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ORIGINAL INVESTIGATION

Improvement of 800-m Running Performance With Prior High-Intensity Exercise

Stephen A. Ingham, Barry W. Fudge, Jamie S. Pringle, and Andrew M. Jones

Prior high-intensity exercise increases the oxidative energy contribution to subsequent exercise and may enhance exercise tolerance. The potential impact of a high-intensity warm-up on competitive performance, however, has not been investigated. ***Purpose****:* To test the hypothesis that a high-intensity warm-up would speed VO_2 kinetics and enhance 800-m running performance in well-trained athletes. ***Methods****:* Eleven highly trained middle-distance runners completed two 800-m time trials on separate days on an indoor track, preceded by 2 different warm-up procedures. The 800-m time trials were preceded by a 10-min self-paced jog and standardized mobility drills, followed by either 6 × 50-m strides (control [CON]) or 2 × 50-m strides and a continuous high-intensity 200-m run (HWU) at race pace. Blood [La] was measured before the time trials, and VO_2 was measured breath by breath throughout exercise. ***Results****:* 800-m time-trial performance was significantly faster after HWU (124.5 ± 8.3 vs CON, 125.7 ± 8.7 s, $P < .05$). Blood [La] was greater after HWU (3.6 ± 1.9 vs CON, 1.7 ± 0.8 mM; $P < .01$). The mean response time for VO_2 was not different between conditions (HWU, 27 ± 6 vs CON, 28 ± 7 s), but total O_2 consumed (HWU, 119 ± 18 vs CON, 109 ± 28 ml/kg, $P = .05$) and peak VO_2 attained (HWU, 4.21 ± 0.85 vs CON, 3.91 ± 0.63 L/min; $P = .08$) tended to be greater after HWU. ***Conclusions****:* These data indicate that a sustained high-intensity warm-up enhances 800-m time-trial performance in trained athletes.

Keywords*:* prior exercise, warm-up; priming, middle-distance running

Prior warm-up exercise is a ubiquitous feature of performance preparation in most competitive sports.[1] It is surprising, therefore, that relatively little research has focused on optimizing precompetition warm-up procedures.

It is now well known that prior high-intensity exercise (ie, heavy or severe exercise performed above the lactate threshold or gas-exchange threshold) profoundly alters the VO_2 response to subsequent high-intensity exercise.[2–5] Specifically, such priming exercise increases the amplitude of the fundamental component of VO_2 and reduces its subsequent slow component.[2–4,6,7] This results in an overall speeding of the VO_2 kinetics and thus a greater oxidative-energy contribution to the total energy transfer.[3,4,8] Studies investigating the physiological effects of priming exercise have typically employed a continuous period of high-intensity exercise,[2–4,7,9] but it has been shown that a single sprint[10,11] or a series of sprints[12] evokes similar changes to VO_2 kinetics during subsequent high-intensity exercise. VO_2 kinetics is not altered when high-intensity exercise is preceded by low-intensity exercise performed below the gas-exchange threshold.[3] The physiological mechanisms underpinning these effects remain unclear but likely include increased substrate availability, reduced oxidative metabolic inertia and increased muscle O_2 utilization, and changes to motor-unit recruitment patterns.[5]

An overall speeding of VO_2 kinetics during high-intensity exercise would be predicted to reduce the extent of intramuscular metabolic perturbation (ie, to blunt the reduction of phosphocreatine and the accumulation of inorganic phosphate and hydrogen ions) and retard the rate of fatigue development.[3,13–15] Consistent with this, it has been reported that prior high-intensity exercise can result in an enhanced exercise tolerance during subsequent high-intensity exercise, at least when the recovery interval between the priming exercise bout and the criterion exercise bout is ≥9 minutes.[16–18] The enhanced tolerance to high-intensity exercise after priming, which can amount to a 15% to 30% increase in time to exhaustion at a fixed high-intensity work rate,[16,17] suggests that effective priming might enhance performance during athletic competition. If so, this could have important implications for the structuring of athletes' precompetition warm-up procedures.

