Title	High-intensity cycling re-warm up within a very short time-frame increases the subsequent intermittent sprint performance
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Relation	

High-intensity cycling re-warm up within a very short time-frame increases the subsequent intermittent sprint performance

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High-intensity cycling re-warm up within a very short time-frame increases the subsequent intermittent sprint performance

This study investigated the effect of high-intensity cycling re-warm up (RW) within a very short time-frame on the subsequent intermittent sprint performance. Twelve active males completed three trials in random order: control (CON); 3-min RW at 30% of maximal oxygen uptake (VO_{2max}) (RW30); and 1-min RW at 90% of VO_{2max} (RW90). During the experimental trials, participants performed 40 min of intermittent cycling exercise followed by 15 min of rest. During the rest period, participants completed CON, RW30, or RW90. After the rest period, participants performed the Cycling Intermittent-Sprint Protocol (CISP), which consisted of 10 seconds of rest, 5 seconds of maximal sprint, and 105 seconds of active recovery with the cycles repeated over 10 min. The mean work during sprint for the CISP was significantly higher in both RW trials than in the CON trial (mean ± standard deviation; CON: 3539 ± 698 J; RW30: 3724 ± 720 J; RW90: 3739 ± 736 J; $p < 0.05$). The mean electromyogram amplitude during the sprint for the CISP was higher in the RW30 trial than in the CON trial; however, there was no significant difference between the two trials ($p = 0.06$). The mean median frequency during sprint for the CISP was significantly higher in the RW90 trial than in the CON and RW30 trials ($p < 0.05$). Rectal temperature did not differ between trials. Oxygenated haemoglobin during the initial 30 s of the CISP was significantly higher in the RW90 trial than in the CON trial ($p < 0.05$). Compared with seated rest, RW, irrespective of whether it comprised 1 min at 90% of VO_{2max} or 3 min at 30% of VO_{2max}, increased the subsequent intermittent sprint performance.

Keywords: intermittent team sport; cycling sprint; muscle activation; body temperature; gas analysis; muscle oxygenation

Introduction

The ability to perform high-intensity exercise is important for intermittent sports players.

However, this ability decreases after half-time during intermittent team sports, including football and rugby (Bradley et al., 2009; Lovell, Barrett, Portas, & Weston, 2013). The distance covered while running at high-speed during a football match was reduced by 8.4% during the initial part of the second half compared with the initial part of the first half (Weston et al., 2011). Furthermore, the sprint performance was reduced by 2.4% at the onset of the second half compared with at the onset of the first half (Mohr, Krustrup, Nybo, Nielsen, & Bangsbo, 2004). These reductions resulted from the passive recovery during half-time and have been associated with physiological changes, including loss of muscle (T_m) and core temperatures (T_c), decrement of muscle activation and reduction of oxygen availability in the muscle (Russell, West, Harper, Cook, & Kilduff, 2015; Silva, Neiva, Marques, Izquierdo, & Marinho, 2018; Yanaoka, Hamada, et al., 2018).

The efficacy of a re-warm up (RW) at half-time has been recently reviewed (Hammami, Zois, Slimani, Russel, & Bouhlel, 2018; Russell et al., 2015; Silva et al., 2018). RW is important to avoid a decrease in the ability to perform sprinting, jumping and endurance exercise because it helps to maintain or increase T_m, T_c, muscle activation and oxygen availability in muscle (Russell et al., 2015; Silva et al., 2018; Yanaoka, Hamada, et al., 2018; Yanaoka, Kashiwabara, et al., 2018). Although recent reviews have recommended RW at moderate-intensity for 5 to 7 min to avoid reductions in exercise performance immediately after a rest period (Hammami et al., 2018; Russell et al., 2015; Silva et al., 2018), the RW protocol may not be suitable for competitions because of time limits that restrict the implementation of RW in real-world settings (Towlson, Midgley, & Lovell, 2013). However, no studies have addressed an effective RW protocol that can be performed within a very short time-frame. This issue is important to address since fitness coaches and sports scientists are challenged to provide evidence-based recommendations for an RW protocol that could increase the subsequent high-intensity exercise performance during intermittent team sports.

Increases in exercise performance after a warm-up depend on the net balance between fatigue and potentiation (Bishop, 2003; Seitz & Haff, 2016). A high-intensity warm-up has greater influences on body temperature, muscle activation, anaerobic metabolism, aerobic metabolism and acute fatigue compared with a low-intensity warm-up (Bishop, 2003; McGowan, Pyne, Thompson, & Rattray, 2015). Particularly, a high-intensity warm-up may impair subsequent sprint performance due to acute fatigue compared with a low-intensity warm-up when the matched for warm-up durations (McGowan et al., 2015). For example, maximal sprint performance decreases after a cycling warm-up at 110% of peak aerobic power compared with those at 40% and 80% of peak aerobic power (Wittekind, Cooper, Elwell, Leung, & Beneke, 2012). In contrast, a high-intensity warm-up may have a similar potentiation effect on exercise performance compared a low-intensity warm-up when matched for total volume during warm-up. A previous study has compared the effects of low-intensity, long-duration warm-ups and high-intensity, short-duration warm-ups on exercise performance when matched for total warm-up volume and suggested that similar positive effects on exercise performance were observed for these protocols (Shima, Maeda, & Nishizono, 2006). However, it is not known whether RW has similar, if any, benefits in increasing the subsequent exercise performance.

Therefore, the purposes of the present study were 1) to investigate the effect of high-intensity RW within a very short time-frame on the subsequent intermittent cycling sprint performance and 2) to compare the effects of high-intensity RW within a very short time-frame and an established lower-intensity RW with a longer duration (Yanaoka, Hamada, et al., 2018) on intermittent cycling sprint performance. Based on a previous study, the present study defined an intermittent sprint as a short-duration sprint interspersed with recovery periods long enough to allow nearly complete recovery of sprint performance (Girard, Mendez-Villanueva, & Bishop, 2011). We hypothesized that high-intensity RW within a very short time-frame and lower-intensity RW with a longer duration would have similar beneficial effects on the intermittent cycling sprint performance. In the present study, a 3-min RW at 30% of maximal oxygen uptake (VO_{2max}) was chosen since it has been established as the lowest-volume RW that increased intermittent sprint performance (Yanaoka, Hamada, et al., 2018)

METHODS

Materials and Methods

Participants

Twelve active males who habitually exercised for more than 2 days per week participated in this study. Participants were included in the study if they had no recent history of illness, injury, or rehabilitation during the testing schedule. The physical characteristics of the participants were as follows: age, 23 ± 2 years; height, 1.71 ± 0.05 m; body mass, 68.5 ± 8.7 kg; and VO_{2max}, 47.7 ± 6.6 mL/kg/min (mean ± standard deviation [SD]). This study was approved by the Ethics Review Committee on Research with Human Subjects of Waseda University (approval number: 2017-286), and all participants provided written informed consent before participating in this study.

