The aim of this study was to determine the influence of type of warm-up on metabolism and performance during high-intensity exercise. Eight males performed 30 s of intense exercise at 120% of their maximal power output followed, 1 min later, by a performance cycle to exhaustion, again at 120% of maximal power output. Exercise was preceded by active, passive or no warm-up (control). Muscle temperature, immediately before exercise, was significantly elevated after active and passive warm-ups compared to the control condition (36.9 ± 0.18°C, 36.8 ± 0.18°C and 33.6 ± 0.25°C respectively; mean ± s) (P < 0.05). Total oxygen consumption during the 30 s exercise bout was significantly greater in the active and passive warm-up trials than in the control trial (1017 ± 22, 943 ± 53 and 838 ± 45 ml O₂ respectively). Active warm-up resulted in a blunted blood lactate response during high-intensity exercise compared to the passive and control trials (change = 5.53 ± 0.52, 8.09 ± 0.57 and 7.90 ± 0.38 mmol·l⁻¹ respectively) (P < 0.05). There was no difference in exercise time to exhaustion between the active, passive and control trials (43.9 ± 4.1, 48.3 ± 2.7 and 46.9 ± 6.2 s respectively) (P = 0.69). These results indicate that, although the mechanism by which muscle temperature is elevated influences certain metabolic responses during subsequent high-intensity exercise, cycling performance is not significantly affected.

Keywords: blood lactate, cycling, muscle temperature.

Introduction

The effects of heating on the contractile properties of skeletal muscle have been studied extensively. It is clear from this research that increasing muscle temperature increases the speed of muscle contraction, thereby decreasing both time to peak tension and half relaxation time (Davies and Young, 1983; Bennett, 1984). Furthermore, these findings are consistent irrespective of whether muscle temperature is elevated as a consequence of exercise or passive heating (Davies et al., 1982).

Studies of the effects of increasing muscle temperature on metabolism during subsequent high-intensity exercise, however, have produced conflicting findings dependent on the nature of the warm-up used. Robergs et al. (1991) reported a greater increase in the aerobic contribution to a standard high-intensity exercise bout after an active warm-up, whereas an increase in the contribution from anaerobic sources was observed during a similar high-intensity exercise bout after a local passive warm-up (Febbraio et al., 1996). In both these studies, it was suggested that the alterations in metabolic response during exercise were associated with elevations in muscle temperature. To date, only two studies have assessed the metabolic response during exercise after both an active and a passive warm-up (Elbel and Mikols, 1972; Inger and Stromme, 1979). It is difficult to draw any firm conclusions from the results of these studies because of the failure to control for muscle temperature between the experimental trials.

The effects of elevated muscle temperature on performance indices during high-intensity dynamic exercise of short duration have also been investigated; again equivocal findings have been reported. Where local passive warm-up has been used to increase muscle temperature, either an improvement (Sargeant, 1987) or no beneficial effect (Davies and Young, 1983) on subsequent short-term power output has been reported. When exercise is immediately preceded by a low-intensity active warm-up (30–60% of maximal oxygen

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uptake, \( \dot{V}O_{2\text{max}} \), maximal peak power and exercise time to exhaustion are enhanced, whereas after a higher-intensity warm-up (70–100% \( \dot{V}O_{2\text{max}} \)), there is a decrement in these performance parameters (De Bruyn-Prevost and Lefebvre, 1980; Sargeant and Dolan, 1987). When recovery of 5–6 min is introduced between a high-intensity warm-up and exercise, there is an improvement in maximal peak power (Sargeant and Dolan, 1987), but still no effect on exercise time to exhaustion (De Bruyn-Prevost and Lefebvre, 1980). The sports practice of both recreational and elite athletes will always include an active warm-up that incorporates both low- and high-intensity dynamic exercise followed by an intervening rest period when preparing for a high-intensity event. To date, no well-controlled studies have looked at the effect of this type of warm-up on subsequent high-intensity exercise performance.

The aims of the present study were two-fold: first, to compare metabolic responses to high-intensity exercise after active, passive or no warm-up and, secondly, to determine the effects of an active warm-up, typical of an athlete’s preparation for high-intensity exercise performance, compared to passive warm-up and a control. We hypothesized that differing metabolic responses will be observed during exercise when pre-exercise muscle temperature is elevated by active and passive mechanisms and that these differences may affect high-intensity cycling performance of short duration.

