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## The effects of work–rest duration on intermittent exercise and subsequent performance

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### Abstract

This study examined the effects of different work–rest durations during 40 min intermittent treadmill exercise and subsequent running performance. Eight males (mean  $\pm$  s: age  $24.3 \pm 2.0$  years, body mass  $79.4 \pm 7.0$  kg, height  $1.77 \pm 0.05$  m) undertook intermittent exercise involving repeated sprints at 120% of the speed at which maximal oxygen uptake ( $v\text{-}\dot{V}O_{2\max}$ ) was attained with passive recovery between each one. The work–rest ratio was constant at 1:1.5 with trials involving short (6:9 s), medium (12:18 s) or long (24:36 s) work–rest durations. Each trial was followed by a performance run to volitional exhaustion at 150%  $v\text{-}\dot{V}O_{2\max}$ . After 40 min, mean exercise intensity was greater during the long ( $68.4 \pm 9.3\%$ ) than the short work–rest trial ( $54.9 \pm 8.1\%$   $\dot{V}O_{2\max}$ ;  $P < 0.05$ ). Blood lactate concentration at 10 min was higher in the long and medium than in the short work–rest trial ( $6.1 \pm 0.8$ ,  $5.2 \pm 0.9$ ,  $4.5 \pm 1.3$  mmol  $\cdot$  l<sup>-1</sup>, respectively;  $P < 0.05$ ). The respiratory exchange ratio was consistently higher during the long than during the medium and short work–rest trials ( $P < 0.05$ ). Plasma glucose concentration was higher in the long and medium than in the short work–rest trial after 40 min of exercise ( $5.6 \pm 0.1$ ,  $6.6 \pm 0.2$  and  $5.3 \pm 0.5$  mmol  $\cdot$  l<sup>-1</sup>, respectively;  $P < 0.05$ ). No differences were observed between trials for performance time (72.7  $\pm$  14.9, 63.2  $\pm$  13.2, 57.6  $\pm$  13.5 s for the short, medium and long work–rest trial, respectively;  $P = 0.17$ ), although a relationship between performance time and 40 min plasma glucose was observed ( $P < 0.05$ ). The results show that 40 min of intermittent exercise involving long and medium work–rest durations elicits greater physiological strain and carbohydrate utilization than the same amount of intermittent exercise undertaken with a short work–rest duration.

**Keywords:** Blood lactate, exercise, heart rate, oxygen consumption, plasma glucose, recovery

### Introduction

A considerable amount of research into exercise physiology and performance has employed continuous exercise protocols. Recently, the interest in intermittent exercise has increased due to its closer resemblance to that seen in team sports. Many of the protocols used in these intermittent exercise studies are based on information from match analysis (e.g. Reilly & Thomas, 1976; Withers, Maricic, Wasilewski, & Kelly, 1982) and may employ a range of work intensities and durations (Drust, Reilly, & Cable, 2000; Nicholas, Nuttal, & Williams, 2000).

Christmass, Dawson, Passeretto and Arthur (1999a) compared the physiological responses of 90 min intermittent running and continuous running of similar energy expenditure in physically active individuals. The intermittent exercise, which involved repeated blocks of 12 s exercise and 18 s

passive rest (12:18 s), demonstrated greater carbohydrate utilization and lower fat utilization than the continuous exercise. Furthermore, when work–rest durations of 6:9 s and 24:36 s were compared, the latter was observed to accentuate carbohydrate utilization (Christmass, Dawson, & Arthur, 1999b). The physiological responses of all three of these work–rest durations and their effects on subsequent performance, however, were not examined.

Although the 24:36 s protocol employed by Christmass *et al.* (1999b) may not truly represent a work–rest duration in many team sports competitions, it is relatively close to that undertaken in a range of training scenarios for sports such as athletics. An examination of the underlying physiological responses during different work–rest durations and a demonstration of the effects on performance will be of use to athletes and coaches alike. Of particular interest would be the possible

interaction of metabolic substrate utilization and the incidence of overtraining. For example, increased carbohydrate metabolism, such as that observed during periods of intense training, has been suggested to contribute to mechanisms underpinning overtraining (Petibois, Cazorla, Poortmans, & Deleris, 2002). Consequently, a comparison of the physiological and metabolic responses of different potential training practices (work–rest durations) may aid coaches in planning appropriate training sessions and in avoiding negative training adaptations. The aim of this study was to examine the hypothesis that intermittent running of long work–rest duration would elicit greater physiological strain and poorer subsequent running performance when compared with intermittent running of short work–rest duration.