In track athletic running events, athletes typically employ a warm-up procedure that includes low-intensity jogging, mobilization exercises, and short-duration fast-running strides (observations from UK elite athletes). It is much less common for athletes to include a sustained

Ingham, Fudge, and Pringle are with the English Institute of Sport, Loughborough University, Loughborough, UK. Jones is with Sport and Health Sciences, University of Exeter, Exeter, UK.

higher-intensity exercise bout in the warm-up protocol, such as the continuous high-intensity priming bouts that appear to be important in enhancing VO_2 kinetics.[3,11,16,17] It is therefore possible that the warm-up procedures employed by many, if not most, middle-distance athletes are suboptimal and that including a sustained bout of high-intensity exercise in the precompetition warm-up might enhance VO_2 kinetics and performance. In considering an optimal warm-up, however, it is important to account for the "holding" of athletes before major competition; this can last for 20 to 40 minutes, during which time supplementary preparation is limited.

The purpose of the current investigation was to test the hypothesis that including a high-intensity priming exercise bout in the warm-up would speed VO_2 kinetics and improve the performance of well-trained athletes during a simulated 800-m track race. To enhance the ecological validity of the investigation, we compared a standard race-specific warm-up method with a modified version that incorporated a priming bout of sustained high-intensity exercise, and we also included a holding period between the warm-up and the simulated performance trial.

Methods

Participants

Eleven (7 male, 4 female) well-trained middle-distance runners of national and international standard provided informed consent to participate in the study, which had received ethical approval from the English Institute of Sport under "normal service delivery." Their mean ± SD age, body mass, height, and VO_{2max} were 20 ± 4 years, 59.7 ± 8.9 kg, 1.76 ± 0.07 m, and 70.8 ± 5.4 mL · kg^{-1} · min^{-1}, respectively, for the male participants, and 26 ± 5 years, 57.1 ± 3.5 kg, 1.68 ± 0.03 m, and 60.8 ± 4.3 mL · kg^{-1} · min^{-1} for the female participants. The study took place when participants were in their specific competition preparation period. They were informed that the purpose of the investigation was to compare the effects of 2 different warm-up regimens on 800-m performance; they were not aware of the study hypothesis.

Experimental Design

Participants reported to the laboratory or indoor 200-m running track in a rested and fully hydrated state, at least 2 hours postprandial and having avoided strenuous exercise in the 24 hours preceding a test session. Laboratory conditions were held constant at 20°C and 40% to 45% relative humidity. The laboratory-based treadmill test was used to determine VO_{2max} and the VO_2–speed relationship. Subsequently, the participants completed two 800-m time trials on an indoor synthetic track, at the same time of day, separated by at least 7 days, and with the conditions presented in random order. For each participant, all 3 tests were completed within 14 days.

Incremental Treadmill Test

After a 10-minute warm-up period, the participants completed an incremental treadmill test[19] on a motorized treadmill (HP Cosmos Saturn, Traunstein, Germany). The test involved 6 submaximal stages, each of 3 minutes duration, interspersed with 30-second breaks to facilitate blood sampling. Running speed was increased by 1 km/h at the end of each stage. After a 15-minute rest period, the participants resumed running at a speed that was 2 km/h slower than the final speed attained during the submaximal phase of the test, and the treadmill gradient was increased by 1% each minute until the participants reached volitional exhaustion.[19]

800-m Time-Trial Performance

The 800-m performance trials were performed on a 200-m indoor track (Mondo, Gallo, Italy). The performance trials were always preceded by a 10-minute self-paced jog and standardized and supervised mobility drills. In the control (CON) condition, participants preceded the performance trial with 6 × 50-m strides, interspersed with a "walk-back" recovery (45–60 s). This warm-up procedure was very similar to what the participants would ordinarily complete before a competition. In the intervention trial (HWU), participants completed 2 × 50-m strides (as per the CON condition) in addition to a continuous 200-m high-intensity run. All of these runs (50-m strides and the 200-m run) were completed at estimated 800-m race pace. The respective warm-up procedures were followed by 20 minutes of seated rest. This was included to simulate athlete "call-up" procedures in major track competitions. At the end of the rest period, the participants' perceived race readiness was assessed. Participants were asked "How effective do you feel the warm-up was in preparation for racing?" and required to rate their readiness from 1 (*not effective at all*) to 10 (*extremely effective*). The 800-m performance trial commenced 5 minutes later. During this period, the participants completed a further 2 × 50-m strides. Overall performance time and split times at 100-m intervals during the 800-m performance trial were measured using infrared timing gates (Brower, UT).

Measurements

Blood samples of 25 µL were collected from an earlobe at the end of each submaximal stage during the incremental treadmill test, at rest before the warm-up, and after the warm-up procedures of jogging, strides (either 6 × 50-m or 2 × 50-m and 200-m), 20 minutes rest, and preperformance 2 × 50-m strides, approximately 2 minutes before the performance trial. Blood lactate concentration (blood [La]) was measured using an automated device (Biosen, EKF, Germany) that was calibrated using a 12-mM reference solution.