Participants were asked to not alter their regular lifestyle habits, exercise and diet throughout the study. They recorded all the food and drinks consumed for 24 h prior to each experimental trial, and they replicated their dietary intake during subsequent trials to ensure that they were standardised across trials. Participants refrained from consuming alcohol and caffeine for 24 h prior to each experimental trial. Furthermore, they fasted for 3 h before each experimental trial and were only allowed to consume water during that time period.

Experimental Design

Participants completed three trials in randomised, counterbalanced order after one practice trial to familiarise themselves with the experiment at least 3 days before the first experimental trial. All trials were separated by 3 to 13 days. During the experimental trials, two consecutive intermittent cycling exercises separated by a 15-min rest period were performed on a cycle ergometer (Monark 894E, Monark, Varberg, Sweden). Interventions during the 15-min rest period were as follows: seated rest (control: CON); 3-min RW at 30% of VO_{2max} (RW30); and 1-min RW at 90% of VO_{2max} (RW90). The RW30 was previously reported as the lowest work during RW (Yanaoka, Hamada, et al., 2018). The mean temperature and humidity during the experimental trials were 20.6 ± 0.5°C and 50.8 ± 1.4% (mean ± SD), respectively. All three experimental trials were performed at the same time of day to avoid any circadian rhythm-related variations in the obtained results.

Graded Exercise Test

Participants initially underwent a graded exercise test to determine their VO_{2max} and maximum heart rate (HR_{max}) on a cycle ergometer (Monark 894E, Monark, Varberg, Sweden). The test started at 40 W, with a target cadence of 80 rpm, and increased by 40 W every 2 min until volitional exhaustion. A breath-by-breath gas analysis was performed using an automatic gas analyser (Quark CPET, COSMED, Rome, Italy). Linear regression for VO_2 against exercise intensity was calculated and used to predict the relative exercise intensity during the experimental trials (i.e., 60% and 130% of VO_{2max}).

Exercise Protocol

The exercise protocol used in the present study was the same as that of a previous study (Yanaoka, Hamada, et al., 2018). In the experimental trials, participants performed 40 min of intermittent cycling exercise followed by 15 min of rest and 10 min of the Cycling Intermittent-Sprint Protocol (CISP) on a cycle ergometer (Monark 894E, Monark, Varberg, Sweden) (Figure 1). First, participants rested on a chair for 5 min, followed by a standardised warm-up (i.e., 5 min of cycling at 95 W and 30 s of cycling at 120 W). Then, they performed 40 min of intermittent cycling exercise that consisted of 20 repetitions that lasted 2 min each. Each 2-min period started with 15 s of passive rest, followed by 25 s of unloaded cycling, 10 s of cycling at 130% of VO_{2max} and 70 s of cycling at 60% of VO_{2max}. After the 15-min rest period, they performed the CISP, which consisted of 5 repetitions that lasted 2 min each. Each 2-min period started with 10 s of passive rest, followed by 5 s of maximal sprint against a resistance of 7.5% of body mass and 105 s of cycling at 50% of VO_{2max}. Each sprint was initiated from a stationary start, with the right pedal crank at approximately 90° to the horizontal plane. Pedal cadence throughout the trial was 80 rpm, except during the 5-s maximal sprint. The CISP that was described previously was used to assess the intermittent sprint performance of athletes (Hayes et al., 2013).

FIGURE 1 ABOUT HERE

RW Intervention

During the 15-min rest period, participants rested on the cycle ergometer for 15 min

(CON), rested on the cycle ergometer for 11 min followed by cycling at 30% of VO_{2max} for 3 min (RW30), or rested on the cycle ergometer for 13 min followed by cycling at 90% of VO_{2max} for 1 min (RW90). The intensity of the RW90 was chosen to equalise the exercise volume (i.e., energy expenditure), which is estimated using oxygen uptake values and exercise duration according to the formula of the American College of Sports Medicine (American College of Sports Medicine, 2010) during RW, with the RW30. Each RW trial was completed 1 min prior to the commencement of the CISP.

Measurements

Sprint performance

Power during 5 s of sprinting of the CISP was calculated using a Monark Anaerobic Test software (Monark, Varberg, Sweden), which accounted for both the load on the flywheel and crank kinematics. Work was defined as the mean power multiplied by the duration of the sprint (i.e., 5 s). High reliability of the work during sprints for the CISP has been previously reported (i.e., intra-class correlation = 0.9) (Hayes et al., 2013).

Surface electromyogram

An electromyogram (EMG) of the muscle bellies of the right vastus lateralis was recorded during the 5-s sprint using a surface electrode (SX230-1000, Biometrics, Newport, United Kingdom), with the ground electrode placed on the left wrist (sampling frequency: 1000 Hz, band pass filter: 10–500 Hz). Electrode placement was defined by 30% of the length between the patella and greater trochanter (Takagi et al., 2014). To reduce impedance (< 2 kΩ), the skin was abraded and washed before electrode placement. The root mean square (RMS) and median frequency (MDF) as the mean values between the onset and the end of the burst were calculated for each sprint.

The RMS values were normalised to the 100% maximum voluntary isometric contraction (MVC) value obtained from 3-s MVC against manual resistance before each experimental trial. The 100% MVC value was obtained from a 1-s window during the 3-s MVC. Onset of the burst was defined by using an electric threshold of ± 0.2 mV (Racinais et al., 2007).

Body temperature

Rectal temperature (T_r) was measured using a thermistor (401J, Nikkiso-therm, Tokyo, Japan) from a depth of 10 cm past the anal sphincter at 1-min intervals. Skin temperature (T_s) was measured using a button-type data logger (Thermochron SL, KN Laboratories, Osaka, Japan) at 1-min intervals, and the logger was attached to four sites (i.e., chest, forearm, thigh and calf). The mean T_s was calculated as follows: $T_s = 0.3 \times (\text{chest} + \text{forearm}) + 0.2 \times (\text{thigh} + \text{calf})$ (Ramanathan, 1964). The T_m at the thigh was estimated from the T_s using the following equation: $T_m = 1.02 \times T_s$ at the thigh + 0.89 (de Ruiter, Jones, Sargeant, & de Haan, 1999).

