplitude no longer increased. After the determination of supramaximal current, three twitch contractions were electrically elicited with at least a 15 s rest period.
between twitches. The contractile response of these 3 twitch contractions were 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 either traditional WU or experimental WU. Twitch contractions were again elicited 30 s after warm-up and continued every minute for 30 min. Only resting, 1, 5, 10, 15, 20, 25, and 30 min were statistically analyzed. This was done to minimize type II error. The 6.5 min rest periods during the traditional warm-up allowed the assessment of the impact of the added sprints during this warm-up. 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 in this study. During the 1 min lead-in, subjects were instructed not to pedal any 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 x 100). The torque-angular velocity relationship during the
acceleration phase of the Wingate tests were compared to see if there was evidence of fatigue early in the Wingate test. Fatigue will cause a shift to the left (down) 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 ([Bla]) was measured using a hand-held analyzer (Lactate Pro LT-1710, Arkray KDK, Kyoto, Japan). The finger-tip was cleaned with alcohol and gauze to reduce the risk of infection. The skin of a finger-tip was punctured with a lancet device and a blood sample was collected. [Bla] measurements were made at 6 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 [Bla] measurements 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 an Atago SUr-Ne clinical hand-held refractometer, (Atago Co. Ltd, Tokyo, Japan) which 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 or not their USG indicated they were hypohydrated (USG > 1.020 g·ml⁻¹) or hyperhydrated (USG < 1.005 g·ml⁻¹) and were encouraged (or not) to consume water accordingly. This was done to limit the influence of hydration status on performance. In Part 2,
two subjects in the experimental WU condition and four in the traditional WU condition had USG measurements >1.020 g·ml⁻¹. No subjects had a USG < 1.005 g·ml⁻¹.

Statistics

Results are expressed as mean ± standard error of the mean and all data were analyzed using SPSS analysis software V15.0. Linear regression was performed on torque-angular velocity data to determine OC. A two-factor repeated-measures analysis of variance (ANOVA) was used to determine whether or not there was a significant treatment x time interaction for the following: 1) contractile response measurements at only 1, 5, 10, 15, 20, 25, and 30 min, 2) blood lactate measurements at rest, 1 min pre-Wingate, and 2, 5, 8, and 20 min post-Wingate test, and 3) skin temperature at the beginning of WU, the end of WU, immediately prior to the Wingate test lead-in, at the time of PPO during 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 1-30 min but only 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, a one-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 HR for
each individual, as well as between the USG measurements in experimental WU and traditional WU conditions.

Results

In Part 1 and 2 of this study, 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 (see Figure 1). HRs during experimental WU and traditional WU were close to targets during testing. Subjects reached 74 ± 0.8 % HRmax during the experimental WU and 94 ± 0.8 % HRmax during the traditional WU prior to the acceleration and first sprint. There was no significant difference (p=0.197) between HR reached during the Wingate test after experimental WU (184 ± 2.5 bpm) and traditional WU (181 ± 3.6 bpm). In Part 1, the twitch contractile responses were measured before and after the two WUs. Prior to WU, there was no difference (p=0.806) in electrically elicited twitch contractile response between experimental WU and traditional WU (53.6 ± 4.7 and 52.2 ± 5.2 Nm respectively).

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

The PAT during the recovery period following each WU is shown in Figure 3. There was a significant treatment x time interaction (p=0.047) in PAT. PAT following Experimental WU was significantly different from that after traditional WU at 1, 10, and 15 min after WU. The
PAT measured after the traditional WU was significantly less than pre-WU PAT at all times evaluated, but only at 5, 25 and 30 min after experimental WU. The PAT at 12 min (30 s prior to the time of the beginning of the Wingate test in Part 2) was 85.8 ± 3.4% and 95.7 ± 2.6% of PAT values measured prior to the WU for traditional WU 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 (Figure 2 and 3) is consistent with relative PAP. This is a time when PAT should increase due to recovery from fatigue but the dissipation of PAP is decreasing the contractile response.

Although in most cases, the pattern of change in PAT was similar between subjects, (PAT decreased then increased to a plateau level) there were substantial differences between individuals for magnitude of contractile response following both the experimental WU and the traditional WU. An example illustrating such differences in magnitude can be seen in Figure 4. Generally, there is an early decrease in PAT following WU to minimal levels at approximately 4-5 min. This decline is followed by a steady increase until PAT reaches a plateau around 12-15 min.