## Methods

Eight males (mean  $\pm$  s: age  $24.3 \pm 2.0$  years, body mass  $79.4 \pm 7.0$  kg, height  $1.77 \pm 0.05$  m) volunteered to participate in the study, which had received university ethics committee approval. All participants were recreationally active and trained for games activities two to three times a week. Before testing, each participant was informed of the experimental procedures and provided written informed consent.

During the first visit to the laboratory, each participant's height and body mass were recorded. The participants then undertook an incremental treadmill test to determine maximal oxygen consumption ( $\dot{V}O_{2\max}$ ) on a motorized treadmill (Woodway ELG 55 Ergo). The participants were initially required to run for 5 min at a speed of between 6 and 8 km  $\cdot$  h $^{-1}$  as a warm-up. After completing the warm-up, the treadmill test started at a speed of 8 km  $\cdot$  h $^{-1}$  and was subsequently increased by 1 km  $\cdot$  h $^{-1}$  each minute until volitional exhaustion. The treadmill grade during the test was set at a 1% incline, as this has been shown to elicit the energy costs of outdoor running (Jones & Doust, 1996).

The participants were connected to an online metabolic cart (Vacumed Turbofit, Vacumed, USA) via a facemask and expired air sample line. Expired air was analysed for oxygen consumption ( $\dot{V}O_2$ ), carbon dioxide production ( $\dot{V}CO_2$ ), minute ventilation ( $\dot{V}_E$ ) and respiratory exchange ratio (RER) with a sample time of 15 s. Fingertip arterialized capillary samples (20  $\mu$ l) were collected for the analysis of blood lactate concentration at rest and 5 min after volitional exhaustion (Analox P-LM5, Analox Instruments). Heart rate was recorded at rest and throughout exercise (Polar Heart Rate Monitor, Kempele, Finland). The participants were familiarized with all the test procedures and were requested to wear a safety harness throughout exercise.

On subsequent visits to the laboratory, each participant undertook three different intermittent exercise protocols on separate occasions. The order of testing was randomized and separated by at least 7 days. The participants were required to maintain a similar diet and exercise regimen in the 3 days before participation in each protocol. Before each intermittent test, they were required to undertake an overnight fast.

Each protocol lasted 40 min and involved a repeated exercise bout consisting of a work–rest duration of 1:1.5 (Christmass *et al.*, 1999a,b). The protocols employed short duration work–rest exercise, which involved a repeated work–rest bout of 6 s exercise and 9 s passive recovery (6:9 s), medium duration work–rest exercise (12:18 s) or long duration work:rest exercise (24:36 s). The speed of the intermittent protocols was equivalent to 120% of each participant's maximal running speed in the preliminary  $\dot{V}O_{2\max}$  test ( $v\text{-}\dot{V}O_{2\max}$ ) (Christmass *et al.*, 1999a). The participants wore a safety harness at all times as in the preliminary tests. Before each sprint (passive recovery), the participants stood astride the moving belt and then transferred themselves onto the moving belt to begin exercise. All participants were familiar with the technique and were able to accelerate to the required sprinting speed quickly. The treadmill gradient was set at 1% throughout each protocol. Each protocol was identical in terms of treadmill speed (120%  $\dot{V}O_{2\max}$ ) and total work duration (16 min). Consequently, each trial was matched for total work done. Before each intermittent protocol, the participants underwent a 10 min warm-up. This consisted of 5 min running on the treadmill followed by 5 min of the participant's usual stretching routine. The treadmill speed was the same for each participant for each trial (no more than 12 km  $\cdot$  h $^{-1}$ ). Once the warm-up was completed, the 40 min intermittent running protocol began. On completion of the final sprint of each protocol, arterialized capillary blood samples were taken (see later in Methods) during the appropriate rest period (total trial time = 40 min). A post-exercise venous blood sample was then taken. As soon as possible after blood sampling, the participants were required to exercise continuously on the treadmill until volitional exhaustion at a treadmill speed set to elicit 150%  $v\text{-}\dot{V}O_{2\max}$ .