Gas analysis

A breath-by-breath gas analysis was continuously performed using an automatic gas analyser (Quark CPET, COSMED, Rome, Italy) during the experimental trial. The analysers were calibrated before each graded exercise test with gases of known concentrations (O_2: 16%, CO_2: 5%), and the tube flowmeter was calibrated using a 3-L syringe. The mean VO_2, carbon dioxide production (VCO_2) and respiratory exchange ratio (RER) were calculated.

Muscle oxygenation measurements

Two-wavelength (770 and 830 nm) light-emitting diode near-infrared spatial-resolved spectroscopy (NIR_{SRS}: Hb14, ASTEM, Kanagawa, Japan) was used to measure muscle oxygenation of the right vastus lateralis, which was defined as 30% of the length between the patella and the greater trochanter above the patella at 5 Hz (Yanaoka, Hamada, et al., 2018). The NIR_{SRS} probe consisted of one light source and two photodiode detectors, and the optode distances were 20 and 30 mm. The NIR_{SRS} technique provided continuous, non-invasive monitoring of changes in oxygenated (Δoxy-Hb), deoxygenated (Δdeoxy-Hb) and total haemoglobin (Δtotal-Hb) concentrations from rest before a standardised warm-up, and muscle oxygen saturation (SmO_2). The Δtotal-Hb and SmO_2 were calculated with the following equations: Δtotal-Hb = Δoxy-Hb + Δdeoxy-Hb; SmO_2 = oxy-Hb / total-Hb. The NIR_{SRS} variables were affected by the thickness of the fat layer (Niwayama, Lin, Shao, Kudo, & Yamamoto, 2000). However, the NIR_{SRS} data can be corrected by using the fat layer thickness (Niwayama, Suzuki, Yamashita, & Yasuda, 2012). Therefore, the fat layer thickness at the measurement site was assessed using an ultrasound device (LogiQ3, GE Healthcare, Tokyo, Japan) before each trial, and the NIR_{SRS} variables were calculated using fat-correction software (Hb14, ASTEM, Kanagawa, Japan). The within-subject coefficient of variation for the fat layer thickness was 3.6 ± 1.5%.

HR and the Rating of Perceived Exertion

HR was measured using a wireless HR monitor at 5-s intervals during the experimental trials (Polar RCX3, Polar Electro, Kempele, Finland). The rating of perceived exertion (RPE) was assessed before and after 40 min of cycling intermittent exercise, after the rest period and after the CISP (i.e., at 0, 40, 55 and 65 min) (Borg, 1982).

Statistical Analyses

The sample size was estimated using G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007), using the data from a previous study that investigated the warm-up effects on exercise performance when the total work during a warm-up was matched (Shima et al., 2006). To detect improvements in exercise performance with a power of 80% and an alpha level of 5%, a sample size of ≥7 participants was required. Statistics were computed using SPSS computer software (version 25.0, SPSS Japan Inc., Tokyo, Japan). All values are shown as mean ± SD. The Shapiro–Wilk test was used to check for normality of distribution. All measurements were found to be normally distributed. A repeated-measures two-factor analysis of variance was used to examine differences among the three trials for all measurements. Mauchly's test was consulted and Greenhouse–Geisser correction was applied if sphericity was violated. When significant interactions and trial effects were detected, post-hoc multiple comparisons were made using the Bonferroni method. Statistical significance was set at $p < 0.05$. Unfortunately, some data were missing; T_r data are presented for 11 participants, T_s and estimated T_m data are presented for 10 participants and NIR_{SRS} data are presented for 9 participants.

Results

Sprint Performance

The mean work during sprint for the CISP was significantly higher in both RW trials than in the CON trial (RW30: p = 0.038, RW90: p = 0.021, Figure 2a).

FIGURE 2 ABOUT HERE

Neuromuscular Activity

The mean RMS during sprint for the CISP was higher in the RW30 trial than in the

CON trial; however, there was no significant difference between the two trials ($p = 0.056$) (Figure 2b). The mean MDF during sprint for the CISP was significantly higher in the RW90 trial than in the CON and RW30 trials (CON: $p = 0.014$, RW30: $p = 0.040$) (Figure 2c).

Body Temperature

T_r did not differ among the three trials (Table 1). Mean T_s and estimated T_m at 65 min was significantly higher in both RW trials than in the CON trial (T_s: RW30; $p = 0.042$, RW90; $p = 0.037$, T_m: RW30; $p = 0.003$, RW90; $p = 0.013$) (Table 1).

TABLE 1 ABOUT HERE

Gas Analysis and Muscle Oxygenation

Mean VO_2, VCO_2 and RER during the first 40-min intermittent exercise did not differ among the three trials. The mean values of VO_2, VCO_2 and RER during the CISP are provided in Figure 3. The mean VO_2 during the initial 30 s of the CISP was significantly higher in both RW trials than in the CON trial (RW30: $p = 0.001$, RW90: $p < 0.001$), and it was significantly higher in the RW90 trial than in the RW30 trial ($p = 0.005$) (Figure 3a). The mean VCO_2 for the CISP was significantly higher in the RW30 trial than in the CON trial ($p = 0.02$) (Figure 3b). The mean RER for the CISP was significantly higher in both RW trials than in the CON trial (RW30: $p = 0.021$, RW90: $p = 0.016$) (Figure 3c).

All NIR_{SRS} variables during the first 40-min intermittent exercise did not differ among the three trials. The mean values of all NIR_{SRS} variables during the CISP are provided in Figure 4. The mean Δoxy-Hb during the initial 30 s of the CISP was significantly higher in the RW90 trial than in the CON trial ($p = 0.012$) (Figure 4a). The mean Δdeoxy-Hb in the initial 30 s of the CISP was higher in the RW30 trial than in the CON trial; however, there was no significant difference between the two trials ($p = 0.061$) (Figure 4b). The mean Δtotal-Hb during the initial 30 s of the CISP was higher in both RW trials than in the CON trial; however, there were no significant differences between the trials (RW30: $p = 0.099$, RW90: $p = 0.083$) (Figure 4c). The mean SmO_2 during the CISP did not differ among the three trials.

FIGURES 3 and 4 ABOUT HERE

HR and RPE

There was a main effect of trial ($p < 0.001$) and trial × time interaction ($p < 0.001$) for the HR. The HR before the commencement of the CISP was significantly higher in both RW trials than in the CON trial (CON: 46 ± 5% HR_{max}, RW30: 49 ± 5% HR_{max}, $p = 0.038$, RW90: 68 ± 4% HR_{max}, $p < 0.001$), and significantly higher in the RW90 trial than in the RW30 trial ($p < 0.001$). The HR during the CISP was significantly higher in the RW90 trial than in the other trials (CON: 70 ± 5% HR_{max}, $p = 0.015$, RW30: 71 ± 4% HR_{max}, $p = 0.008$, RW90: 74 ± 6% HR_{max}).