**Methods**

**Participants**

Eight healthy males volunteered to participate in the study, which received approval from the University of Strathclyde Ethics Committee. Before the study, all participants were required to sign a letter of informed consent. The age, height, body mass, percent body fat, peak oxygen uptake (\( \dot{V}O_{2\text{peak}} \)) and maximal power output of the participants were 27.3 ± 1.9 years, 1.81 ± 0.02 m, 81.4 ± 2.5 kg, 17.1 ± 1.1%, 47.2 ± 1.8 ml·kg\(^{-1}\)·min\(^{-1}\) and 333 ± 13 W respectively (mean ± s.e.).

**Experimental design**

Each participant was required to visit the laboratory on six separate occasions over 4–5 weeks to complete the following tests:

**Determination of maximal power output and peak oxygen uptake.** Peak oxygen uptake was determined directly for each participant using a continuous incremental cycling test to volitional exhaustion on a friction-braked cycle ergometer (Monark, Sweden). The test was initiated at 35 W and increased by 35 W every 2 min for the first 6 min and then every minute until the participants could continue no longer. Expired air was analysed continuously throughout the test using an automated on-line gas analysis system (Oxycongamma, Mijnhardt BV, Holland). The workload at which a participant reached exhaustion was taken to be the maximal power output at \( \dot{V}O_{2\text{peak}} \). During this visit, percent body fat was estimated from skinfold thickness measured at four sites (biceps, triceps, subscapular and suprailiac; Durnin and Womersley, 1974) using constant pressure calipers.

**Familiarization trials.** Two familiarization trials were conducted 5–7 days apart. The purpose of these trials was to accustom the participants with the experimental protocol and procedures, and with high-intensity exercise, before undertaking the main experimental trials. In addition, these trials were used to monitor the warm-up effects on both muscle temperature response and hydration status.

**Experimental trials.** Three experimental trials were performed 1 week apart, at the same time of day and in the same environmental conditions (22.4 ± 0.1°C, 50 ± 2% relative humidity). During these trials, the participants performed a criterion exercise task that consisted of cycling at 120% of their individual maximal power output for 30 s. After 1 min rest, the participants completed a performance test that required them to cycle to exhaustion, again at 120% of maximal power output. Exhaustion was defined as the instant at which a participant was no longer able to maintain the required pedal cadence (120 rev·min\(^{-1}\)) and, despite verbal encouragement to do so, remained below this target for 3 s. At this time, the test was terminated and exercise time to exhaustion was recorded. The participants were not informed of their exercise duration at any stage during the study.

On each visit to the laboratory, exercise was preceded by one of three experimental conditions:

- **Active warm-up:** the participants were required to cycle at 40% of maximal power output for 5 min. After 1 min rest, they then performed four 15 s sprints at 120% of maximal power output, with 15 s rest between sprints.
- **Passive warm-up:** the participants were required to sit quietly in an environmental chamber (SANYO Gallenkamp plc, UK) maintained at constant temperature (45°C) and relative humidity (70%) until muscle temperature reached the same value achieved during the active warm-up (determined from either the main trial or the familiarization trial). After the warm-up, the participants exited the chamber and transferred to the cycle ergometer.

Control trial: the participants were required to remain on the examination couch in the laboratory for the ‘warm-up’ period before transferring to the cycle ergometer for the remainder of the trial.

Throughout the passive warm-up (14:55 ± 1:16 min:s; range 11:30–22:00), water (0.28 ± 0.01 l) was administered. This volume equated to 100% of the fluid lost during the familiarization trial. We determined from the familiarization trial that fluid loss during the active warm-up was negligible (0.048 ± 0.001 l); thus, in the active warm-up, no water was given. In the active and passive trials, exercise commenced 5 min after the completion of the warm-up. It has previously been shown that a recovery period of this duration does not affect subsequent high-intensity performance (De Bruyn-Prevost and Lefebvre, 1980). Furthermore, pilot studies have indicated that muscle temperature is maintained for at least 5 min after a passive warm-up. Thus, we considered 5 min a sufficient recovery period, during which time all relevant data could be collected without compromising the elevation in muscle temperature. The order of trials was determined using a Latin square crossover randomization design.