Expired air was analysed continuously at rest, during the 40 min intermittent exercise protocol and performance trial for  $\dot{V}O_2$ ,  $\dot{V}CO_2$ ,  $\dot{V}_E$  and RER. Respiratory data were averaged over 1 min intervals (Christmass *et al.*, 1999b). Although each intermittent protocol did not elicit true "steady-state" responses, the use of a 1 min average has been previously justified (Christmass *et al.*, 1999b). In brief, this procedure can be used when stable lactate

and bicarbonate pools are established, usually within 15 min. Consequently, 1 min respiratory averages after this point in time have been considered valid. Furthermore, indirect calorimetry can be used when constant  $\dot{V}_E$  and  $\dot{V}CO_2$  responses are observed (Christmass *et al.*, 1999b). In the present study, these responses were stable over each analysis period and consequently indirect calorimetry was performed. The percentage energy utilization from carbohydrate and fat were subsequently calculated from standard methods based on non-protein RER values. Heart rate was monitored continuously.

Fingertip arterialized capillary blood samples (20  $\mu$ l) were collected and analysed for blood lactate at rest, after 5, 10, 20, 30 and 40 min of exercise and after completion of the performance test. A venous blood sample (7 ml) was collected from the ante-cubital vein at rest and at the end of the 40 min protocol. Once collected, the samples were centrifuged for 15 min after which the plasma was collected and transferred in equal amounts to two Eppendorf tubes (1.75 ml). The Eppendorf tubes were then frozen at  $-20^\circ\text{C}$  for later analysis of glucose (Analox GM7 Multi-assay analyser, Analox Instruments).

Triplicate haematocrit samples were analysed using a micro-capillary centrifuge for 15 min (International Equipment Company, Massachusetts, USA) and a portable micro-haematocrit reader (Hawksley Reader, Hawksley & Sons, Sussex, UK). Further capillary blood samples were collected into three 10  $\mu$ l microcurvettes for the analysis of haemoglobin (Clandon HemoCue, HemoCue Ltd, Sheffield, UK). Values for pre- and post-exercise haematocrit and haemoglobin were used to estimate changes in plasma volume (Dill & Costill, 1974). Body mass was also recorded before and after exercise.

The analysis of heart rate, RER,  $\dot{V}O_2$  and blood parameters was performed using a two-way analysis of variance (ANOVA) with repeated measures on both factors (trial  $\times$  time). Statistical significance was set at  $P < 0.05$ . In the case of statistical significance, Scheffé *post-hoc* analysis was undertaken. Changes in body mass, plasma volume and performance time data were analysed by one-way ANOVA with repeated measures. Correlations between physiological parameters at the end of 40 min intermittent exercise and performance time were calculated using Pearson's correlation coefficient ( $r$ ). All statistical procedures were undertaken using conventional statistical software (SPSS).

## Results

The physiological characteristics of the participants together with their resultant treadmill speeds for the intermittent protocol are shown in Table I.

There was a significant main effect of heart rate over time ( $P < 0.05$ ), whereas heart rate during both the medium and long work–rest trials tended to be higher than in the short work–rest trial from 5 min of exercise ( $161 \pm 8$ ,  $167 \pm 6$ ,  $166 \pm 7$  beats  $\cdot$  min $^{-1}$  for the short, medium and long trials, respectively) until the end of the exercise period (main effect for trial  $P = 0.07$ ; Figure 1).

A significant main effect was also observed for oxygen consumption between trials ( $P < 0.05$ ; Figure 2). *Post-hoc* analysis revealed differences between the short and long work–rest protocols ( $P < 0.05$ ). From 10 min of exercise,  $\dot{V}O_2$  remained relatively constant in all protocols ( $2.35 \pm 0.81$ ,  $2.65 \pm 0.84$ ,  $3.09 \pm 0.93$  l  $\cdot$  min $^{-1}$  for the short, medium and long trials, respectively) until the end of exercise ( $2.54 \pm 0.59$ ,  $2.68 \pm 0.71$ ,  $3.02 \pm 0.47$  l  $\cdot$  min $^{-1}$  for the short, medium and long trials, respectively). Mean exercise intensities over the entire 40 min protocol for the short,

Table I. Physiological characteristics of the participants and intermittent exercise protocols (mean  $\pm$  s)