There was a main effect of trial ($p = 0.001$) and trial × time interaction ($p = 0.007$) for the RPE. The RPE at 55 min was significantly higher in the RW90 trial than in the other trials (CON: 9.5 ± 2.4 arbitrary units [A.U.], $p = 0.008$, RW30: 10.4 ± 2.0 A.U., $p = 0.023$, RW90: 11.8 ± 2.1 A.U.).

Discussion

To our knowledge, the present study is the first to investigate the effect of 1-min high-intensity cycling RW on the subsequent intermittent sprint performance. The main findings of the present study were that 1) the RW90 trial showed that the subsequent

286 cycling intermittent sprint performance was increased by 5.7% compared with the CON
287 trial and 2) the RW90 trial was as effective as the RW30 trial for increasing the cycling
288 sprint performance. Moreover, the rates of increase of the cycling intermittent sprint
289 performances were similar compared with those of RW protocols reported previously
290 (i.e., 7-min RW at 70% of HR_{max}: 4.1% [Yanaoka, Kashiwabara, et al., 2018] and 3-min
291 RW at 60% of VO_{2max}: 7.1% [Yanaoka, Hamada, et al., 2018]). Many fitness coaches
292 believed that the major limitation of the implementation of RW is lack of time (Towlson
293 et al., 2013). Therefore, the present findings may be of value for players and coaches
294 who are generally busy with other ergogenic strategies during half-time.

295 Exercise performance improvements after a warm-up are generally attributed to
296 increased body temperature, resulting in increases in adenosine triphosphate turnover
297 and cross-bridge cycling rate, as well as improvements in muscle fibre functionality and
298 muscle fibre conduction velocity (MFCV) (McGowan et al., 2015). Furthermore, sprint
299 performance after RW for 7 min was increased because of maintained or increased T_r
300 and T_m (Hammami et al., 2018; Russell et al., 2015; Silva et al., 2018). For example,
301 Mohr et al. reported that a moderate-intensity RW for 7 min maintained T_m during half-
302 time of actual soccer matches, and there was a correlation (r = 0.6) between the change
303 in T_m and sprint performance (Mohr et al., 2004). In the present study, both RW trials
304 showed increased estimated T_m at 65 min. This increase in the estimated T_m during the
305 CISP may contribute to the increased intermittent sprint performance because of the
306 physiological changes that occur with increasing body temperature. However, since the
307 T_m in the present study was estimated from the T_s, the T_m may be underestimated. T_s at
308 the thigh might have decreased after commencement of a cycling exercise due to reflex
309 vasoconstriction, and it is followed by an increase (Nakayama, Ohnuki, & Niwa, 1977).
310 However, we have no direct T_m data. Therefore, T_m, which is measured directly,

311 requires further study.

312 Enhanced muscle activation is one of the factors for an acute increase in exercise
313 performance after a warm-up or RW (McGowan et al., 2015; Yanaoka, Hamada, et al.,
314 2018). For example, a previous study that used the same exercise protocol as the one
315 described in the present study indicated that the 3-min low-intensity RW increased the
316 subsequent intermittent cycling sprint performance and RMS during sprints (Yanaoka,
317 Hamada, et al., 2018). It has been suggested that enhanced muscle activation, as
318 evidenced by increased EMG activity during sprints, may be related to the acute
319 increase in the intermittent cycling sprint performance after RW (Yanaoka, Hamada, et
320 al., 2018) because a previous study reported that there is a linear relationship between
321 RMS and power output during cycling (Hug & Dorel, 2009). Although there was no
322 significant difference between the two trials for the mean RMS ($p = 0.056$) (Figure 2b),
323 the mean RMS during sprinting for the CISP was higher in the RW30 trial than in the
324 CON trial. Moreover, the RW90 trial increased MDF during sprints for the CISP
325 compared with the CON and RW30 trials. These findings suggested that the RW90 trial
326 may increase the MFCV since a previous study reported that the MDF reflected the
327 MFCV (Stewart, Macaluso, & De Vito, 2003). MFCV increases after active warm-up
328 via increased core and muscle temperatures or a higher recruitment of type II muscle
329 fibres (Kupa, Roy, Kandarian, & De Luca, 1995; Morimoto, Umazume, & Masuda,
330 1980; Sadoyama, Masuda, Miyata, & Katsuta, 1988). In the present study, both RW
331 trials did not influence the T_r or estimated T_m during the rest period. Therefore, it is a
332 possible that the RW90 trial may increase the recruitment of type II muscle fibres.

333 A previous study reported that high-intensity voluntary contractions lead to
334 enhancement in voluntary muscular performance in subsequent exercise, which is a

phenomenon called post-activation potentiation (PAP) (Blazevich & Babault, 2019). Increased intermittent cycling sprint performance after the RW90 (i.e., high-intensity RW) trial may be related to the PAP effect. The effect of high-intensity RW aimed at a PAP effect on sprint performance was investigated, and the results suggested that a five-repetition maximal leg press RW could improve subsequent sprint performance (Zois, Bishop, Fairweather, Ball, & Aughey, 2013). The potential mechanisms underlying the PAP effect are an increase in calcium (Ca^{2+}) sensitivity of the acto-myosin complex caused by phosphorylation of the myosin regulatory light chain and an increase in higher-order motor neuron recruitment (Blazevich & Babault, 2019; Sale, 2002). A previous study suggested that the PAP effect is greater in type II muscle fibres than in type I muscle fibres since type II muscle fibres have lower basal Ca^{2+} sensitivity and type I muscle fibres already have higher Ca^{2+} sensitivity (Blazevich & Babault, 2019). Our speculation (i.e., increased recruitment of type II muscle fibres) may be consistent with these mechanisms of the PAP effect. However, further investigations of the high-intensity RW used in the present study and the PAP effect are needed since the intensity of the RW90 trial was lower than that in a previous study (i.e., 90% of VO_{2max} or a 5-repetition maximal leg press) (Zois et al., 2013).