Experimental protocol

On each occasion, the participants reported to the laboratory 3 h post-prandial, having abstained from alcohol, caffeine and strenuous physical activity in the preceding 24 h. Furthermore, each participant was required to record and replicate the same dietary intake and physical activity pattern during the 48 h before each trial.

On arrival at the laboratory, the participants were weighed and then a rectal thermistor probe (Grants Instruments Ltd, UK) was inserted 10 cm beyond the anal sphincter to allow continuous monitoring of rectal temperature. They then rested on an examination couch while a flexible muscle temperature probe (Ellab (UK) Ltd, Norfolk) was introduced into the vastus lateralis muscle to a depth of 3 cm (Sargeant, 1987), at an angle of approximately 45° and in the direction of the muscle fibres, using a Microlance 18G single-use injection needle (Becton Dickinson, Dublin, Ireland). The needle was then withdrawn from the muscle and the probe was secured in place with micropore tape. The temperature probe was connected to a medical precision thermometer (Ellab (UK) Ltd, Norfolk), which allowed continuous monitoring of muscle temperature. The participants then rested quietly for approximately 90 min until muscle temperature reached a value standardized for each individual during their experimental trials. During this time, the participants were instrumented with skin thermistors (Grants Instruments Ltd, UK) and a heart rate monitor (Polar Vantage NV™, Polar Electro, Finland). Using the temperature at four sites (right chest, right medial tricep, right front thigh and right medial calf), weighted mean skin temperature was calculated using the method of Ramanathan (1964). Approximately 10 min before the end of the rest period, an indwelling cannula (Venflon 18G, BOC Ohmeda, Sweden) was inserted into an antecubital vein for the collection of venous blood samples. Throughout the trials, the cannula was kept patent by the injection of a small amount (1 ml) of sterile saline solution (Baxter Healthcare Ltd, UK) at regular intervals.

Blood samples were collected and heart rate (HR) was recorded at rest, immediately before and after the criterion exercise test and performance test, and 5 and 10 min into recovery. Rectal temperature, muscle temperature and weighted mean skin temperature were recorded at rest and before the criterion exercise task only. If a participant was unable to exercise comfortably with the flexible probe secured in position in the muscle during the active warm-up, then this was removed and a copper constantan thermocouple needle probe (Ellab (UK) Ltd, Norfolk), inserted at the same angle, direction and depth as the flexible probe, but only held in place long enough to obtain a stable muscle temperature reading (~3–5 s), was used. Both the needle and the flexible probe were checked against a certified reference mercury thermometer (Zeal, UK) at temperatures of 30 and 40°C, and then against each other in situ in the muscle. The in situ coefficient of variation was 0.58%. In the present study, only two participants were unable to cycle with the flexible probe in place in the muscle.

In all three trials, breath-by-breath gas analysis was performed using an Airspec QP9000 mass spectrometer (CaSE Ltd, UK) during the criterion exercise test to identify any differences in total oxygen uptake ($V\text{O}_2$) between trials. Only $V\text{O}_2$ during the first 30 s of exercise was measured, as it has previously been reported that observed differences in $V\text{O}_2$ after a warm-up are transient and are overridden by the duration of the subsequent exercise bout (Robergs et al., 1991). After initial time alignment of all points, the breath-by-breath data obtained during each trial were plotted and total $V\text{O}_2$ was calculated by integrating the area under the curve.

Blood sampling and metabolite analysis

Blood samples were collected using a dry syringe. For all samples, 2.5 ml of blood were dispensed into a tube containing potassium ethylenediaminetetraacetic acid (K$_3$EDTA). Duplicate aliquots (100 µl) were removed immediately from the K$_3$EDTA tube and were deproteinized in 1 ml of ice-cold 0.4 mmol·1$^{-1}$ perchloric
acid (PCA). The aliquots were centrifuged for 3 min at 4000 rev·min⁻¹ and the resultant supernatant was used for the fluorimetric determination of blood lactate (Maughan, 1982) (modified for use on the Cobas Fara II, Roche Diagnostics, UK). In addition, 1 ml of blood was removed immediately from the EDTA tube and centrifuged for 30 s. The resultant plasma was refrigerated and used for the spectrophotometric determination of plasma ammonia within 2 h of collection, using an MPR1 Ammonia kit (Boehringer Mannheim, UK) (Cobas Fara II, Roche Diagnostics, UK).

