

# Effects of work-matched moderate- and high-intensity warm-up on power output during 2-min supramaximal cycling

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**ABSTRACT:** We tested the hypothesis that compared with a moderate-intensity warm-up, a work-matched high-intensity warm-up improves final-sprint power output during the last 30 s of a 120-s supramaximal exercise that mimics the final sprint during events such as the 800-m run, 1,500-m speed skate, or Keirin (cycling race). Nine active young males performed a 120-s supramaximal cycling exercise consisting of 90 s of constant-workload cycling at a workload that corresponds to 110% peak oxygen uptake ( $VO_{2peak}$ ) followed by 30 s of maximal cycling. This exercise was preceded by 1) no warm-up (control), 2) a 10-min cycling warm-up at a workload of 40%  $VO_{2peak}$  (moderate-intensity), or 3) a 5-min cycling warm-up at a workload of 80%  $VO_{2peak}$  (high-intensity). Total work was matched between the two warm-up conditions. Both warm-ups increased 5-s peak (observed within 10 s at the beginning of maximal cycling) and 30-s mean power output during the final 30-s maximal cycling compared to no warm-up. Moreover, the high-intensity warm-up provided a greater peak ( $577 \pm 169$  vs.  $541 \pm 175$  W,  $P=0.01$ ) but not mean ( $482 \pm 109$  vs.  $470 \pm 135$  W,  $P=1.00$ ) power output than the moderate-intensity warm-up. Both  $VO_2$  during the 90-s constant workload cycling and the post-warm-up blood lactate concentration were higher following the high-intensity than moderate-intensity warm-up (all  $P \leq 0.05$ ). We show that work-matched moderate- ( $\sim 40\% VO_{2peak}$ ) and high- ( $\sim 80\% VO_{2peak}$ ) intensity warm-ups both improve final sprint ( $\sim 30$  s) performance during the late stage of a 120-s supramaximal exercise bout, and that a high-intensity warm-up provides greater improvement of short-duration ( $< 10$  s) maximal sprinting performance.

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## INTRODUCTION

Male athletes can complete an 800-m run, 1,500-m speed skate, or Keirin (cycle race) in about 120 s. In trained runners, the contributions of the aerobic and anaerobic energy systems during an 800-m run are approximately 60-70% and 30-40%, respectively [1, 2]. This is indicative of the importance of both energy systems during an 800-m running race and other competitive sport events of similar duration.

A critical factor often determining the winner of a race is the final sprint to the finish line. To achieve better performance during the final sprint, the racer wants to utilize more aerobic energy before the sprint so as to spare the limited source of anaerobic energy used to accelerate during the final all-out sprint. Warming up prior to competitions can increase aerobic energy recruitment, thereby enabling better subsequent heavy-intensity exercise performance [3, 4]. The effect of the warm-up is determined by several factors, including warm-up intensity [5-9], duration [10-12], and the transition time after warm-up [13]. It appears that a higher intensity warm-up (e.g.,

above the anaerobic threshold) is required to effectively augment the oxygen uptake ( $VO_2$ ) response during subsequent heavy-intensity exercise [14, 15]. In line with this, a warm-up performed at a workload of  $\sim 70\%$  peak oxygen uptake ( $VO_{2peak}$ ) is reportedly optimal for enhancing maximal exercise performance lasting 70-120 s [16, 17]. However, the studies that evaluated maximal exercise performance tested different warm-up intensities (55-80%  $VO_{2peak}$ ) at a fixed duration [16, 17]. Consequently, higher-intensity warm-up involved a larger amount of total work. Given that total work, per se, can independently modulate the effect of warm-up on anaerobic exercise performance [4, 18, 19], those results [16, 17] may be influenced by differences in warm-up intensity, total work, and a combination of both.

A few studies have evaluated the effect of warm-up intensity on exercise performance such that total work of warm-up was matched among conditions, though the performance evaluation exercise employed in those studies was of longer duration ( $> 7$  min) [20, 21].