Characteristic	Mean $\pm$ s
$\dot{V}O_{2\text{max}}$ (ml $\cdot$ kg $^{-1}$ $\cdot$ min $^{-1}$ )	$55.7 \pm 8.5$
$\dot{V}O_{2\text{max}}$ (l $\cdot$ min $^{-1}$ )	$4.40 \pm 0.70$
Peak heart rate (beats $\cdot$ min $^{-1}$ )	$187 \pm 9$
Blood lactate peak (mmol $\cdot$ l $^{-1}$ )	$8.0 \pm 2.2$
Peak RER	$1.10 \pm 0.10$
$\dot{V}_{E\text{peak}}$ (l $\cdot$ min $^{-1}$ )	$67.7 \pm 9.2$
Treadmill speed at 120% $\dot{V}O_{2\text{max}}$ (km $\cdot$ h $^{-1}$ )	$17.8 \pm 1.7$
Treadmill speed at 150% $\dot{V}O_{2\text{max}}$ (km $\cdot$ h $^{-1}$ )	$21.9 \pm 2.2$
Distance covered during 40 min (m)	$4755 \pm 464$

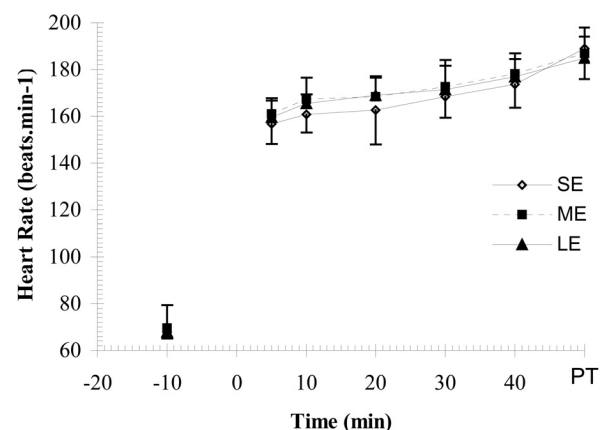


Figure 1. Heart rate at rest, during intermittent exercise of different work–rest durations and after completion of the performance test (PT).  $\diamond$ , short work–rest trial;  $\blacksquare$ , medium work–rest trial;  $\blacktriangle$ , long work–rest trial. Significant main effect observed for time:  $P < 0.05$ .

medium and long work–rest trials were  $54.9 \pm 8.1$ ,  $59.0 \pm 8.4$  and  $68.4.2 \pm 9.3\%$   $\dot{V}O_{2max}$ , respectively ( $P < 0.05$ ).

There was a significant main effect of RER between trials ( $P < 0.05$ ). The RER during both the short and medium work–rest trials was lower than in the long work–rest trial ( $P < 0.05$ ). The RER was consistently higher during the long work–rest trial from 5 min of exercise ( $0.87 \pm 0.03$ ,  $0.89 \pm 0.06$ ,  $0.94 \pm 0.04$  for the short, medium and long trials, respectively) until the end of exercise ( $0.92 \pm 0.02$ ,  $0.94 \pm 0.02$ ,  $0.96 \pm 0.03$  for the short medium and long trials, respectively; Figure 3).

Although  $\dot{V}O_2$  and the RER were higher during the long work–rest trial, energy expenditure at 5 min of exercise was not significantly different compared with the short and medium work–rest

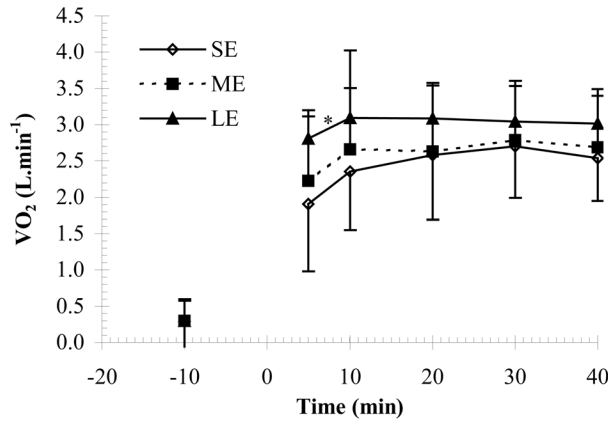


Figure 2. Oxygen consumption ( $\dot{V}O_2$ ) at rest and during intermittent exercise of different work–rest durations.  $\diamond$ , short work–rest trial;  $\blacksquare$ , medium work–rest trial;  $\blacktriangle$ , long work–rest trial. \* Significantly different from short work–rest trial (main effect for trial:  $P < 0.05$ ).