Statistical analysis

Two-way analysis of variance (ANOVA) with repeated measures on two factors (experimental treatment and sampling time) was used to determine differences between trials for heart rate, rectal temperature, skin temperature, muscle temperature, blood lactate and plasma ammonia. When this analysis revealed significant main trial effects, post-hoc comparisons were analysed using the Tukey test. A one-way ANOVA, followed by a Tukey test where relevant, was used to identify differences over time and differences at specific times. Time to exhaustion and oxygen uptake were analysed using a one-way analysis of variance and Tukey post-hoc test where appropriate. Significance was set at P < 0.05. The results are presented as the mean ± standard error of the mean (sₑ).

Results

Muscle, rectal and skin temperature

Muscle temperature was not significantly different between trials at rest. After the active and passive warm-ups, muscle temperature was higher (P < 0.05) than resting values so that, before the criterion exercise test, muscle temperature in the active and passive trials was significantly higher than in the control trial (P < 0.05). At no time was there a significant difference in muscle temperature between the active and passive trials (Table 1).

There was no significant difference in rectal temperature between trials either at rest or before the criterion exercise test. However, both the active and passive warm-ups resulted in a small increase (P < 0.05) in rectal temperature such that, before the criterion exercise test, it was elevated (P < 0.05) above resting values in both the active and passive trials (Table 1).

After a whole-body passive warm-up, mean skin temperature in the passive trial was higher (P < 0.05) than at rest and higher than the corresponding values in the active and control trials before the criterion exercise test (Table 1). There was no difference in mean skin temperature between the active and control trials (Table 1).

Heart rate

After the warm-up, heart rate was higher (P < 0.05) than at rest in both the active and passive trials so that, before the criterion exercise test, there were significant differences (P < 0.05) between all three trials (Table 2). Before the onset of exercise, heart rate in the control trial was also increased above resting values (P < 0.05). Differences in heart rate between trials were seen throughout the exercise period, although these vanished 5 min into recovery (Table 2).

Blood metabolites

After the warm-up in the active trial, blood lactate was higher (P < 0.05) than in the passive and control trials at all times (Table 3). Blood lactate was not significantly different between the passive and control trials, although in both trials concentrations of this metabolite were higher than resting values (P < 0.05) from after the criterion exercise test. The change in blood lactate concentration from before to after the criterion exercise test was greater (P < 0.05) in the passive and control trials than in the active trial (0.82 ± 0.11, 1.05 ± 0.23 and 0.38 ± 0.21 mmol·l⁻¹, respectively). Moreover, the change between before the criterion exercise test and

| Table 1. Muscle temperature (n = 8), rectal temperature (n = 7) and mean skin temperature (n = 8) at rest and before the criterion exercise test (CE) in the active warm-up, passive warm-up and no warm-up (control) trials (mean ± sₑ) |
|-----------------|-----------------|-----------------|
|                 | Rest            | Pre-CE          |
| **Muscle temperature (°C)** |                 |                 |
| Active          | 33.9 ± 0.3      | 36.9 ± 0.2*     |
| Passive         | 33.7 ± 0.3      | 36.8 ± 0.2*     |
| Control         | 33.8 ± 0.3      | 33.6 ± 0.3      |
| **Rectal temperature (°C)** |                 |                 |
| Active          | 36.9 ± 0.1      | 37.1 ± 0.1*     |
| Passive         | 37.0 ± 0.1      | 37.2 ± 0.1*     |
| Control         | 37.0 ± 0.1      | 37.0 ± 0.1      |
| **Mean skin temperature (°C)** |                 |                 |
| Active          | 31.4 ± 0.3      | 31.2 ± 0.3      |
| Passive         | 31.4 ± 0.3      | 32.9 ± 0.5*     |
| Control         | 31.1 ± 0.2      | 31.1 ± 0.3      |

* Significantly different from rest, P < 0.05. + Significantly different from control, P < 0.05. # Significantly different from active warm-up, P < 0.05.
peak lactate concentrations was also greater ($P < 0.05$) in the passive and control trials than in the active trial ($8.09 \pm 0.57$, $7.90 \pm 0.38$ and $5.53 \pm 0.52$ mmol·l$^{-1}$ respectively).