Another potential mechanism contributing to the increased intermittent cycling sprint performance after both RW trials might be an enhancement of the primary VO_2 response after commencement of the CISP. A previous study suggested that there is a close relationship between the ability to maintain intermittent sprint performance and faster VO_2 kinetics (Dupont, McCall, Prieur, Millet, & Berthoin, 2010). A reasonable hypothesis (Edholm, Krustrup, & Randers, 2015) that RW may enhance the primary VO_2 response to the subsequent exercise was suggested since soccer players started the second half with a higher HR, which is related to VO_2 responses during varying non-steady state exercises (Bot & Hollander, 2000), after RW. In the present study, higher VO_2 and HR after both RWs were observed, suggesting that the present results supported a previously proposed hypothesis (Edholm et al., 2015), and that an enhanced primary VO_2 response may contribute to increased intermittent sprint performance in both RW trials. Moreover, the RW90 trial increased Δoxy-Hb during the CISP, suggesting that oxygen availability in muscle increased after RW. Increased oxygen availability in muscle may accelerate the re-synthesis of phosphocreatine, which is directly related to the ability to perform high-intensity exercise after sprints (Girard et al., 2011; Spencer, Bishop, Dawson, & Goodman, 2005). Therefore, increased oxygen availability in muscle may contribute to the increased intermittent cycling sprint performance after the RW90.

The potential mechanism of oxygen availability in the muscle in the RW90 trial may increase the oxygen supply to the muscle. The Δoxy-Hb is an indicator of the balance between O_2 supply and utilization (Takagi, 2016). No differences in the mean Δdeoxy-Hb, which is an indicator of the balance between O_2 unloading in the muscle and blood outflow from the muscle (Takagi, 2016), were observed among the three trials, thus suggesting the possibility of increased O_2 supply but not decreased O_2 utilization. Previous reviews have suggested that a warm-up increases the oxygen supply to the muscle via vasodilation of blood vessels and an increase in blood flow to the muscles during subsequent exercise (Bishop, 2003; Jones, Koppo, Burnley, & Carter, 2003). A previous study reported that relative changes in the oxy-Hb increased after a warm-up, and that this may occur due to the increased blood flow to the muscle (Takizawa & Ishii, 2006). Moreover, it has been suggested that a specific core RW may increase muscle blood flow, as evidenced by decreased mean T_s, which was possibly a result of cutaneous reflex vasoconstriction with exercise (Tong, Baker, Zhang, Kong, &

Nie, 2019). The redistribution of blood flow from skin to active muscles to meet the augmented metabolic demand is a compensatory vasoregulation after the commencement of exercise (Nakayama et al., 1977). However, no studies have addressed the muscle and skin blood flow, measured directly following RW. Future research should be focused on muscle and skin blood flow.

The present study did not observe decreased mean T_s at 55 min after both RW trials compared with the CON trial, which is not consistent with a previous study (Tong, Baker, Zhang, Kong, & Nie, 2019). This may be due to differences in the measuring method of T_s between the present and previous studies (Tong, Baker, Zhang, Kong, & Nie, 2019). Although the mean T_s was calculated from 4 sites in the present study, it was calculated from 12 sites (i.e., head, upper arm, forearm, finger, chest, upper back, lower back, anterior thigh, posterior thigh, anterior calf and posterior calf) in the previous study (Tong, Baker, Zhang, Kong, & Nie, 2019). The decrease in T_s after the commencement of exercise is greater in the extremities than in the trunk (Nakayama et al., 1977). Indeed, the previous study showed that the T_s at the finger most decreased after RW (Tong, Baker, Zhang, Kong, & Nie, 2019). Thus, because of differences in the assignment of regional proportions to calculate T_s between the present and previous studies, decrements of T_s after both RW trials may not be observed in the present study.

Although both RW trials had similar positive influences on the subsequent intermittent sprint performance, the present study reported that RPE at 55 min was significantly higher in the RW90 trial than in the RW30 trial. According to Towlson et al., another situational factors perceived as a major barrier to the implementation of RW was interference with the psychological preparation of the players (Towlson et al., 2013). However, the RPE at 55 min in the RW90 trial was 11.8 ± 2.1 (i.e., between "light" and "somewhat hard"), suggesting that a 1-min RW at 90% of VO_{2max} may not be considered more difficult exercise for the active, younger individuals who participated in this study.

This study had some limitations. First, there was a difference between the exercise mode and intensity used in the present study and that of actual intermittent team sports. This study used two consecutive intermittent cycling exercises. However, most intermittent team sports involve running, jumping and multidirectional running. Moreover, it was not possible to conclude whether the present results could be obtained using actual intermittent team sports. However, a previous study has suggested that there was a moderate correlation between repeated sprint performance performed on a cycle ergometer and during running on the ground (i.e., total work vs total run time) (Fitzsimons, Dawson, Ward, & Wilkinson, 1993). Therefore, intermittent sprint performance following a RW may be increased during actual intermittent team sports. Second, the type of participants involved in the present study did not allow us to make comparisons with professional athletes. Therefore, it is not possible to conclude whether the present results can be applied to these activities or actual intermittent team sports played by professional athletes.

In conclusion, the 1-min cycling RW at 90% of VO_{2max} increased the subsequent intermittent cycling sprint performance over 10 min after the 15-min rest period compared with seated rest, and it was as effective as the 3-min cycling RW at 30% of VO_{2max}. These evidence-based findings may contribute to the implementation of RW within a very short time-frame.

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Declaration of Interest Statement

The authors have no conflicts of interest to disclose.

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585 **Figure captions**

586 Figure 1. Schematic representation of the study protocol.

587 CON: 15 min of seated rest trial, RW30: 3-min RW at 30% of VO_{2max} trial, RW90: 1-
588 min RW at 90% of VO_{2max} trial, CISP: The Cycling Intermittent-Sprint Protocol.

589 Figure 2. The mean work (a), RMS (b) and MDF (c) during sprint for the CISP
590 among three trials.

591 CON: 15 min of seated rest trial, RW30: 3-min RW at 30% of VO_{2max} trial, RW90: 1-
592 min RW at 90% of VO_{2max} trial, RMS: root mean square, MDF: median frequency,
593 CISP: The Cycling Intermittent-Sprint Protocol. (n = 12, mean ± SD)
594 Means were compared by using a repeated-measures two-factor analysis of variance.
595 Mean work: trial $p = 0.002$, RMS: trial $p = 0.024$, MDF: trial $p = 0.004$.

596 Figure 3. VO_2 (a), VCO_2 (b) and RER (c) of the mean values during the CISP.

597 CON: 15 min of seated rest trial, RW30: 3-min RW at 30% of VO_{2max} trial, RW90: 1-
598 min RW at 90% of VO_{2max} trial, VO_2: oxygen uptake, VCO_2: carbon dioxide
599 production, RER: respiratory exchange ratio. (n = 12, mean ± SD)
600 Data are displayed as 30-s averages. Means were compared by using a repeated-
601 measures two-factor analysis of variance. VO_2: trial $p = 0.298$; interaction $p < 0.001$,
602 VCO_2: trial $p = 0.016$; interaction $p < 0.001$, RER: trial $p = 0.002$; interaction $p < 0.001$.
603 * Significant difference between the CON and RW30 trials ($p < 0.05$)
604 # Significant difference between the CON and RW90 trials ($p < 0.05$)
605 † Significant difference between the RW90 and RW30 trials ($p < 0.05$)

606 Figure 4. Changes in oxy-Hb (a), deoxy-Hb (b) and total-Hb (c) from the rest
607 period before the standardised warm-up and SmO_2 (d) of the mean values during
608 the CISP.