Because the effect of warm-up differs depending on performance evaluation exercise duration [4, 22], the above-mentioned results cannot be simply applied to exercise performance lasting  $\sim 120$  s. Moreover, no previous study has evaluated the warm-up effect on a performance evaluation exercise that continues for  $\sim 120$  s and simulates a final all-out sprint type competition. Whether a work-matched, high-intensity warm-up yields a better final sprint at the end of a  $\sim 120$ -s supramaximal exercise than a moderate-intensity warm-up remains to be investigated. The purpose of this study, therefore, was to test the hypothesis that in comparison to a moderate-intensity warm-up ( $40\% \text{VO}_{2\text{peak}}$ ), a work-matched high-intensity warm-up ( $80\% \text{VO}_{2\text{peak}}$ ) leads to better last-stage maximal exercise performance during the last 30 s of a 120-s supramaximal exercise.

## MATERIALS AND METHODS

### Subjects

This study was approved by the University Committee in agreement with the Declaration of Helsinki. Written informed consent was obtained from all participants before their participation. Nine young, highly active (3-6 days per week, 30-120 min of structured physical activity per day) males volunteered for this study. All participants were free of prescription medications and chronic disease, and were not cigarette smokers. The participants' age, height, body mass, and  $\text{VO}_{2\text{peak}}$ , presented as means  $\pm$  standard deviation, were  $22 \pm 2$  years,  $1.72 \pm 0.06$  m,  $64.5 \pm 4.6$  kg, and  $55.1 \pm 6.4 \text{ mL kg}^{-1} \text{ min}^{-1}$ , respectively. Before each experiment, participants abstained from over-the-counter medication for at least 48 hours, alcohol, caffeine, and intense exercise for more than 12 hours, and any food for at least 2 hours prior to the start of the experiment.

### Procedure

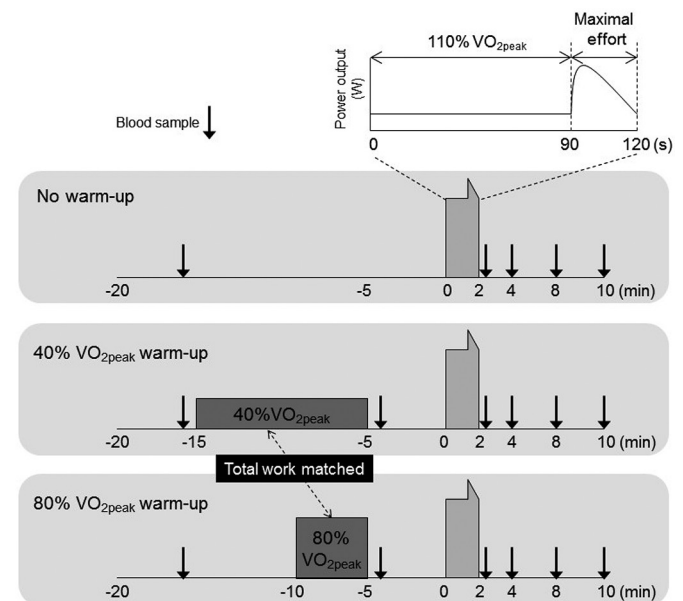
#### $\text{VO}_{2\text{peak}}$ measurement

All participants initially completed an incremental cycling bout until exhaustion to determine their  $\text{VO}_{2\text{peak}}$  measured on an electromagnetic brake bicycle ergometer (Powermax-V2, COMBI, Tokyo, Japan). The participants initially cycled at a workload of 70 W for 120 s, after which the load was increased by 35 W every 120 s while the pedalling rate was kept constant at 70 rpm. The test continued until the participants could no longer maintain a pedalling rate of  $>60$  rpm or volitional fatigue. Throughout the test, the participants breathed through a mask that covered their mouth and nose. A mass-flow sensor (hot-wire type) and a gas-sampling tube (the sampling volume rate was below  $0.2 \text{ l min}^{-1}$ ) were connected to the mask, and the expired volume and gases were analysed continuously via an electric gas flow meter (Model RM300i, Minato Medical Science, Japan).  $\text{VO}_{2\text{peak}}$  was determined as the highest value measured over a 1 min period. The test was performed in an environmental chamber (Fujiika, Chiba, Japan) regulated to  $25^\circ\text{C}$  and 50% relative humidity with a wind speed of  $<0.2 \text{ m s}^{-1}$ . We elected to use a room temperature of  $25^\circ\text{C}$  for the  $\text{VO}_{2\text{peak}}$  measurement, as we previously