Pulmonary gas exchange and minute ventilation were measured breath by breath during the incremental exercise test and performance trials. Participants breathed through a low-dead-space (90 mL), low-resistance (0.1 kPa · L^{-1} · s^{-1} at 15 L/s) facemask assembly throughout each test. Expired air was sampled through a capillary line at a rate of 60 mL/min and analyzed for O_2 and CO_2 concentrations derived from an electrochemical cell and from thermal conductivity, respectively (Oxycon Mobile, Cardinal Health, Warwick UK). The analyzers were calibrated before each test with gases of known concentration. Expiratory volumes were determined using a turbine volume transducer (Viasys, UK) that was calibrated before each test using a 3-L syringe. A computer integrated the volume and concentration signals, with account taken of the gas transit delay through the capillary line. Respiratory gas-exchange variables were calculated and displayed for every breath.

During the treadmill test and performance trials, the VO_{2max} was determined as the highest 30-second mean value achieved. During the 800-m performance trials, breath-by-breath VO_2 after the onset of exercise was modeled using iterative nonlinear-regression techniques using Microsoft Excel. The mathematical model consisted of one exponential term, starting at the onset of exercise,

$$VO_2(t) = VO_2(b) + A(1 - e^{-t/\tau})$$

where $VO_2(b)$ is the resting baseline value, taken as a mean of the final 2 minutes before the start of the performance trial; A is the asymptotic amplitude for the exponential term; and τ is the time constant (equivalent here to the mean response time). The total O_2 requirement during the 800-m performances was estimated using the VO_2–speed relationship established during the submaximal phase of the incremental treadmill test for each athlete.

Statistics

Physiological and performance differences between the 2 warm-up conditions (CON and HWU) were assessed using paired t tests. The Mann-Whitney U test was used to explore differences between conditions for perceived race readiness. Statistical significance was accepted when $P < .05$. Data are presented as mean ± SD.

Results

The 800-m performance was significantly better ($P < .05$) for HWU (124.5 ± 8.3 s) than for CON (125.7 ± 8.7 s), with 7 of 11 participants having a faster time for HWU. The split times indicated that participants tended to be faster in HWU than in CON between 400 and 500 m ($P = .08$) and between 700 and 800 m ($P = .08$). The running speeds measured during the 800-m performance trials in the HWU and CON conditions are shown in Figure 1.

Before the 800-m performance trials, baseline blood [La] was 1.8 ± 0.3 mM greater after HWU than in CON (HWU, 3.6 ± 1.9 vs CON, 1.7 ± 0.8 mM; $P < .01$), with no differences observed posttrial. Baseline VO_2 was not different between groups (HWU, 0.81 ± 0.21 vs CON, 0.93 ± 0.24 L/min; $P > .05$). The participants reported greater race readiness in HWU than in CON (HWU, 6.3 ± 1.0 vs CON, 4.8 ± 1.7; $P < .05$).

The total O_2 consumed was greater after the intervention (HWU, 119 ± 18 vs CON, 109 ± 28 mL/kg, $P = .05$), and there was a tendency for a greater in-trial peak VO_2 (HWU, 4.21 ± 0.85 vs CON, 3.91 ± 0.63 L/min; $P = .08$). The mean response time for the VO_2 response was not different between conditions (HWU, 27 ± 6 vs

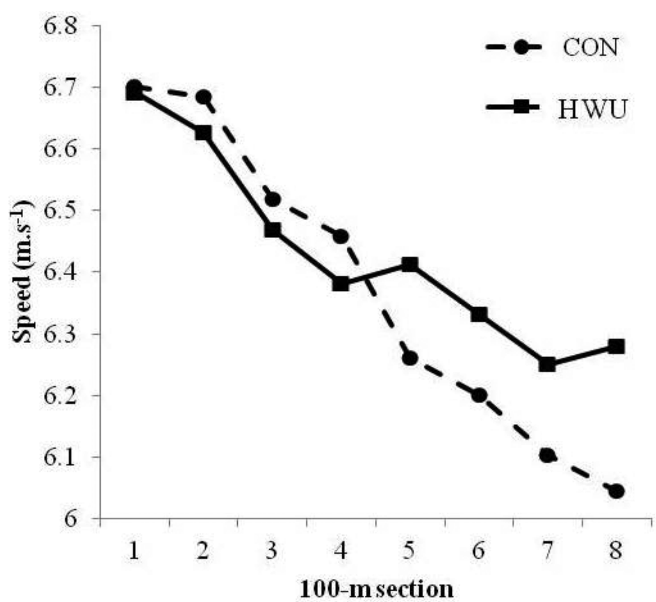

Figure 1 — The profile of mean running speed during the 800-m performance trial after high-intensity warm-up (HWU) and control (CON). Overall 800-m time was shorter ($P = .04$), and the 400- to 500-m and 700- to 800-m sections tended ($P = .08$) to be completed faster after the high-intensity warm-up.

