External muscle heating during warm-up does not provide added performance benefit above external heating in the recovery period alone.

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ABSTRACT

Purpose: Having previously shown the use of passive external heating between warm-up completion and sprint cycling to have had a positive effect on muscle temperature (T_m) and maximal sprint performance, we sought to determine whether adding passive heating during active warm up was of further benefit. **Methods:** 10 trained male cyclists completed a standardised 15 min sprint based warm-up on a cycle ergometer, followed by 30 min passive recovery before completing a 30 sec maximal sprint test. Warm up was completed either with or without additional external passive heating. During recovery, external passive leg heating was used in both standard warm-up (CONHOT) and heated warm-up (HOTHOT) conditions, for control, a standard tracksuit was worn (CON). **Results:** T_m declined exponentially during CON, CONHOT and HOTHOT reduced the exponential decline during recovery. Peak (11.1%, 1561 ± 258 W & 1542 ± 223 W), relative (10.6% 21.0 ± 2.2 W.kg^{-1} & 20.9 ± 1.8 W.kg^{-1}) and mean (4.1%, 734 ± 126 W & 729 ± 125 W) power were all improved with CONHOT and HOTHOT respectively compared to CON (1397 ± 239 W; 18.9 ± 3.0 W.kg^{-1} and 701 ± 109 W). There was no additional benefit of HOTHOT on T_m or sprint performance compared to CONHOT. **Conclusion:** External heating during an active warm up does not provide additional physiological or performance benefit. As noted previously, external heating is capable of reducing the rate of decline in T_m after an active warm-up, improving subsequent sprint cycling performance.

KEYWORDS: MUSCLE TEMPERATURE, POWER OUTPUT, PERFORMANCE, INSULATION, CLOTHING, HEATING

Introduction

It is well established that muscle temperature (T_m) has a significant effect on muscle function, force and power production (Asmussen and Boje 1945; Bergh and Ekblom 1979; De Ruiter and De Haan 2000; Edwards et al. 1972; Racinais et al. 2005; Sargeant 1987). Much of the available literature suggests that events that require high levels of power production tend to benefit from increases in muscle temperature (Asmussen and Boje 1945; Hajoglou et al. 2005). For example, it has been reported that there is a ~4%$\cdot^{\circ}$C^{-1} improvement in vertical jump performance as T_m increased (Bergh and Ekblom 1979). In addition, it has been shown that changes in T_m following water immersion of the legs influences maximal power output during isokinetic sprint cycling (Sargeant 1987). Thus, there is a great deal of support for the long held belief that completion of a warm up prior to the execution of sprint and power based activities will maximize exercise performance. However, it is possible that there may be an upper T_m threshold beyond which similar impairments to muscle function are evident. *In vitro* data suggests that at temperatures at or above 43°C there are impairments in the electrical conductivity of rat skeletal muscle (McRae and Eskrick 1993), which may impact upon subsequent performance.

Where athletes experience a delay in performance onset following the completion of a warm up, or between bouts or rounds of activity it is possible that T_m may drop below an optimal level (Faulkner et al. 2013; Kenny et al. 2002; Kilduff et al. 2012). This may have a detrimental effect on performance, particularly during power-based activities such as weight lifting, jumping and sprinting. A detailed time course of post exercise decline in T_m has been reported on a number of occasions (Aikas et al. 1962; Allsop et al. 1991; Kenny et al. 2002; Kenny et al. 2003; Saltin et al. 1970; Saltin et al. 1972) however, with none directly assessing any subsequent performance changes following reductions in T_m. In general, it appears that T_m begins to decline immediately post exercise (Allsop et al. 1991; Kenny et al. 2003; Saltin et al. 1970), with the rate at which T_m declines being affected by environmental conditions (Saltin et al. 1970; Saltin et al. 1972) with colder ambient conditions leading to a faster decline in muscle temperature. This effect of the greater temperature gradient, owing to the increased temperature difference between the muscle, skin and the ambient air, will be modulated by several other factors, one being clothing insulation.

As well as performing active warm up activities, muscle temperature can be passively elevated in a variety of ways, with the most widely used methods reported within the literature being warm water immersion (Sargeant 1987), or the use of heated blanket (Gray et al. 2006), which can elevate muscle temperature by as much as 3-4°C and have been shown to be beneficial to power based performance (Sargeant 1987). However, these passive methods are difficult to implement outside of the laboratory, so their practical use is currently limited.