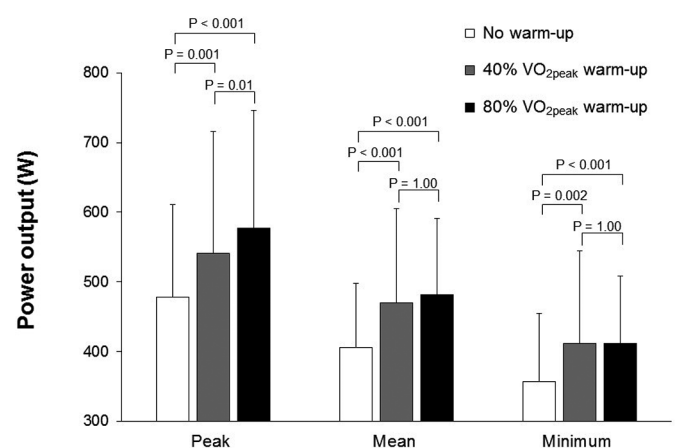
found that this temperature to be comfortable for most young males performing the same increment cycling.

### Experimental session

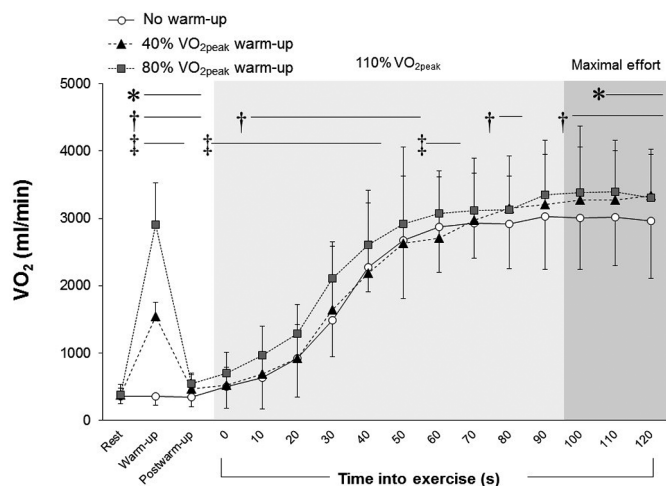
At least 2 days after completing the  $\text{VO}_{2\text{peak}}$  measurement, the participants joined the experimental session. After instrumentation, the participants performed a 120-s supramaximal cycling exercise that



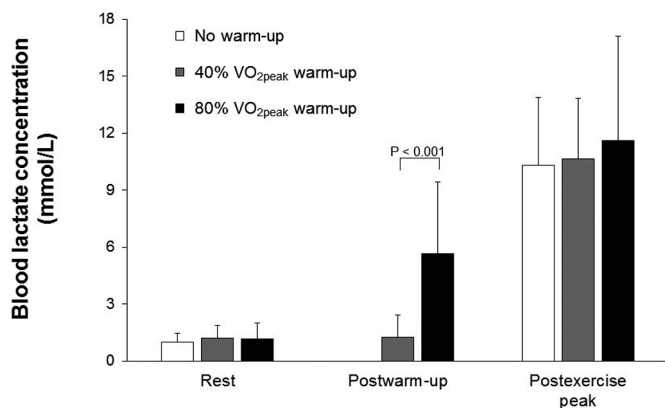
**FIG. 1.** A schematic overview of the experimental procedure.  $\text{VO}_{2\text{peak}}$ , peak oxygen uptake.



**FIG. 2.** Peak, mean, and minimum power outputs measured during 30 s of maximal cycling that was preceded by 90 s of cycling performed at a workload of 110% peak oxygen uptake ( $\text{VO}_{2\text{peak}}$ ). This cycling was conducted 5 min after each of three warm-up conditions: 1) no warm-up (control), 2) a 10-min cycling warm-up at  $40\% \text{VO}_{2\text{peak}}$ , or 3) a 5-min cycling warm-up at  $80\% \text{VO}_{2\text{peak}}$ . Data are presented as the mean  $\pm$  95% confidence interval.



**FIG. 3.** Oxygen uptake ( $VO_2$ ) measured during rest (before warm-up), warm-up, post-warm-up rest, and 120 s of supramaximal cycling consisting of 90 s of cycling at a workload that corresponds to 110% peak  $VO_2$  ( $VO_{2peak}$ ) followed by 30 s of maximal cycling. Measurements were made under three warm-up conditions: 1) no warm-up (control), 2) a 10-min cycling warm-up at 40%  $VO_{2peak}$ , or 3) a 5-min cycling warm-up at 80%  $VO_{2peak}$ . \* $P \leq 0.05$  (no warm-up vs. 40%  $VO_{2peak}$  warm-up); †  $P \leq 0.05$  (no warm-up vs. 80%  $VO_{2peak}$  warm-up); ‡  $P \leq 0.05$  (40% vs. 80%  $VO_{2peak}$  warm-up). Data are presented as the mean  $\pm$  95% confidence interval.