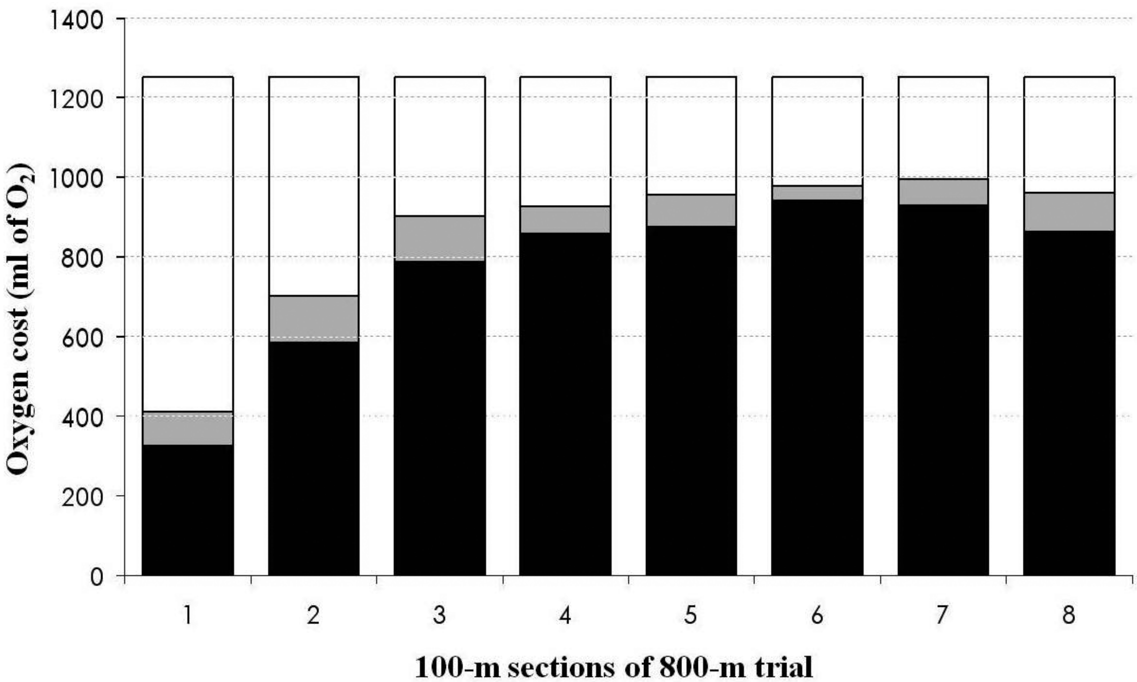

Figure 2 — The mean oxygen uptake per 100-m section of the 800-m performance trial for high-intensity warm-up (gray) and control (black) relative to the estimated oxygen cost (white) of running at the mean 800-m race speed.

CON 28 ± 7 s). Figure 2 illustrates the VO_2 response throughout the 800-m performance trials in the CON and HWU conditions.

Discussion

The major original finding of this investigation was that, compared with a standard warm-up regimen, a warm-up regimen including a sustained bout of high-intensity exercise significantly improved 800-m running performance in highly trained middle-distance runners. The improved 800-m performance after HWU was accompanied by a greater total O_2 consumption during the trial. On average, the HWU procedure resulted in a 1.2-second improvement in 800-m performance compared with CON. While this might appear to be a small difference in absolute terms, the improvement (close to 1%) represents a meaningful and practically significant difference in performance at the elite level.