There was no difference between trials for plasma ammonia concentration at any time (Table 3). Likewise, there was no difference in the change in ammonia concentration between before the criterion exercise test and peak values ($100 \pm 30.6$, $78.0 \pm 18.3$ and $79.3 \pm 23.5$ μmol·l$^{-1}$ for the active, passive and control trials respectively). Plasma ammonia concentration was higher ($P < 0.05$) than at rest 5 min into recovery in all trials, although by 10 min post-exercise concentrations of this metabolite remained higher ($P < 0.05$) than at rest in the active and passive trials only.

**Oxygen uptake**

Total oxygen uptake during the criterion exercise test was higher ($P < 0.05$) in the active and passive trials than in the control trial (Fig. 1), although there was no difference between the active and passive trials.

**Performance test**

There was no significant difference between trials during the performance test as measured by exercise time to exhaustion ($43.9 \pm 4.1$, $48.3 \pm 2.7$ and $46.9 \pm 6.2$ s for the active, passive and control trials respectively; $P = 0.69$). The coefficient of variation for the performance test (determined from pilot work) was 4.6%. This means that for a test lasting approximately 46 s, one can expect 2 s of variability owing to the test itself.

**Discussion**

The results of the present study demonstrate that, after an active warm-up, there is an increase in total VO$_2$ and a blunted blood lactate response during exercise compared to no warm-up. These findings are similar to those of Robergs *et al.* (1991), who reported a transient increase in VO$_2$ and a decrease in blood lactate accumulation during 2 min of cycling at 120% maximum power output. They suggested that the elevation in muscle temperature after an active warm-up indicated a potential for increased blood flow to the working muscle, thereby increasing the aerobic contribution to energy metabolism at the onset of exercise. However, despite no differences in muscle temperature immediately before the criterion exercise test between the active and passive trials in the present study, a differing blood lactate response was observed between these trials during exercise. This would suggest that, after an

### Table 2. Heart rate (beats·min$^{-1}$) at rest, before and after the criterion exercise test (CE), after the performance test (EE) and 5 and 10 min into recovery ($n = 8$) in the active warm-up, passive warm-up and no warm-up (control) trials (mean ± s)

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>Pre-CE</th>
<th>Post-CE</th>
<th>Post-EE</th>
<th>5 min</th>
<th>10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active</td>
<td>60 ± 6</td>
<td>101 ± 7*</td>
<td>165 ± 4*</td>
<td>180 ± 3*</td>
<td>94 ± 5</td>
<td>94 ± 4*</td>
</tr>
<tr>
<td>Passive</td>
<td>60 ± 4</td>
<td>77 ± 5*b</td>
<td>153 ± 5*</td>
<td>174 ± 4*</td>
<td>94 ± 7</td>
<td>93 ± 6*</td>
</tr>
<tr>
<td>Control</td>
<td>57 ± 3</td>
<td>70 ± 4*</td>
<td>154 ± 4*</td>
<td>167 ± 2*</td>
<td>92 ± 6</td>
<td>89 ± 4*</td>
</tr>
</tbody>
</table>

* Significantly different from rest, $P < 0.05$. * Significantly different from control, $P < 0.05$. * Significantly different from active warm-up, $P < 0.05$.

### Table 3. Blood lactate concentration and plasma ammonia concentration at rest, before and after the criterion exercise test (CE), after the performance test (EE) and 5 and 10 min into recovery ($n = 8$) in the active warm-up, passive warm-up and no warm-up (control) trials