**FIG. 4.** Blood lactate concentrations measured during rest (before warm-up), post-warm-up rest, and following a 120-s cycling exercise consisting of 90 s of cycling at a workload equal to 110% peak oxygen uptake ( $VO_{2peak}$ ) plus 30 s of maximal cycling. Data are presented as the mean  $\pm$  95% confidence interval.

consisted of 90 s of cycling at a constant workload equal to 110%  $VO_{2peak}$  at a pedalling rate of 70 rpm followed by 30 s of maximal cycling (i.e., Wingate anaerobic test). It has been shown that cycling at a workload that corresponds to 110%  $VO_{2peak}$  can be sustained for ~3 min [23]; hence, 90 s of cycling at this exercise intensity was

not exhaustive and allowed participants to perform the subsequent 30 s of maximal cycling. This was verified in our pilot study. The 120-s supramaximal cycling was performed following three different interventions on separate days (>2 days between interventions applied in randomized order): 1) no warm-up resting (control), 2) a 10-min cycling warm-up at a workload of 40%  $VO_{2peak}$ , or 3) a 5-min cycling warm-up at a workload of 80%  $VO_{2peak}$  (Figure 1). There was a 5-min resting recovery period between each warm-up and the subsequent 120-s supramaximal cycling. As designed, total work during the warm-up was matched between the two warm-up conditions, which was achieved by adjusting warm-up duration. External workload during the warm-up was maintained at  $124 \pm 10$  W and  $249 \pm 21$  W in the 40%  $VO_{2peak}$  and 80%  $VO_{2peak}$  warm-up conditions, respectively ( $P < 0.05$  for between conditions). The ratio of heat production to external workload during the warm-up was similar between the 40%  $VO_{2peak}$  and 80%  $VO_{2peak}$  warm-up conditions ( $3.33 \pm 0.22$  vs.  $3.23 \pm 0.29$ ,  $P = 0.45$ ), suggesting that mechanical efficiency was not greatly different between the two warm-up conditions. After the 120-s supramaximal cycling, the participants dismounted from the bicycle and remained seated in a chair located next to the bicycle ergometer for 10 min. The environmental chamber was regulated to 22°C, 50% relative humidity, and a wind speed of  $< 0.2$  m s<sup>-1</sup>, throughout the experiment.

*Measurements*

The power outputs were fed into a computer every 0.1 s and were averaged over every 5 s.  $VO_2$  measurements determined by gas analysers (Minato Medical Science) were recorded over each 10-s period during the 120-s supramaximal cycling.  $VO_2$  during rest before warm-up, during warm-up, and during rest following warm-up were obtained by averaging values over the last 1 min of each period. Blood samples were taken from a warmed finger at rest before and immediately after warm-up, and during post-exercise recovery periods (upon cessation of exercise, and 2, 6, and 8 min into post-exercise recovery) (Figure 1). Blood samples were analysed using a lactate analyser (YSI 2500 SPORT; YSI, Ohio, USA) to determine blood lactate concentrations.

*Data analyses*

The highest and lowest 5-s powers recorded during the 30-s maximal cycling were defined as the peak and minimum power, respectively. Mean power was calculated by averaging the power over the entire 30 s of maximal cycling. Peak blood lactate concentration was determined from the highest value achieved during the post-exercise recovery period.

*Statistical analyses*

Data are presented as the mean  $\pm$  95% confidence interval unless otherwise noted. Time-dependent  $VO_2$  data (Figure 3) were analysed using two-way repeated-measures analysis of variance with two factors: intervention (no warm-up, 40% and 80%  $VO_{2peak}$  warm-up)

and time (pre-warm-up rest, during warm-up, post-warm-up rest, every 10 s of the 120-s supramaximal cycling). One-way repeated-measures analysis of variance with one factor (intervention) was employed for power outputs (Figure 2) and blood lactate concentrations at each time point (Figure 4). When a main effect or an interaction was detected, *post hoc* multiple comparisons were carried out using a modified Bonferroni procedure (i.e., Hochberg procedure [24]). Paired *t*-tests were also used to compare variables where applicable. Correlative relationships were assessed between  $\text{VO}_{2\text{peak}}$  and the extent to which each warm-up improved peak and mean power outputs relative to non-warm up condition, using Pearson's product moment correlation coefficients. Values of  $P \leq 0.05$  were considered statistically significant. Statistical analyses were performed using the software package SPSS 24 (IBM, Armonk, NY, USA).