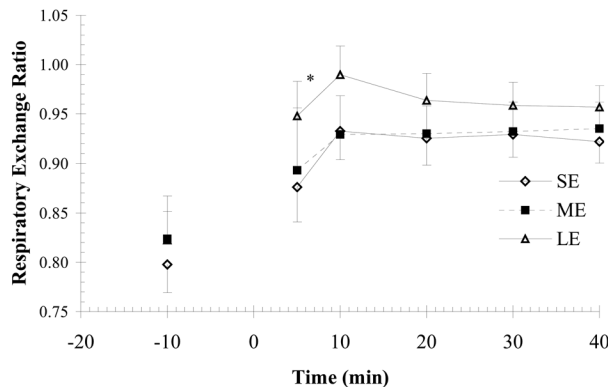


Figure 3. Respiratory exchange ratio at rest and during intermittent exercise of different work–rest durations.  $\diamond$ , short work–rest trial;  $\blacksquare$ , medium work–rest trial;  $\blacktriangle$ , long work–rest trial. \* Significantly different from both the short and medium work–rest trials (main effect for trial:  $P < 0.05$ ).

trials ( $10.8 \pm 4.5$ ,  $11.6 \pm 5.1$ ,  $12.5 \pm 5.2$  kcal·min<sup>-1</sup>, respectively). However, energy expenditure increased for all trials ( $P < 0.05$ ) by the end of exercise period ( $13.1 \pm 3.2$ ,  $14.1 \pm 4.6$ ,  $15.9 \pm 2.3$  kcal·min<sup>-1</sup> for the short, medium and long trials, respectively). Significant main effects were observed for percent carbohydrate utilization between trials and over time ( $P < 0.05$ ). *Post-hoc* analysis revealed differences between the short and medium compared with the long work–rest trial for percent carbohydrate utilization ( $P < 0.05$ ), with the values remaining fairly constant from 10 min of exercise ( $77 \pm 10\%$ ,  $75 \pm 15\%$ ,  $92 \pm 9\%$  for the short, medium and long trials, respectively) until the end of exercise ( $73 \pm 3\%$ ,  $73 \pm 8\%$ ,  $87 \pm 11\%$  for the short, medium and long trials, respectively).

The blood lactate concentrations for all trials at rest, during each intermittent protocol and performance test are shown in Figure 4. Main effects for both time and trial were observed ( $P < 0.05$ ). *Post-hoc* analysis of the main effect between trials revealed that all trials were significantly different from each other (short vs. medium, short vs. long and medium vs. long,  $P < 0.05$ ). Blood lactate concentration increased from rest ( $1.7 \pm 0.8$ ,  $1.9 \pm 0.7$ ,  $1.9 \pm 0.6$  mmol·l<sup>-1</sup> for the short, medium and long trials, respectively) revealing a graded response at 10 min of exercise ( $4.5 \pm 1.3$ ,  $5.2 \pm 0.9$ ,  $6.1 \pm 0.8$  mmol·l<sup>-1</sup> for the short, medium and long trials, respectively). Concentrations were then similar until the end of exercise ( $5.8 \pm 2.4$ ,  $5.1 \pm 1.1$ ,  $6.5 \pm 1.1$  mmol·l<sup>-1</sup> for the short, medium and long trials, respectively).

Plasma glucose concentration before and after each intermittent protocol is shown in Figure 5. No differences were noted between groups, although a

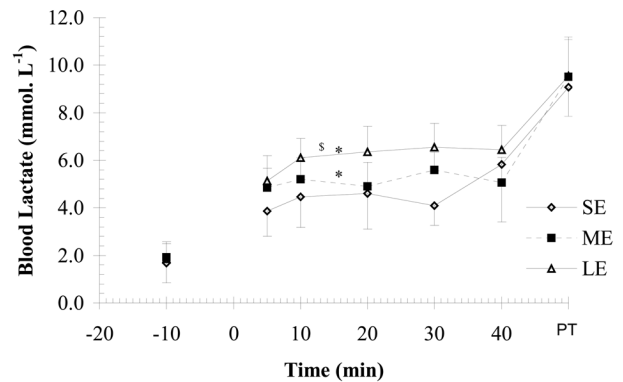


Figure 4. Blood lactate concentration at rest, during intermittent exercise of different work–rest durations and after completion of the performance test (PT).  $\diamond$ , short work–rest trial;  $\blacksquare$ , medium work–rest trial;  $\blacktriangle$ , long work–rest trial. \* Significantly different from short work–rest trial (main effect for trial:  $P < 0.05$ ). <sup>S</sup> Significantly different from medium work–rest trial (main effect for trial:  $P < 0.05$ ).