609 CON: 15 min of seated rest trial, RW30: 3-min RW at 30% of VO_{2max} trial, RW90: 1-
610 min RW at 90% of VO_{2max} trial, (n = 9, mean ± SD)
611 Data are displayed as 30-s averages. Means were compared by using a repeated-
612 measures two-factor analysis of variance. Δoxy-Hb: trial $p = 0.051$; interaction p =

0.004, Δdeoxy-Hb: trial $p = 0.859$; interaction $p = 0.004$, Δtotal-Hb: trial $p = 0.318$; interaction $p = 0.001$, SmO_2: trial $p = 0.651$; interaction $p = 0.447$.

Significant difference between the CON and RW90 trials ($p < 0.05$)

Table 1. Rectal (T_r), mean skin (T_s) and estimated muscle (T_m) temperatures at each measurement point among three trials.

Variables	Trials	Time (min)				p values
		Pre (before first intermittent exercise)	40 (after first intermittent exercise)	55 (before the CISP)	65 (after the CISP)	
T_r (°C)	CON	37.2 ± 0.2	38.0 ± 0.2	37.8 ± 0.3	37.8 ± 0.3	Trial: $p > 0.05$ Interaction: $p > 0.05$
	RW30	37.2 ± 0.3	37.9 ± 0.3	37.7 ± 0.3	37.9 ± 0.2	
	RW90	37.2 ± 0.2	38.0 ± 0.2	37.8 ± 0.2	38.0 ± 0.2	
Mean T_s (°C)	CON	33.0 ± 0.9	35.3 ± 0.7	33.1 ± 1.0	33.3 ± 1.2	Trial: $p > 0.05$ Interaction: $p < 0.05$
	RW30	33.1 ± 0.6	35.4 ± 0.6	33.5 ± 0.9	34.2 ± 1.0*	
	RW90	33.1 ± 0.7	35.4 ± 0.7	33.4 ± 1.0	34.2 ± 1.2*	
Estimated T_m (°C)	CON	34.0 ± 1.0	37.0 ± 0.9	35.9 ± 0.8	35.5 ± 1.0	Trial: $p > 0.05$ Interaction: $p < 0.05$
	RW30	34.3 ± 1.1	37.3 ± 0.8	36.0 ± 1.1	36.3 ± 1.1*	
	RW90	34.3 ± 0.8	37.3 ± 0.7	36.2 ± 0.8	36.5 ± 1.0*	

Means were compared by using a repeated-measures two-factor analysis of variance. CON: 15 min of seated rest trial, RW30: 3-min RW at 30% of VO_{2max} trial, RW90: 1-min RW at 90% of VO_{2max} trial, CISP: The Cycling Intermittent-Sprint Protocol. (T_r: n = 11, mean T_s and estimated T_m: n = 10, mean ± SD)

* Significantly different from the CON trial ($p < 0.05$)

Figure 1

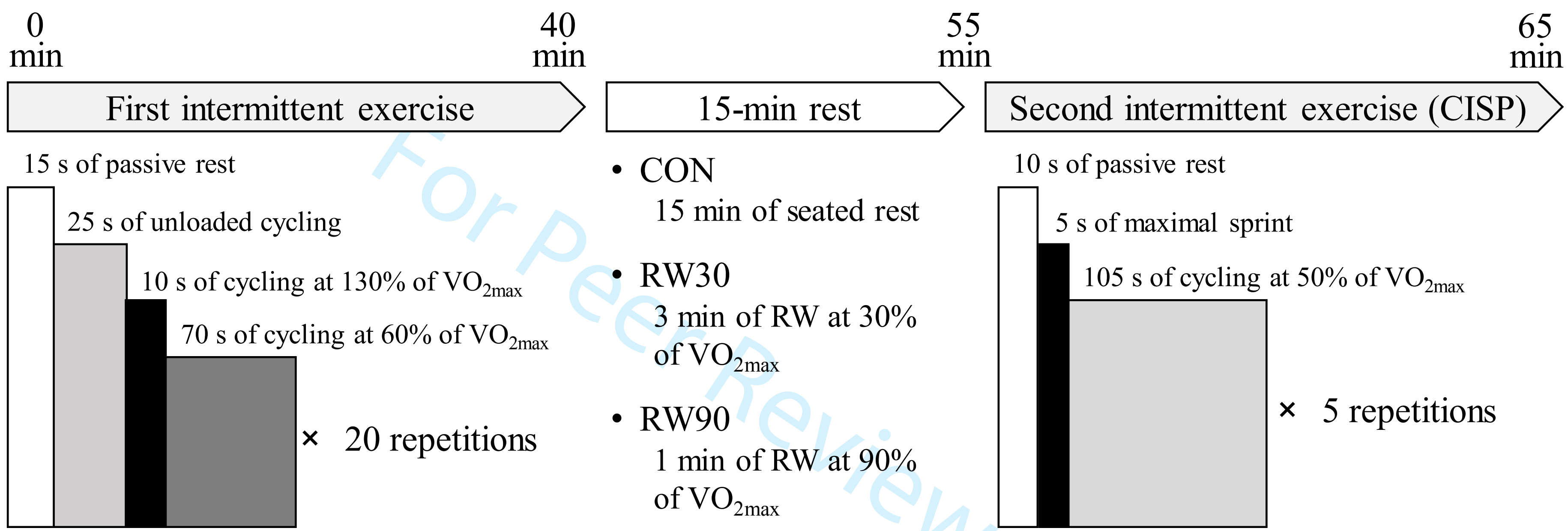

0 min
40 min
55 min
65 min
First intermittent exercise
15-min rest
Second intermittent exercise (CISP)
15 s of passive rest
25 s of unloaded cycling
10 s of cycling at 130% of VO_{2max}
70 s of cycling at 60% of VO_{2max}
× 20 repetitions
• CON
15 min of seated rest
• RW30
3 min of RW at 30% of VO_{2max}
• RW90
1 min of RW at 90% of VO_{2max}
10 s of passive rest
5 s of maximal sprint
105 s of cycling at 50% of VO_{2max}
× 5 repetitions