## RESULTS

### *Power output*

Power outputs during the 30-s maximal cycling evaluated as peak, mean, and minimum were all greater after either the 40% or 80%  $\text{VO}_{2\text{peak}}$  warm-up than after no warm-up (Figure 2). In addition, peak power output after the 80%  $\text{VO}_{2\text{peak}}$  warm-up was greater than after the 40%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 2). The mean and minimum power outputs did not differ between the two warm-up conditions (Figure 2).

### *Aerobic metabolism*

$\text{VO}_2$  during the rest before warm-up was similar under all three conditions (Figure 3).  $\text{VO}_2$  during both warm-ups was higher than in the no warm-up condition, and was higher in the 80%  $\text{VO}_{2\text{peak}}$  warm-up than the 40%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 3). Following both warm-ups,  $\text{VO}_2$  sharply declined but remained higher than in the no-warm up condition, and there was no difference in the post-warm-up value between the 40% vs. 80%  $\text{VO}_{2\text{peak}}$  warm-ups (Figure 3). During the 90-s constant workload cycling performed at a workload of 110%  $\text{VO}_{2\text{peak}}$ ,  $\text{VO}_2$  did not differ between the no warm-up and 40%  $\text{VO}_{2\text{peak}}$  warm-up conditions, but it was higher in the 80%  $\text{VO}_{2\text{peak}}$  warm-up condition than in the other two conditions (Figure 3). During the subsequent 30-s maximal cycling, both warm-ups resulted in a greater  $\text{VO}_2$  value than in the no warm-up condition, with no difference between the 40% and 80%  $\text{VO}_{2\text{peak}}$  warm-ups (Figure 3).

### *Blood lactate concentration*

Blood lactate concentrations were similar across all three conditions before warm-up under the resting conditions (Figure 4). Following the two warm-ups, blood lactate concentrations were higher in the 80% than the 40%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 4). However, the peak blood lactate concentrations did not differ among the three conditions after completion of the 120-s supramaximal cycling exercise (Figure 4).

## DISCUSSION

We evaluated for the first time whether work-matched moderate- (40%  $\text{VO}_{2\text{peak}}$ ) and high- (80%  $\text{VO}_{2\text{peak}}$ ) intensity warm-ups differ in terms of their effect on anaerobic exercise performance measured during 30 s of maximal cycling that was preceded by 90 s of cycling at a workload of 110%  $\text{VO}_{2\text{peak}}$ . We found that both warm-ups improved peak and mean power outputs during the 30-s maximal cycling as compared to no warm-up, and that the magnitude of the increase in peak power was greater after the high-intensity than the moderate-intensity warm-up.  $\text{VO}_2$  during the 90 s of cycling at a workload equal to 110%  $\text{VO}_{2\text{peak}}$  was increased only by the high-intensity warm-up. Post-warm-up resting blood lactate concentrations were greater following the high-intensity than moderate-intensity warm-up. Collectively, these results suggest that when total work during warm-up is matched, 1) both moderate- and high-intensity warm-ups augment peak and mean power outputs during the last 30-s maximal cycling performed after the initial 90 s of supramaximal constant workload cycling, and 2) greater improvement in peak power is obtained with the high-intensity warm-up.

We found that power output during the last 30-s maximal cycling was greater after either warm-up than with no warm-up (Figure 2). This may reflect the higher  $\text{VO}_2$  during that period after both the 40% and 80%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 3). Thus the aerobic energy provided during the maximal exercise was greater with both warm-ups. This ultimately increased the total energy supply, thereby contributing to greater power output. In addition, exercise-induced increases in muscle temperature [25, 26] may be associated with greater peak power output, as a higher muscle temperature leads to greater peak power output during maximal cycling [27].