main effect for time was observed ( $P < 0.05$ ). Despite similar pre-exercise plasma glucose concentrations ( $4.8 \pm 0.6$ ,  $5.1 \pm 0.4$ ,  $4.7 \pm 0.6 \text{ mmol} \cdot \text{l}^{-1}$  for the short, medium and long trials, respectively), a small increase only in plasma glucose was observed for the short work–rest trial post exercise ( $5.3 \pm 0.5 \text{ mmol} \cdot \text{l}^{-1}$ ) compared with the much greater increases during the longer exercise protocols ( $6.6 \pm 0.2$ ,  $5.9 \pm 0.1 \text{ mmol} \cdot \text{l}^{-1}$  for the medium and long trials, respectively;  $P < 0.05$ ).

No differences were observed for change in body mass between trials ( $0.8 \pm 0.3$ ,  $0.9 \pm 0.4$ ,  $0.9 \pm 0.5 \text{ kg}$  for the short, medium and long trials, respectively;  $P > 0.05$ ) or change in plasma volume ( $-3.09 \pm 4.82$ ,  $-3.87 \pm 2.36$  and  $-0.04 \pm 9.79\%$  for the short, medium and long trials, respectively;  $P > 0.05$ ). Changes in body mass extrapolated to sweat rates of  $1.2 \pm 0.5$ ,  $1.4 \pm 0.7$  and  $1.4 \pm 0.8 \text{ l} \cdot \text{h}^{-1}$ , respectively ( $P > 0.05$ ).

Performance data for the three exercise protocols are shown in Table II. Although not significant, the longest run times to volitional exhaustion were observed for the short work–rest trial when compared with the medium and long work–rest trials ( $72.7 \pm 14.9$ ,  $63.2 \pm 13.2$ ,  $57.6 \pm 13.5 \text{ s}$ , respec-

tively;  $P = 0.17$ ). Regarding the relationship between the duration of the run to exhaustion and the physiological parameters after 40 min intermittent exercise, significant correlations were only observed between performance duration and plasma glucose concentration ( $r = -0.46$ ;  $P < 0.05$ ) and between performance duration and heart rate ( $r = -0.50$ ;  $P < 0.05$ ).

## Discussion

The main finding of this study is that 40 min of intermittent exercise involving long and medium work–rest durations elicits greater physiological strain and carbohydrate utilization than the same duration of intermittent exercise with a short work–rest duration. Furthermore, performance duration was related to plasma glucose concentration and heart rate post intermittent exercise.

Despite running speed and total exercise time (and therefore total work done) during each protocol being matched, heart rate tended to be higher during the long and medium work–rest trials than the short work–rest trial. This finding suggests that medium and long work–rest trials were physiologically more demanding. Interestingly, heart rate during all trials was above 90% of maximal heart rate as previously recorded for the medium work–rest trial (89%; Christmass *et al.*, 1999a) and consistent with the heart rates recorded during many popular sporting activities (Boyle, Mahoney, & Wallace, 1983; DeAngelis, Vinciguerra, Gasabari, & Pacitti, 1998; Ekblom, 1986; McInnes, Carlson, Jones, & McKenna, 1995). The distance covered during the 40 min of exercise was also similar to that reported for high-level soccer (Bangsbo, 1994). Although the physiological demands of each protocol differed between trials, each protocol may be considered as representative of intermittent team sports and similar to previous studies for comparison.