Figure 2

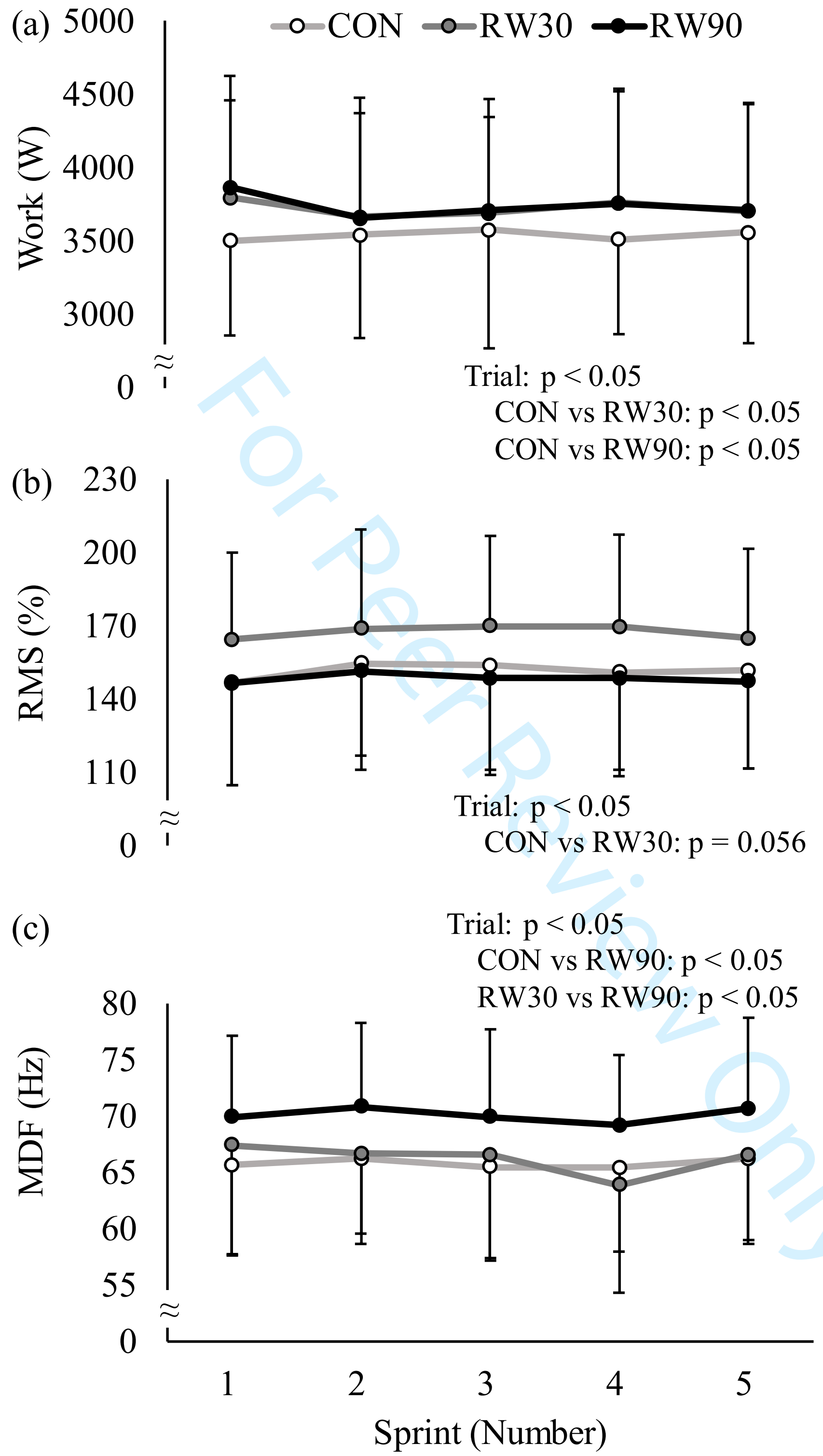

(a)
CON
RW30
RW90
Work (W)
5000
4500
4000
3500
3000
0
Trial: p < 0.05
CON vs RW30: p < 0.05
CON vs RW90: p < 0.05
(b)
RMS (%)
230
200
170
140
110
0
Trial: p < 0.05
CON vs RW30: p = 0.056
(c)
Trial: p < 0.05
CON vs RW90: p < 0.05
RW30 vs RW90: p < 0.05
MDF (Hz)
80
75
70
65
60
55
0
1
2
3
4
5
Sprint (Number)