In line with our original hypothesis, we demonstrated that peak power output was greater after the 80%  $\text{VO}_{2\text{peak}}$  warm-up than the 40%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 2). Because the aerobic energy supply, as reflected by  $\text{VO}_2$  during the 30-s maximal cycling, was similar after the two warm-ups (Figure 3), the greater peak power observed after the 80%  $\text{VO}_{2\text{peak}}$  warm-up appears to be due to a larger anaerobic energy supply. Given that  $\text{VO}_2$  during the first 90-s constant workload exercise at a workload that corresponds to 110%  $\text{VO}_{2\text{peak}}$  was greater after the 80% than 40%  $\text{VO}_{2\text{peak}}$  warm-up (Figure 3), this indicates that the aerobic energy supply is increased with the 80%  $\text{VO}_{2\text{peak}}$  warm-up, which may ultimately spare the anaerobic energy source. This spared anaerobic energy appears to be utilized at the beginning of the 30-s maximal cycling, leading to greater peak power. In addition, post-activation potentiation, a phenomenon wherein muscle performance is acutely enhanced by a previous maximal or near-maximal neuromuscular activation exercise [3, 28], may also be partly responsible for the greater peak power output observed after the high-intensity warm-up (i.e., 80%  $\text{VO}_{2\text{peak}}$  warm-up). However, in contrast to peak power output, mean power output over the entire 30-s period did not differ between the two warm-ups (Figure 2). Hence the spared anaerobic energy source and/or post-activation potentiation do not appear to be sufficient to sustain

higher power output over the entire period of 30-s maximal cycling.

The increased  $\text{VO}_2$  during the 90-s cycling at a workload equal to 110%  $\text{VO}_{2\text{peak}}$  after the 80%  $\text{VO}_{2\text{peak}}$  warm-up may be associated with increased post-warm-up blood lactate levels (Figure 4). To augment the  $\text{VO}_2$  response during exercise, a blood lactate level  $>3 \text{ mmol L}^{-1}$  is reportedly required before the performance evaluation exercise [14, 15]. Consistent with that, the 80%  $\text{VO}_{2\text{peak}}$  warm-up in the present study caused blood lactate concentration to increase to  $5.6 \pm 3.8 \text{ mmol L}^{-1}$  (Figure 4). By contrast, the blood lactate concentration following the 40%  $\text{VO}_{2\text{peak}}$  warm-up was only  $1.3 \pm 1.2 \text{ mmol L}^{-1}$  (Figure 4), and there was no increase in  $\text{VO}_2$  during the 90-s cycling at a workload of 110%  $\text{VO}_{2\text{peak}}$ . The precise mechanism underpinning the link between higher baseline blood lactate and an enhanced  $\text{VO}_2$  response during subsequent high-intensity exercise remains to be determined.

As opposed to our results after 80%  $\text{VO}_{2\text{peak}}$  warm-up, previous studies suggest that warm-ups at similar exercise intensities (i.e., 75-80%  $\text{VO}_{2\text{peak}}$ ) do not improve 70- to 120-s anaerobic exercise performance [16, 17]. Stewart and Sleivert [17] reported that although a warm-up performed at a workload of 60-70%  $\text{VO}_{2\text{peak}}$  lengthened the time to exhaustion during maximal running in comparison to no warm-up, a higher-intensity warm-up at a workload of 80%  $\text{VO}_{2\text{peak}}$  did not [17]. Bishop et al. [16] reported that the average power output during the first half of a 2-min bout of maximal kayaking was lower after a warm-up at a workload of 75%  $\text{VO}_{2\text{peak}}$  than after a warm-up at a workload of 55% or 65%  $\text{VO}_{2\text{peak}}$ . It should be noted that in the present study we matched the total work during the warm-ups by adjusting their duration, but this was not done in the aforementioned studies [16, 17], as warm-up duration was the same under all warm-up conditions. Hence the lack of beneficial effect of warming up at workloads of 75-80%  $\text{VO}_{2\text{peak}}$  reported in previous studies [16, 17] could be a result of greater total work, and therefore a greater energy expenditure, rather than the high intensity per se.