Similar to heart rate, oxygen consumption was higher during the long compared with the medium and short work–rest durations (approximately 68%, 60% and 55%  $\dot{V}O_{2\text{max}}$ , respectively). This contrasts with the findings of Christmass *et al.* (1999b), who reported lower % $\dot{V}O_{2\text{max}}$  values for the long (65%) than the short work–rest trial (71%). These authors suggested that there was an extra oxygen cost during short work–rest durations, possibly due to more frequent transfers on and off the moving treadmill belt. However, the authors also presented data on vastus lateralis haemoglobin saturation during both the short and long protocols that indicated no differences in oxygen metabolism between the two trials. Differences in oxygen cost between trials therefore may not have been due to the activity of the lower limbs *per se*, but instead due to the more

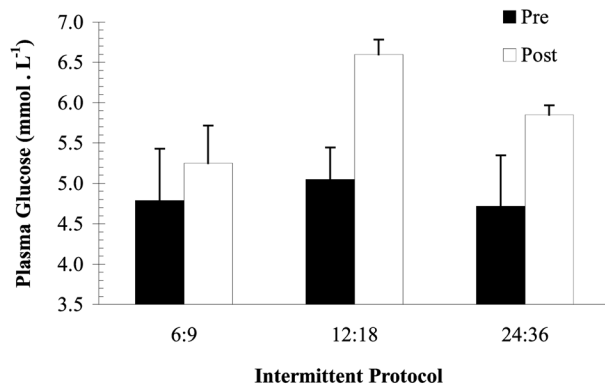


Figure 5. Plasma glucose concentration before (■) and after (□) 40 min of intermittent exercise of differing work–rest durations. Significant main effect observed pre and post exercise ( $P < 0.05$ ).

Table II. Performance trial data for the short, medium and long work–rest trials (mean  $\pm$  s). Heart rate and blood lactate data are end exercise values

	Intermittent protocol		
	Short (6:9 s)	Medium (12:18 s)	Long (24:36 s)
Time (s)	72.7 $\pm$ 14.9	63.2 $\pm$ 13.2	57.6 $\pm$ 13.5
Distance covered (m)	369 $\pm$ 160	330 $\pm$ 140	309 $\pm$ 143
Heart rate (beats $\cdot$ min <sup>-1</sup> )	189 $\pm$ 13	187 $\pm$ 11	185 $\pm$ 9.0
Blood lactate (mmol $\cdot$ l <sup>-1</sup> )	9.1 $\pm$ 1.0	9.5 $\pm$ 2.0	9.5 $\pm$ 2.0

frequent use of the arms in transferring the participant on and off the treadmill. This explanation, however, is not supported by the results of the present study. The transfer on and off the treadmill belt would certainly contribute to total exercise time for each 6 s sprint and should be considered in light of the lower  $\dot{V}O_2$  during the short work–rest trial in the present study. As the treadmill belt was moving continuously at the test speed, all participants reached the test speed very quickly and probably with less acceleration time than sprints performed in the field, where it takes longer to reach a given running speed. In addition, the participants were familiarized with such procedures and all of them adjusted to the treadmill speed rapidly during each trial. We are confident that the present observations are primarily due to underlying physiological responses rather than any significant methodological differences between protocols.

Although the present study was unable to examine specific muscle metabolites, it is pertinent to speculate the possible role of phosphocreatine and underlying energy systems during the protocols employed. Bogdanis, Nevill, Boobis and Lakomy (1996) noted that aerobic metabolism contributed substantially to adenosine triphosphate re-synthesis during high-intensity exercise without a dramatic decline in power output. Although the protocol of Bogdanis *et al.* consisted of a series of sprints, lasting much less than 40 min in duration, their results do demonstrate how aerobic metabolism can contribute to sprint performance of longer durations. A substantial contribution of the aerobic energy pathways has indeed been acknowledged by a number of authors (Bogdanis *et al.*, 1996; Gaitanos, Williams, Boobis, & Brooks, 1993; Gastin, 2001). The exercise intensities in these earlier studies were generally maximal sprints, whereas those in the present study, although of high intensity, were lower at 120% of maximal aerobic power. It is reasonable to suggest that the rate of phosphocreatine utilization during each run in the present study would be lower, presumably also requiring less (although still significant) re-synthesis than single/multiple sprint studies. A lower initial rate of phosphocreatine utilization, resulting in less depletion, may allow this energy system to contribute to energy requirements for longer and thus be a more significant contributor to total energy expenditure during the short work–rest trial. This would certainly be consistent with the lower oxygen consumption and blood lactate concentrations during the short work–rest trial.