The overall VO_2 response during the 800-m performance trial was augmented after HWU, as indicated by an increase in total O_2 consumed and a trend toward a greater peak VO_2 during the trial (Figure 2). These data are consistent with several previous studies that reported a greater oxidative contribution to total energy transfer in the transition to very-high-intensity exercise after priming.[8,12,13,16,17] Given that the total nonoxidative-energy yield during exhaustive high-intensity exercise is believed to be finite,[20,21] a greater total contribution from oxidative metabolism to energy turnover after the onset of such exercise would be expected to increase the total energy yield and enhance performance.[5,20] In the current study, the mean response time for VO_2 was not significantly different between the conditions, but the peak VO_2 showed a tendency to be greater after HWU; in absolute terms, VO_2 was higher throughout the 800-m performance trial after HWU. These findings are similar to those of Wilkerson et al,[12] who reported that prior multiple 30-second sprint exercise significantly increased the peak VO_2 measured during "extreme" (supramaximal) exercise.

The mechanistic bases for the greater VO_2 during primed than unprimed exercise remain controversial. There is evidence that priming exercise may increase bulk blood flow to the muscle through the combined effects of elevated cardiac output and greater vasodilatation.[4,8] Moreover, muscle oxygenation (as estimated by near-infrared spectroscopy) is enhanced after priming exercise,[4,9,22,23] and this might facilitate a greater matching of local O_2 delivery to metabolic rate.[24] Priming exercise might also increase the activation of rate-limiting enzymes in the respiratory chain, reducing oxidative metabolic inertia and increasing muscle O_2 extraction after the onset of exercise.[8,9,16,25,26] Finally, priming exercise might invoke alterations in neuromuscular activity that facilitate exercise performance.[5,6] Several studies have reported an increased integrated electromyogram signal after priming exercise and interpreted this to indicate that motor-unit recruitment is enhanced in the early stages of a primed bout of high-intensity exercise.[6,13,27] This might be advantageous for muscle performance because it would reduce the tension required per fiber and therefore reduce the metabolic disturbance experienced by the muscle as a whole. It is possible, of course, that a number, if not all, of the aforementioned mechanisms could contribute to the higher VO_2 (and better performance) during high-intensity exercise after priming, with the greater potential for muscle O_2 utilization being supported by an increased muscle O_2 delivery. Elevated muscle temperature does not appear to be important for the priming effect[11,28]; in this regard, the effects of prior exercise on VO_2 kinetics are not a consequence of warm-up, per se.

The CON condition was designed to reproduce a typical warm-up regimen for a middle-distance runner and included low-intensity running, mobility exercises, and a series of short-duration race-pace efforts followed by a period of rest. The HWU condition matched the CON condition in terms of total distance covered and distance covered at race pace. However, in HWU, rather than perform multiple short-duration strides as part of the warm-up (as is typically done; see CON), an equivalent distance was completed continuously (200 m compared with 4 × 50 m). The rest period separating the completion of the different warm-up regimens and the 800-m performance trials was designed to simulate a high-level competition format, wherein athletes are held before racing. It has been shown that VO_2 kinetics remains facilitated for at least 45 minutes after a bout of priming exercise.[29] Our results therefore indicate that, at least in this situation, the warm-up regimen typically used by middle-distance runners might not be optimal and that including a sustained bout of high-intensity exercise in the warm-up might enhance race performance. Consistent with this, participants reported significantly greater race readiness after HWU than in CON.

The continuous race-pace exercise used in the HWU condition significantly elevated blood [La] compared with CON. The mean blood [La] after HWU in the current study was 3.6 mM, which is within the range that appears to be optimal for enhanced performance after priming (3–5 mM).[16–18] It has been suggested previously that prior exercise regimens that do not alter blood [La] do not alter VO_2 kinetics or exercise tolerance,[2,3,29] whereas prior exercise regimens that result in high blood [La] (>6 mM) may affect VO_2 kinetics but not enhance (or may even impair) subsequent exercise tolerance.[12,16,21] On this basis, it would seem important for both the intensity and the duration of the priming exercise bout, and the subsequent recovery duration before the competition itself, to be carefully considered when designing a warm-up protocol. The recovery duration applied in the current study (20 min) is in keeping with the recommendations of Bailey et al,[16] who reported that tolerance of high-intensity exercise was enhanced to the greatest extent when the priming bout (6 min of severe-intensity exercise) was followed by 20 minutes of recovery. It was speculated that this protocol optimized the balance between preserving a facilitated VO_2 response and allowing complete or near-complete restoration of muscle energetic reserves (for example, phosphocreatine) and homeostasis.[16] It is important to note, however, that other combinations of prior exercise intensity/duration and subsequent recovery intensity/duration might also be effective in enhancing performance.