Using a novel technique of combining insulated pants with built in passive, battery powered electrical heating, Faulkner et al. (2013) have previously shown that it is possible to attenuate the decline in muscle temperature that is evident during post exercise rest/recovery in cool ambient conditions by approximately 1°C, and improve both absolute and relative peak power outputs by ~10% . However, as external passive heating was only used during the recovery portion of the protocol in this previous study (Faulkner et al. 2013), the question of whether an active warm up coupled with simultaneous external passive heating further increases in T_m and affects maximal sprint performance after a recovery period remains to be elucidated. As elevations in muscle temperature are a key determinant of sprint and power based performance, it follows that if T_m can be further elevated via the use of a heating garment during an active warm up, over and above that possible by an active warm up alone, then it may be possible to further improve power related performance variables. Therefore, the addition of a heated garment to the active warm up may convey an additional increase in T_m following warm up completion and after the subsequent period of passive recovery, thus potentially further enhancing sprint cycling performance.

The aims of the present study were threefold. Firstly, to investigate whether there is any additional benefit of adding passive external heating during active warm up on the increase in muscle temperature. Secondly, to evaluate the any differences in time course of T_m decline during recovery. Finally, to quantify any differences in sprint performance resulting from the maintenance or further elevation of Tm as a result of passive heating during recovery or during both warm up and recovery. We hypothesized that the use of passive heating during an active warm up will lead to additional gains in T_m over and above that of an active warm up alone, and that the combination of an active warm up

with passive heating will result in a greater T_m after the recovery period above passive heating in the recovery period alone, resulting in improved sprint cycling performance.

Methods

Participants

Ten healthy male nationally competitive cyclists and triathletes (age 23.5 ± 3.4 yrs; height 1.8.9 ± 0.4m; body mass 73.7 ± 0.7 kg; mean ± SD) volunteered to participate in this study. All participants performed at least 3 cycle based training sessions per week (16.2 ± 6.4 hrs.wk^{-1}) in addition to other sport specific training including (10 ± 3 sessions.wk^{-1}). Participants completed a general health-screening questionnaire, were non-smokers and free from injury. They were informed of the requirements of the study before providing their written informed consent. All procedures were approved by the Loughborough University Ethical Advisory Committee.

Study Overview

Prior to the experimental trials, participants were familiarised with the nature of the exercise testing and general measurement procedures. 7-10 days prior to their first experimental visit, participants completed at least four 30 sec maximal sprint tests separated by 10 minutes of passive recovery. Trials were continued until the time to reach peak power output showed minimal deviation (±0.5sec). Participants visited the laboratory on three further occasions at the same time of day to minimize any effects of circadian variation on performance. On each occasion they completed a standardised sprint based warm up, followed by a 30 minute seated passive recovery period (simulating a delay between warm up completion and the competition event, based on reports of elite athletes competition practices). Participants completed three experimental interventions: 1) control (CON) where participants wore their own cycle shorts and commercially available tracksuit ensemble during recovery, 2) shorts/heat (CONHOT), where participants warmed up in their normal cycling shorts and then wore a pair of heated pants during the recovery phase; 3) heat/heat (HOTHOT), participants wore the same heated pants during both the warm up and the recovery phase over their cycling shorts. In all conditions participants wore a commercially available 55%polyester, 45% cotton tracksuit top (adidas AG, Germany) during the recovery phase. Immediately after the 30-minute recovery intervention, participants removed the tracksuit top and pants and then completed a 30 second maximal sprint

performance test. All trials were completed using a cross-over design, with a minimum of 7 days between trials. During the 24 hours before each trial, participants were asked to refrain from caffeine and alcohol ingestion and any strenuous exercise. They were also required to keep a record of their food intake and replicate this prior to the subsequent visits. Experiments were performed in an environmental chamber maintained at $16.1 \pm 0.2°C$ and $53 \pm 2.0\%$ relative humidity.

Experimental Protocol

Participants attended the laboratory following a minimum of a four-hour fast, during which time they were allowed to consume water only. On arrival, participants voided and had their height (Seca, Birmingham, UK) and body mass (ID1 Multi Range, Sartorius, Goettingen, DE) recorded. Participants then inserted a rectal probe (Grant Instruments Ltd., UK) 10cm beyond the anal sphincter to allow for monitoring of core temperature (T_c).