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>Pre-CE</th>
<th>Post-CE</th>
<th>Post-EE</th>
<th>5 min</th>
<th>10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Blood lactate (mmol·l$^{-1}$)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>0.61 ± 0.05</td>
<td>4.85 ± 0.65*</td>
<td>4.47 ± 0.61**</td>
<td>6.46 ± 0.65**</td>
<td>10.37 ± 0.74**</td>
<td>9.52 ± 0.84**</td>
</tr>
<tr>
<td>Passive</td>
<td>0.58 ± 0.07</td>
<td>0.65 ± 0.04*</td>
<td>1.47 ± 0.14*</td>
<td>4.45 ± 0.33*</td>
<td>8.75 ± 0.58*</td>
<td>8.13 ± 0.56*</td>
</tr>
<tr>
<td>Control</td>
<td>0.64 ± 0.05</td>
<td>0.68 ± 0.06</td>
<td>1.73 ± 0.26*</td>
<td>4.91 ± 0.52*</td>
<td>8.58 ± 0.38*</td>
<td>8.24 ± 0.43*</td>
</tr>
</tbody>
</table>

| **Plasma ammonia (μmol·l$^{-1}$)** |          |         |         |         |        |          |
| Active             | 40.87 ± 7.75 | 72.87 ± 13.15 | 68.26 ± 12.06 | 72.12 ± 11.99 | 173.50 ± 32.09* | 140.57 ± 27.66* |
| Passive            | 42.35 ± 7.44 | 53.27 ± 6.05 | 42.32 ± 7.95 | 53.48 ± 9.72 | 130.57 ± 19.79* | 109.14 ± 20.83* |
| Control            | 43.65 ± 3.94 | 35.23 ± 5.98 | 36.44 ± 5.47 | 49.62 ± 5.79 | 109.45 ± 19.96* | 85.24 ± 14.70 |

* Significantly different from rest, $P < 0.05$. * Significantly different from control, $P < 0.05$. * Significantly different from active warm-up, $P < 0.05$. 
active warm-up, the observed differences in metabolic responses during high-intensity exercise may not be due entirely to elevations in muscle temperature.

Comparing a local passive warm-up with no warm-up, Febbraio et al. (1996) also suggested that muscle temperature was the major factor influencing the metabolic response of the working muscle during 2 min cycling at 115% $V_{O_2 \text{max}}$, although, in this instance, the authors concluded that an elevated muscle temperature increased the dependency on anaerobic metabolism. As blood, and not muscle, metabolites were measured in the present study, a direct comparison with the findings of Febbraio et al. (1996) cannot be made. However, that there were no differences in blood lactate or plasma ammonia concentrations between the passive and control trials during exercise, despite differences in muscle temperature, does suggest that muscle temperature is not solely responsible for metabolic alterations during exercise after a warm-up. Since a whole-body warm-up was used in the present study, whereas Febbraio et al. (1996) used a local warm-up, it cannot be discounted that differing passive warm-up protocols result in differing metabolic responses during subsequent high-intensity exercise.

Mean skin temperature in the passive trial was higher before the onset of exercise than in the active trial, reflecting a potential increase in skin blood flow (Hasan et al., 1967). This increase in skin blood flow is met by a redistribution of cardiac output from renal and splanchnic regions (Rowell, 1974), although it is not clear whether muscle blood flow is similarly affected (Edholm et al., 1956; Rowell et al., 1970; Detry et al., 1972). During exercise, it would appear that blood flow to the muscle is compromised only when dehydration causes a decrease in cardiac output (Gonzalez-Alonso et al., 1998). It was not possible in this study to determine whether muscle tissue hydration was complete after fluid ingestion during passive warming. However, it has been reported that, at rest, dehydration-induced reductions in plasma volume are attenuated when water is consumed during heat exposure (Harrison, 1985) and that fluid replacement representing 100% of fluid loss maintains plasma volume during exercise (McConnell et al., 1997). Thus, in the present study, where fluid loss was offset by equal amounts of fluid intake during the passive warm-up, dehydration was not believed to be an issue. It therefore appears that, despite an elevated skin temperature in the passive trial, skeletal muscle blood flow was not compromised. This observation is further supported indirectly by similar muscle temperatures in the active and passive trials.

Any differences in cardiac output resulting from a lower heart rate in the passive than in the active trial before the onset of exercise does not affect the rate of oxygen extraction from the muscle (Gonzalez-Alonso et al., 1998). Thus, the differences in blood lactate response observed between trials in this study are not thought to be attributable to variations in heart rate either before or during the criterion exercise test.