Previous studies have shown that an appropriate combination of prior exercise and recovery duration can enhance tolerance of subsequent high-intensity exercise measured as the time to exhaustion at a fixed work rate.[16–18] Relatively few studies, however, have addressed the question of whether priming exercise might enhance simulated performance. Burnley et al[10] used a warm-up regimen similar to that in the current study (including a 30-s sprint) but found that work output during a 7-minute cycling performance trial completed 10 minutes after the completion of the warm-up was not improved compared with a control condition of no warm-up. In the current study, an ~30-second race-pace effort (200-m) was combined with a longer period of recovery. This allowed blood [La] to fall to ~3.6 mM (compared with ~5.9 mM in the Burnley et al study) and may have permitted adequate metabolic recovery while maintaining a priming effect on VO_2[16] such that performance was improved. Burnley et al[10] also reported that prior moderate- and heavy-intensity exercise were equally effective in enhancing performance (by 2–3% compared with control). Similarly, Palmer et al[30] reported that prior heavy exercise and prior self-selected warm-up regimens were equally effective in enhancing laboratory-based 4000-m cycling performance (by ~2% compared with control), a finding complemented by Hajoglou et al[31] for 3000-m cycling performance. However, none of the moderate, heavy, or self-selected warm-up regimens employed in these earlier studies[10,30] elevated blood [La] above 2.5 to 3.0 mM, such that the effects of prior exercise on VO_2 kinetics and performance might have been suboptimal.

While overall 800-m trial performance was improved by HWU, there was little apparent difference in the time taken to cover the first 400 m in HWU compared with CON (Figure 1). Rather, the performance advantage appeared to become manifest in the second half of the trial, with trends toward significantly faster sections of the race between 400 and 500 m and between 700 and 800 m. This finding contrasts with previous work in which 3000-m cycle time-trial performance was facilitated by both easy and hard (~respiratory compensation point) warm-up regimens but with the higher power output being achieved during the earlier stage of the trials.[31] Individual pacing strategies were highly variable and were not controlled in the current study; nevertheless, it would appear that participants were able to perform better during the latter portion of the 800-m performance trial after HWU. It might be speculated that the increased total O_2 consumption in the first half of the performance trial after priming enabled a sparing of the muscle's finite anaerobic reserves (ie, phosphocreatine) and a reduced accumulation of fatigue-related metabolites (ie, inorganic phosphate, hydrogen ions).[13–15,20] This sparing of the finite nonoxidative energy reserves, along with the continued higher oxidative-energy turnover, might then enabled better maintenance of running speed during the latter half of the trial (Figure 1).

We did not include a control trial involving no warm-up in the current study because we did not consider it to be either realistic or appropriate to ask high-performance athletes to undertake an all-out performance trial with no prior warm-up. It is feasible that the low-intensity jogging and race-specific repetitions undertaken in CON might themselves provide some competitive advantage.[10,30,31] If so, this would have blunted the magnitude of the physiological and performance differences between HWU and CON. However, our primary purpose was to investigate whether the addition of a sustained high-intensity exercise bout to the warm-up regimen typically employed by middle-distance athletes could enhance performance.

Given that the participants only completed a single bout of exercise in both the CON and HWU conditions, it was not appropriate to employ complex multiexponential modeling of the VO_2 kinetics; hence, we fitted a single curve through the entire VO_2 response. We acknowledge that the use of exponential-curve fitting to describe and compare the VO_2 responses to imposed work rates assumes that the ATP turnover rate is both constant over time within conditions and identical between conditions. In the current study, the mean speed was slightly higher in HWU than in CON, and in both conditions speed reduced with time. However, in absolute terms, differences in the overall speed and VO_2 profiles between HWU and CON were small, and we therefore believe it is legitimate to characterize and compare the VO_2 kinetics between the conditions using an exponential function.[32] A similar approach has been used in previous studies. The appropriateness of the interpretation arising from this approach is supported by evidence that total O_2 consumed was higher in HWU than in CON.

In conclusion, this is the first study to show that high-intensity priming exercise improves simulated performance in high-level track athletes. Specifically, a warm-up regimen involving a continuous 200-m race-pace effort set in a competition-specific schedule enhances 800-m running performance in highly trained middle-distance runners. The magnitude of the improvement was 1.2 seconds (or approximately 1%), an effect that is practically meaningful in elite-level competition. The physiological mechanisms responsible for the improved performance are unclear but are likely related to the greater total O_2 consumption during competition that is enabled by priming exercise. Athletes should be encouraged to explore whether their current warm-up procedures provide optimal preparation for competition.

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