Figure 3

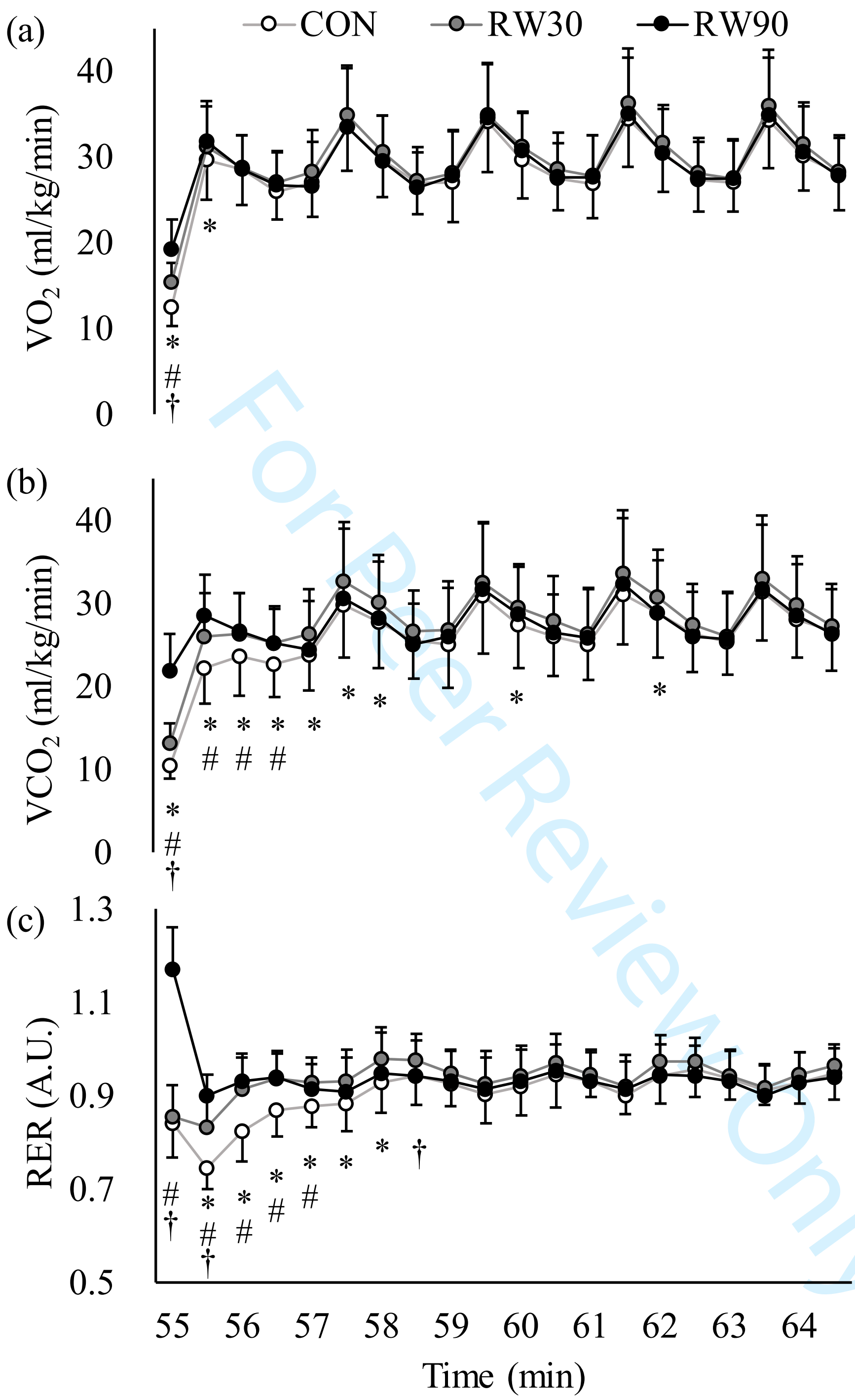
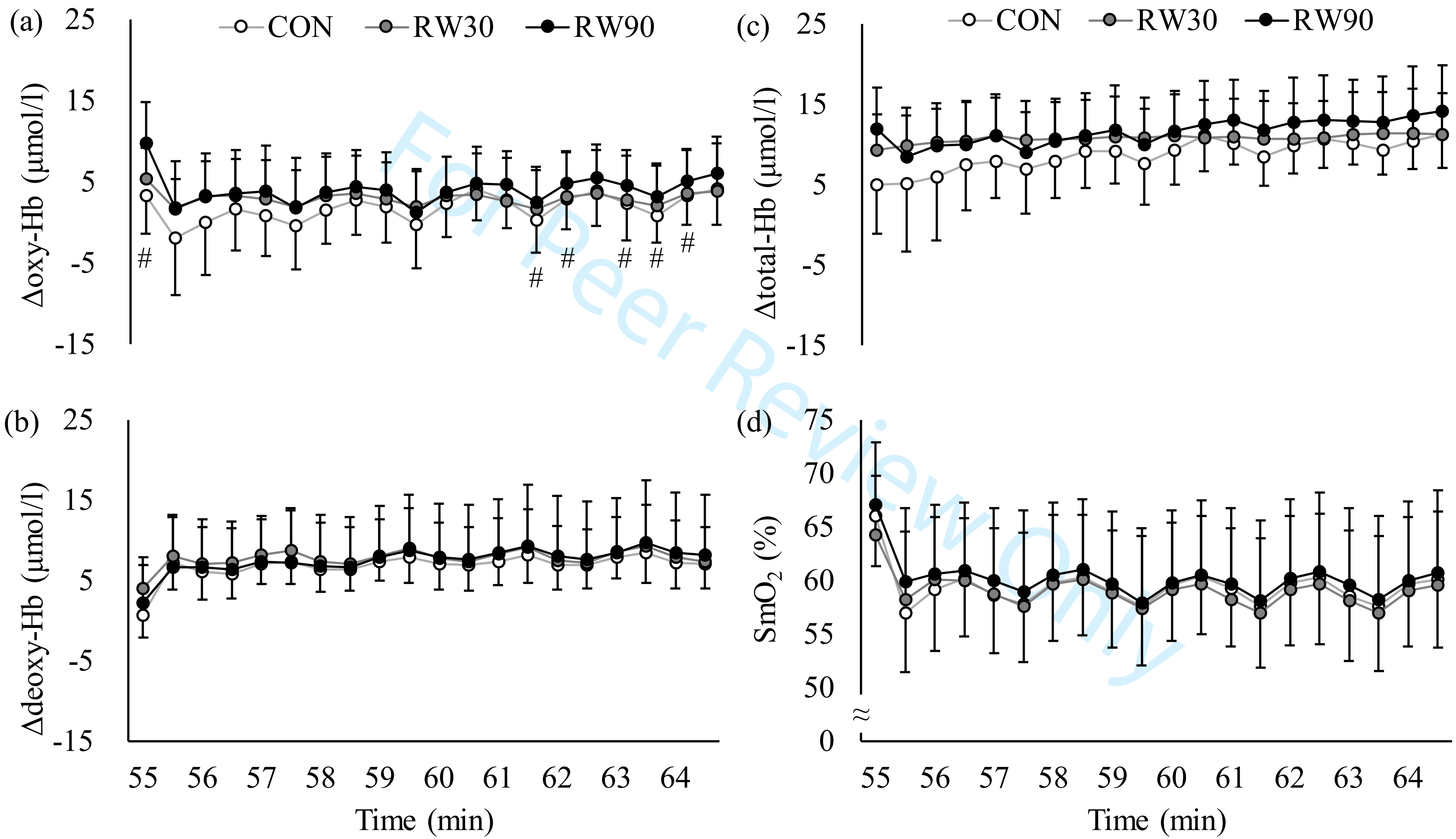

(a)
CON
RW30
RW90
40
30
20
10
0
VO2 (ml/kg/min)
*
*
#
†
(b)
40
30
20
10
0
VCO2 (ml/kg/min)
* * * * * * * * *
# # #
*
#
†
(c)
1.3
1.1
0.9
0.7
0.5
RER (A.U.)
† * # † * # * # * # * * †
55
56
57
58
59
60
61
62
63
64
Time (min)

Figure 4


(a)
CON
RW30
RW90
Δoxy-Hb (μmol/l)
25
15
5
-5
-15
#
#
#
#
#
#
(b)
Δdeoxy-Hb (μmol/l)
25
15
5
-5
-15
55 56 57 58 59 60 61 62 63 64
Time (min)
(c)
CON
RW30
RW90
Δtotal-Hb (μmol/l)
25
15
5
-5
-15
(d)
SmO2 (%)
75
70
65
60
55
50
0
55 56 57 58 59 60 61 62 63 64
Time (min)
For Peer Review Only