Few studies have assessed the effects of different intensity warm-ups with matched total work [20, 21]. The study by Burnley et al. [21] showed that mean power output during 5 min of maximal cycling was similarly improved by moderate- ( $\sim 55\% \text{VO}_{2\text{peak}}$ ) and heavy- ( $\sim 85\% \text{VO}_{2\text{peak}}$ ) intensity warm-ups. This is consistent with what we observed in the present study wherein mean power output during the 30-s maximal cycling was similarly improved by 40% and 80%  $\text{VO}_{2\text{peak}}$  warm-ups (Figure 2). It thus appears that work-matched warm-up performed at 55% to 85%  $\text{VO}_{2\text{peak}}$  increases mean power output equally during maximal cycling lasting 30 s to 5 min.

It should be noted that  $\text{VO}_{2\text{peak}}$  varied among the highly active males of the present study (45.3 to 65.3  $\text{mL kg}^{-1} \text{min}^{-1}$ ). We evaluated correlative relationships between  $\text{VO}_{2\text{peak}}$  and the extent to which

each warm-up improved peak and mean power outputs relative to the no-warm up condition, demonstrating no correlative relations between the two variables. Thus, it appears that the effects of warm-up observed in the current study may not be greatly influenced by the levels of physical fitness. However, future research is warranted to elucidate whether and how different levels of physical fitness modulate warm-up effects on final sprint performance during the late stage of a 120-s supramaximal exercise bout.

### *Practical applications*

The 800-m run, 1,500-m speed skate, and Keirin cycle race are high-intensity sporting events that can be completed within  $\sim 120$  s by male athletes. In those events, the final sprint to the finish is often a key determinant of who wins the race. Indeed, a recent study showed that in 1,500-m speed skating events, a faster last 5 of a total 13.5 laps is linked to a faster finishing time [29]. Our exercise model is unique in that it mimics competitions lasting  $\sim 120$  s and containing a final sprint. Our results show that total work-matched warm-ups performed at workloads of 40% and 80%  $\text{VO}_{2\text{peak}}$  equally improve mean power output during the last 30-s maximal cycling, implying that moderate- or high-intensity warm-up improves the aforementioned sports performance. It is worth noting, however, that peak power early during the last 30-s maximal cycling was greater after high-intensity than moderate-intensity warm-up. This may indicate that during  $\sim 120$ -s competitive sporting events, athletes who perform high-intensity warm-up may be able to more quickly accelerate their pace during a competition, thereby achieving a faster final sprint. In addition, quicker acceleration of the race pace may enable athletes to establish better positioning during the race. Accordingly, our results provide new insight into the potentially favourable effect of high-intensity warm-up for athletes who compete in the 800-m run, 1,500-m speed skate, and Keirin cycling race.

## CONCLUSIONS

We have demonstrated that work-matched moderate- ( $\sim 40\% \text{VO}_{2\text{peak}}$ ) and high- ( $\sim 80\% \text{VO}_{2\text{peak}}$ ) intensity warm-ups improve final sprints ( $\sim 30$  s) at the late stage of  $\sim 120$ -s supramaximal exercise, with a high-intensity warm-up providing greater improvement of short-duration ( $<10$  s) maximal sprinting performance.