Results for: PPO, total work and fatigue index are presented in Table 3. There was significantly greater PPO after the experimental WU compared to traditional WU condition (p<0.01). Total work was also significantly greater after the experimental WU (p<0.01). There was no significant difference in fatigue index (p=0.728) between WU conditions, 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 both WU conditions.
There were no significant differences in resting [Bla] between experimental WU (1.4 ± 0.1 mmol·L⁻¹) and traditional WU (1.1 ± 0.1 mmol·L⁻¹). Blood lactate values obtained after the WU and during the recovery period after the Wingate tests are shown in Figure 6. [Bla] increased as a consequence of the WU, and increased further during the Wingate tests. A significant treatment x time interaction (p<0.01) in [Bla] measurements was observed, indicating that the pattern of change over time was different between treatments. [Bla] was higher after the traditional WU than the experimental WU. 1 min prior to the initiation of the lead-in to the Wingate test, there was still a significant difference in [Bla] between WU conditions (p<0.01). Following each Wingate test, [Bla] reached the highest value, then decreased towards the resting value. Other than the 5 min measurement (see Figure 6), there were no significant differences in [Bla] between conditions during this recovery period.

Skin temperature was monitored throughout the trials in Part 2 (see Figure 7). Statistical comparison between treatments was limited to the following times: prior to and after the WU, immediately prior to the Wingate test and right after the Wingate test. There was no significant treatment x time interaction (p=0.264) and no treatment effect (p=0.261). There was a significant time effect (p<0.001). The skin temperature at the beginning of the WU was significantly different (p<0.01) from that at the remaining times analyzed. Note that although there was a difference in the time-course of change in temperature, at the times analyzed there was no difference between treatments. 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 preWU 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, a time period during which most athletes would be performing their competitive event. PAT also decreased after experimental WU in spite of 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. This is a time when 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). In
spite of the fact that some recovery would also have occurred over the first few min after the
sprint effort, the dissipation of PAP, bringing PAT to values well below the preWU 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 preWU level (see Figure 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 correspond 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 due to 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 would have been completed.
There are several measures that 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 compared to the experimental WU. The higher Wingate test was higher after the traditional WU compared to the experimental WU. The higher [Bla] indicates that more of the traditional WU was conducted using non-aerobic metabolism. It has been suggested that the amount of work that can be done using non-aerobic energy is finite (4, 19, 21). The recovery time needed to permit full restitution of this energy supply is not known. The change in [Bla] during the Wingate test was greater following the experimental WU than the traditional WU, suggesting that non-aerobic metabolism contributed more during the Wingate test following the experimental WU than following the 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 argument against the traditional “more is better” WU concept that is adopted by many competitive athletes. A WU that is performed at too high of an intensity 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. The individual data presented were for two of the best (and similar) Wingate performances (i.e., highest PPO and total work) within this study, yet their responses to WU differed substantially. One athlete demonstrated clear PAP, 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 in order to fully understand and quantify the effect of prior activity on a contractile response, the muscle needs to be tested in a way that bypasses the CNS. This allows the investigator to evaluate the contractile response for a given stimulation. If this study had only consisted of Part 2, with no concern for involuntary contractile response following WU, the improved performance with experimental WU could have been interpreted to suggest that experimental WU elicited PAP while traditional WU did not, neglecting the result that significant fatigue was present in both WU conditions. A further advantage of this study over other studies evaluating PAP is that the criterion performance (Wingate test) was familiar to the subjects, and was performed only once on a given day.

Conclusion

Track cyclists traditionally perform a WU prior to a 200 m sprint that results in significant muscular fatigue and has an adverse effect on short-term all-out performance. In most
subjects, both WU conditions created substantial fatigue. The effects of such fatigue on the contractile response and ultimately the torque-angular velocity relationship diminished the potential benefits of increased muscle temperature and PAP. These negative effects were more evident after the traditional WU than after the experimental WU. Based on the observed impairment of peak power output, we conclude from this study that a shorter and lower intensity WU would benefit athletes competing in sprint track events in cycling. Individual responses to WU need to be taken into consideration when designing WU protocols for competitive athletes. Further work will need to be done to refine/optimize the WU to determine the conditions that yield the most benefit. Such work should take into consideration that track cycling competition involves multiple efforts within a day and needs to consider the effects of WU and cool-down on these multiple performances.
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Disclosures

The authors declare no conflict of interest.
References


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**Figure Legends**

**Figure 1 – Mean % HRmax and power output**

Both maximal heart rate (HRmax) and power output can be used as measures of intensity of exercise. Note the differences in duration between experimental (EWU) and traditional warm-up (TWU). There is also clearly more high intensity exercise during the general phase of the traditional WU. The % HRmax at the time of the Wingate test was not significantly different between warm-up conditions (p=0.197).

**Figure 2 – Peak active torque relative to preWU 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 mean ± SEM. n = 10 subjects.