As the differing blood lactate response between the active and passive trials does not appear to be attributable to muscle temperature, mean skin temperature or heart rate, other factors associated with one or other of the warm-up procedures must account for the present findings. Campbell et al. (1999), who compared a low-intensity (55% $V_{O_2 \text{max}}$) active warm-up with a control, reported a decrease in glycolytic flux and an increase in oxidative flux during 3 min of subsequent high-intensity (90% $V_{O_2 \text{max}}$) exercise. They suggested that the active component of the warm-up dictated the metabolic response of the muscle by providing a readily available supply of acetyl groups before the onset of exercise. It is possible that the type of active warm-up used in the present study, which contained aspects of both low- and high-intensity exercise, also increased the availability of acetyl groups before the onset of high-intensity exercise of short duration, thereby resulting in less accumulation of blood lactate during exercise.

Alternatively, the blunted blood lactate response observed during the active trial may be associated with an increased rate of lactate clearance after the active warm-up. Gladden (2000) reported that, during recovery from high-intensity exercise, there is a net uptake of lactate from the blood by the resting muscles. Furthermore, it has been shown that working skeletal muscle is a major site of blood lactate removal and that this muscle lactate uptake is stimulated by increases in blood lactate concentration and the metabolic rate of the muscle (Stanley et al., 1986; Brooks, 2000; Gladden, 2000). Thus, it is possible that, during both the recovery from the active warm-up and the subsequent exercise...
bout, there was an increased rate of lactate clearance from the blood by skeletal muscle, thereby resulting in the blunted blood lactate response observed in this study.

Plasma ammonia, which is reflective of skeletal muscle adenine nucleotide loss and is elevated when the hydrolysis of adenosine triphosphate exceeds rephosphorylation (Tullson and Terjung, 1991), was not different between trials in the present study. This is possibly due to the large variance in ammonia concentration observed at the various sampling times, which may be indicative of a large variability in skeletal muscle fibre type composition in the groups tested (Dudley et al., 1983).

Heat exposure has consistently been shown to increase both tissue $\dot{V}O_2$ (Abramson et al., 1958) and whole-body $\dot{V}O_2$ (Bazett et al., 1937; Dawson et al., 1965; Hasan et al., 1966; Rowell et al., 1970). Therefore, it is possible that the observed difference in $\dot{V}O_2$ between the passive and control trials during the criterion exercise test in the present study is not associated with the exercise bout per se, but rather is attributable to elevations in resting $\dot{V}O_2$ during the whole-body passive warm-up.

In the present study, there was no significant difference in high-intensity exercise performance irrespective of whether exercise was preceded by active, passive or no warm-up, a finding which is in agreement with previous investigations (De Bruyn-Prevost and Lefebvre, 1980; Davies and Young, 1983). Since elevations in muscle temperature are of most significance when the velocity of muscle contraction is close to, or exceeds, the optimum for maximal power output (110 rev·min$^{-1}$; Sargeant et al., 1981), Sargeant (1987) proposed that Davies and Young (1983) found no differences in performance after a warm-up as the pedal cadence in their study may have been too slow. However, pedal cadence in the present study was maintained at a constant 120 rev·min$^{-1}$, whereas in the study by De Bruyn-Prevost and Lefebvre (1980) it varied between 104 and 128 rev·min$^{-1}$. Thus discrepancies in findings between these studies and that of Sargeant (1987), who observed an improvement in performance after a warm-up, are not likely to be associated with the pedal cadence adopted during exercise. Instead, the equivocal findings may be due to differences in the nature of the performance parameter measured (i.e. exercise time to exhaustion versus peak power) and it is possible that any immediate benefit of a warm-up on power output may have been overridden by the duration of the exercise period (58–112 s in the present study). Although there were no significant differences in performance in the current study, the mean difference between trials varied by as much as 4.4 s, which, for a sprint event such as the 400 m, is considerable. Furthermore, five of the eight participants cycled for longer in the passive than in the active and control trials, although a subsequent power test (Jaccard and Becker, 1983) revealed that 93 participants would be required for statistical significance to be achieved.

In conclusion, the main finding of this study is that, although the mechanism by which muscle temperature is elevated influences certain metabolic responses during high-intensity exercise of short duration, muscle temperature does not appear to be the sole determinant of energy metabolism during exercise. Despite the differing metabolic and physiological responses observed during exercise, however, there was no significant difference in short-duration high-intensity performance irrespective of whether exercise was preceded by active, passive or no warm-up.

**Acknowledgements**

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