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## REFERENCES

1. Spencer MR, Gastin PB. Energy system contribution during 200- to 1500-m running in highly trained athletes. *Medicine & Science in Sports & Exercise* 2001;33(1):157-62.
2. Duffield R, Dawson B, Goodman C. Energy system contribution to 400-metre and 800-metre track running. *J Sport Sci*. 2005;23(3):299-307.
3. McGowan CJ, Pyne DB, Thompson KG, Rattray B. Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. *Sports Med*. 2015;45(11):1523-46.
4. Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. *Sports Med*. 2003;33(7):483-98. Epub 2003/05/24. PubMed PMID: 12762825.
5. Andzel WD. One Mile Run Performance as a Function of Prior Exercise. *J Sport Med Phys Fit*. 1982;22(1):80-4.
6. Bishop D, Bonetti D, Dawson B. The influence of pacing strategy on VO<sub>2</sub> and supramaximal kayak performance. *Med Sci Sport Exerc*. 2002;34(6):1041-7.
7. Mitchell JB, Huston JS. The effect of high- and low-intensity warm-up on the physiological responses to a standardized swim and tethered swimming performance. *J Sport Sci*. 1993;11(2):159-65.
8. Genovely H, Stamford BA. Effects of Prolonged Warm-up Exercise above and Below Anaerobic Threshold on Maximal Performance. *Eur J Appl Physiol O*. 1982;48(3):323-30.
9. Devries HA. Effects of Various Warm-up Procedures on 100-Yard Times of Competitive Swimmers. *Res Quart*. 1959;30(1):11-20.
10. Baklouti H, Chtourou H, Aloui A, Chaouachi A, Souissi N. Effect of active warm-up duration on morning short-term maximal performance during Ramadan. *Libyan J Med*. 2015;10:26229.
11. Baklouti H, Aloui A, Chtourou H, Briki W, Chaouachi A, Souissi N. Does increasing active warm-up duration affect afternoon short-term maximal performance during Ramadan? *PLoS ONE*. 2015;10(2):e0116809.
12. Souissi N, Driss T, Chamari K, Vandewalle H, Davenne D, Gam A, et al. Diurnal variation in Wingate test performances: influence of active warm-up. *Chronobiol Int*. 2010;27(3):640-52.
13. Frikha M, Chaari N, Mezghanni N, Souissi N. Influence of warm-up duration and recovery interval prior to exercise on anaerobic performance. *Biol Sport*. 2016;33(4):361-6.
14. Bailey SJ, Vanhatalo A, Wilkerson DP, Dimenna FJ, Jones AM. Optimizing the „priming“ effect: influence of prior exercise intensity and recovery duration on O<sub>2</sub> uptake kinetics and severe-intensity exercise tolerance. *J Appl Physiol* (1985). 2009;107(6):1743-56.
15. Burnley M, Doust JH, Jones AM. Time required for the restoration of normal heavy exercise VO<sub>2</sub> kinetics following prior heavy exercise. *J Appl Physiol* (1985). 2006;101(5):1320-7.
16. Bishop D, Bonetti D, Dawson B. The effect of three different warm-up intensities on kayak ergometer performance. *Med Sci Sports Exerc*. 2001;33(6):1026-32.
17. Stewart IB, Sleivert GG. The effect of warm-up intensity on range of motion and anaerobic performance. *J Orthop Sports Phys Ther*. 1998;27(2):154-61.
18. Sargeant AJ, Dolan P. Effect of prior exercise on maximal short-term power output in humans. *J Appl Physiol* (1985). 1987;63(4):1475-80.
19. Neiva HP, Marques MC, Barbosa TM, Izquierdo M, Viana JL, Teixeira AM, et al. The Effects of Different Warm-up Volumes on the 100-m Swimming Performance: A Randomized Crossover Study. *J Strength Cond Res*. 2015;29(11):3026-36.
20. Carter H, Grice Y, Dekerle J, Brickley G, Hammond AJ, Pringle JS. Effect of prior exercise above and below critical power on exercise to exhaustion. *Med Sci Sports Exerc*. 2005;37(5):775-81.
21. Burnley M, Doust JH, Jones AM. Effects of prior warm-up regime on severe-intensity cycling performance. *Med Sci Sport Exerc*. 2005;37(5):838-45.
22. Wittekind A, Cooper CE, Elwell CE, Leung TS, Beneke R. Warm-up effects on muscle oxygenation, metabolism and sprint cycling performance. *Eur J Appl Physiol*. 2012;112(8):3129-39.
23. Gastin PB, Costill DL, Lawson DL, Krzeminski K, McConell GK. Accumulated oxygen deficit during supramaximal all-out and constant intensity exercise. *Med Sci Sport Exerc*. 1995;27(2):255-63.
24. Hochberg Y. A Sharper Bonferroni Procedure for Multiple Tests of Significance. *Biometrika*. 1988;75(4):800-2.
25. Kenny GP, Reardon FD, Zaleski W, Reardon ML, Haman F, Ducharme MB. Muscle temperature transients before, during, and after exercise measured using an intramuscular multisensor probe. *J Appl Physiol* (1985). 2003;94(6):2350-7.
26. Gonzalez-Alonso J, Quistorff B, Krstrup P, Bangsbo J, Saltin B. Heat production in human skeletal muscle at the onset of intense dynamic exercise. *J Physiol*. 2000;524 Pt 2:603-15.
27. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiol Scand*. 1979;107(1):33-7.
28. Tillin NA, Bishop D. Factors modulating post-activation potentiation and its effect on performance of subsequent explosive activities. *Sports Med*. 2009;39(2):147-66.
29. Konings MJ, Noorbergen OS, Parry D, Hettinga FJ. Pacing Behavior and Tactical Positioning in 1500-m Short-Track Speed Skating. *Int J Sport Physiol*. 2016;11(1):122-9.