**Figure 3 – Peak active torque relative to preWU (warm-up) peak active torque after experimental and traditional WU.**
Peak active torque was measured at 1 min intervals after the final sprint of each WU. Filled symbols in the graph represent the times for which statistical comparisons were made. Values are mean ± SEM. $n = 10$ subjects. *Significant difference between traditional (TWU) and experimental WU (EWU) ($p<0.05$). ζ Significantly different from preWU ($p<0.05$). The horizontal dashed line represents preWU active torque.

**Figure 4 – Individual peak active torque samples after experimental and traditional warm-up (WU).**

Data for these two subjects are presented relative to preWU peak active torque to illustrate individual variability in response to the two warm-up treatments. In the experimental WU (EWU) condition, subject 6 demonstrated a small postactivation potentiation (PAP) followed by a decline in twitch amplitude to the preWU 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 the traditional WU (TWU) was more depressed than that following the experimental WU. These observations highlight the individual differences in reaction to warm-up. The horizontal dashed line represents preWU active torque.

**Figure 5 – Mean power for 30 s Wingate tests after the experimental and traditional WU.**

Peak power output (PPO) and total work was greater after experimental WU (EWU) than traditional WU (TWU). Fatigue indices were not significantly different between warm-up conditions due to a similar decrease in power output from peak to the end of the test. Data presented as mean ± SEM of 9 subjects.
Figure 6 – Blood lactate after warm-up and after Wingate test.

Data presented are: rest (prior to warm-up), 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 warm-up (EWU) and traditional WU (TWU) conditions 1 min prior to the Wingate test and 5 min after. Values are mean ± SEM. 

n = 9 subjects.

Figure 7 – Mean skin temperature during Part 2 for experimental WU and traditional WU.

Skin temperature increased at the end of traditional warm-up (TWU) to a higher skin temperature than at the end of experimental WU (EWU). However, skin temperature decreased between 6 s sprints of the traditional WU until it reaches a skin temperature similar to that during experimental WU at the time of the Wingate test. Dashed line connects skin temperature at time of Wingate test.
Blood Lactate (mmol·L⁻¹) vs. Time (min)

**Wingate**

- ● EWU
- ■ TWU

**Recovery**

*Significant differences between EWU and TWU recovery phases.*
Table 1. *Traditional WU protocol.*

<table>
<thead>
<tr>
<th>Time (min:s)</th>
<th>Classification</th>
<th>Gear</th>
<th>Instruction</th>
</tr>
</thead>
<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>
</tr>
<tr>
<td>8:00-12:00</td>
<td></td>
<td></td>
<td>70 % HRmax</td>
</tr>
<tr>
<td>12:00-16:00</td>
<td></td>
<td></td>
<td>75 % HRmax</td>
</tr>
<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</td>
<td></td>
<td>Accelerate from 80-95 % 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>21:30-28:00</td>
<td>Rest</td>
<td></td>
<td>Sitting comfortably on chair</td>
</tr>
<tr>
<td>28:00-30:00</td>
<td>Acceleration</td>
<td>46/16</td>
<td>Progressively accelerate from 0-35 km·h⁻¹ over 600 m distance, followed by 6 s sprint</td>
</tr>
<tr>
<td></td>
<td>Sprint</td>
<td></td>
<td></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</td>
<td>48/14</td>
<td>Progressively accelerate from 0-35 km·h⁻¹ over 600 m distance, followed by 6 s sprint</td>
</tr>
<tr>
<td></td>
<td>Sprint</td>
<td></td>
<td></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</td>
<td>48/14</td>
<td>Progressively accelerate from 0-35 km·h⁻¹ over 600 m distance, followed by 6 s sprint</td>
</tr>
<tr>
<td></td>
<td>Sprint</td>
<td></td>
<td></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>
</tr>
</tbody>
</table>

* Based on self-reported maximal heart rate.
Table 2. *Experimental WU protocol.*

<table>
<thead>
<tr>
<th>Time (min:s)</th>
<th>Classification</th>
<th>Gear</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⁻¹</td>
</tr>
<tr>
<td>15:30-15:36</td>
<td>Sprint</td>
<td></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 maximal heart rate.
### Table 3. 30 s Wingate test peak power, total work, and fatigue index after experimental WU and traditional WU conditions.

<table>
<thead>
<tr>
<th></th>
<th>Experimental WU</th>
<th>Traditional WU</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak power (W)</td>
<td>*1390 ± 80</td>
<td>1303 ± 89</td>
<td>6.2 %</td>
</tr>
<tr>
<td>Total Work (kJ)</td>
<td>*29.1 ± 1.2</td>
<td>27.7 ± 1.2</td>
<td>5.0 %</td>
</tr>
<tr>
<td>Fatigue Index (%)</td>
<td>48 ± 2</td>
<td>49 ± 3</td>
<td>2.0 %</td>
</tr>
</tbody>
</table>

Values are mean ± SEM. *n = 9 subjects.* *Significantly different from traditional WU (p<0.01).