After 10 min of exercise, blood lactate concentration in all trials began to plateau, with the highest values consistently observed throughout the long work–rest trial and the lowest values during the short work–rest trial. Such a graded blood lactate

response between trials suggests a difference between the metabolic responses of intermittent exercise with different work–rest durations. Christmass *et al.* (1999b; Christmass, Dawson, Goodman, & Arthur, 2001) have previously demonstrated higher blood lactate concentrations during long compared with short work–rest durations. Our results lend support to this observation. Interestingly, the current study incorporated passive recovery, which, unlike active recovery, does not allow for optimal blood lactate removal (Belcastro and Bonen, 1975). Consequently, the long work–rest protocol may have resulted in a greater disturbance to muscle homeostasis and subsequent performance than if active recovery was employed.

Plasma glucose concentrations on completion of the 40 min intermittent protocol increased for all trials, which is similar to previous studies of intermittent exercise with a range of intensities and durations and at a similar time-point (Nicholas *et al.*, 2000). The increase in plasma glucose during the present study was greater for the medium and long than the short work–rest trial. It is possible that the plasma glucose response experienced during the medium and long work–rest trials was induced by an increased rate of muscle glycogen utilization during the longer exercise durations, increasing the reliance on hepatic glucose release in attaining both blood and muscle glucose homeostasis. Such a response would be consistent with the blood lactate responses observed, in that the longer work–rest duration would require greater glycolytic metabolism. The plasma glucose responses may also be related to catecholamine release and the specific exercise intensity elicited ( $\% \dot{V}O_{2max}$ ) during intermittent exercise. Greater catecholamine release, particularly noradrenaline, is generally observed with higher intensities of exercise (Cooper, Barstow, Bergner, & Lee, 1989; Flore, Therminaris, Oddou-Chirpaz, & Quirio, 1992) resulting in a direct stimulation of hepatic glucose production (Naveri, Kuoppasalmi, & Harkonen, 1985). Christmass *et al.* (1999b) observed similar increases in noradrenaline during both short and long work–rest durations, suggesting similar catecholamine control of metabolism. However, although Christmass *et al.* (1999b) did not measure blood or muscle glucose concentration directly, a greater carbohydrate oxidation was inferred from indirect calorimetry calculations, with the authors suggesting a metabolic control factor inherent to muscle itself. If in the present study catecholamine release was indeed similar between trials, this would not account for the observed differences in plasma glucose concentrations. Other factors such as the differences in elicited exercise intensity ( $\dot{V}O_{2max}$ ) may be responsible. This would certainly be consistent with the lower exercise

intensity during the short work–rest trial, and the modest change in plasma glucose concentration during this trial. It may be more likely that the different exercise intensities observed were a result of differences in the relative contributions of the underlying energy systems, which, in turn, relate to the specific work durations of each trial.

The results of this study all point towards the long work–rest duration in particular, but also the medium one, being physiologically more stressful when compared with the short work–rest duration. Furthermore, despite the running speed and total exercise duration being the same in each trial, the rate at which carbohydrates were utilized was faster during the long work–rest trial. This suggests that glycogen utilization was greater during the long work–rest trial, which may be related to running performance (Saltin, 1973; Walker, Heigenhauser, Hultman, & Spriet, 2000). Although not significant, performance time did tend to be reduced during the longer work–rest trials, and indeed one of the only two significant (inverse) relationships with performance time was 40 min plasma glucose concentration. This would suggest a link between performance trial duration and hepatic glycogenolysis in restoring muscle carbohydrate stores and consequently the work–rest duration.

The range of values within the performance data of the present study, although consistent across trials, is likely to have precluded statistical significance being achieved. However, both the medium and long work–rest trials demonstrated considerable reductions in running performance (88 and 81%, respectively) compared with the short work–rest trial. Further studies with more homogeneous groups, particularly individuals more likely to undertake such training procedures on a regular basis, may produce clearer differences in performance. As blood lactate demonstrated a graded response during the three protocols in the present study, it is possible that muscle and blood pH would be similarly affected. Although pH was not measured, data from our laboratory (unpublished observations) suggest that blood pH is lower during long than short work–rest durations, unlike Christmass *et al.* (1999b), who observed similar values for short and long work–rest durations. The impact of such possible contributing factors to performance requires further study.

In summary, the results of this study show that 40 min of intermittent exercise involving long and medium work–rest durations elicit greater physiological strain and carbohydrate utilization than the same amount of intermittent exercise undertaken with a short work–rest duration. Although no differences were observed in run time to exhaustion after intermittent exercise, the performance duration was related to plasma glucose concentration and

heart rate at 40 min of intermittent exercise, reflecting the greater physiological strain of the long and medium duration protocols.

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