Participants entered the environmental chamber and remained seated for 30 minutes wearing a standard tracksuit (comprising top and pants), cycle clothing and shoes to allow for stabilization of muscle and core temperatures. After the stabilization period, baseline measures were made for thermal sensation (legs and whole body), thermal comfort (legs and whole body), rectal temperature as an indicator of deep body core temperature (Grant Instruments, Cambridge, UK), heart rate (RS800, Polar, Kempele, Fi), blood lactate concentration (Lactate Pro, Arkray, Shiga Japan) and muscle temperature (T_m) using a needle thermistor probe (MKA08050A275TS Ellab, Copenhagen, Denmark). Participants then mounted an electronically braked cycle ergometer (Lode Excalibur Sport, Groningen, The Netherlands) and performed a 15 minute standardised warm up protocol (WUP). This consisted of 5 minutes cycling at an external power output of 100W, followed by five 10 sec maximal sprints against a load equivalent to 10% of body mass, with each sprint separated by 1 min 50 sec of active recovery at 75W. Participants were instructed to maintain a cadence of 85 rpm during the recovery periods, until the start of each sprint. During the final active recovery period, measurements of T_c, heart rate, blood lactate concentration, thermal sensation and thermal comfort were made. In the CON and CONHOT conditions, the warm up was completed in standard cycling attire, in the HOTHOT condition, the heated pants were donned prior to mounting the cycle ergometer.

Immediately after completion of the warm up exercise, participants dismounted from the bike and a flexible indwelling muscle temperature probe (MCA 08170A275TS Ellab, Copenhagen, Denmark) was quickly inserted to a depth of ~2cm into the *vastus lateralis*. Participants then donned a standard tracksuit top, and either tracksuit bottoms (CON) or the heated pants (CONHOT) if not already worn as in the HOTHOT condition. The heating element in the pants was designed to cover the *gluteus maximus*, *vastus medialis, rectus femoris, vastus lateralis, biceps femoris, semitendinosus* and *semimembranosus* of both legs. There was no coverage directly over the adductor muscles to allow for some variation in leg size between subjects, but the heating elements remained in close contact with both thighs in all participants. The heating element was capable of reaching temperatures of ~40˚C, and was powered by a 14.8V battery that generated 7.5W to each heating pad, covering a total surface area of 2,821.6cm^2. Once donned, the participant remained in the environmental chamber in a supine position for 30 minutes (REC). During this period measurements of thermal comfort, thermal sensation, heart rate and T_c were made every 5 minutes. T_m was recorded every 2 minutes. At the end of the 30 minute recovery period, another blood sample was obtained for measurement of blood lactate. The tracksuit top and pants were removed, as was the indwelling muscle temperature probe. The participant then remounted the cycle ergometer and performed a 30s maximal sprint test against a load of 10% body mass, which has been shown to be optimal for well-trained athletes (Dotan and Bar-Or, 1983; Bar-Or, 1987). The sprint test was preceded by a 15 sec period of cycling against 75W at a pedal cadence of 85 rpm. Verbal encouragement was provided for the duration of the 30 sec sprint test, although no indication of elapsed time was provided. Maximum heart rate, T_c, thermal sensation (whole body and legs) and thermal comfort (whole body and legs) were recorded and blood lactate concentration measured within 20 sec of completion of the sprint.

Measurements

Power output and pedal cadence

Power output and pedal frequency were recorded continuously (at a sampling rate of 10Hz) throughout the warm up and sprint tests (Wingate Test Plus Module, Lode, Groningen, The Netherlands). Peak, minimum and mean power output, time to peak power, peak pedal cadence and time to peak pedal cadence were determined. Fatigue index was calculated as the change in power output divided by peak power output multiplied by 100.

Muscle temperature

The initial measurement of muscle temperature, prior to the start of the warm up procedure, was made in the lateral quadriceps of the left leg using a needle thermistor probe (MKA08050A275TS Ellab, Copenhagen, Denmark) with a precision of 0.1°C. The needle probe was first inserted to an initial depth of 3 cm beyond the muscle fascia of the *vastus lateralis*. The temperature was allowed to visually stabilise for 5 sec at each depth before the probe was withdrawn to 2cm and then 1cm depths, with the temperature recorded at each depth after stabilisation. During the recovery phase, continual T_m measures were obtained using a flexible indwelling muscle probe (MCA08170A275TS Ellab, Copenhagen, Denmark) with a precision of 0.1°C. An 18-gauge cannula (Venflon, BD, UK) was first inserted to a depth of 2 cm, with an insertion angle of approximately 45º, and secured in place using film dressings (Tegaderm, 3M, UK). The temperature probe was then fed through the cannula until the tip was residing in the muscle tissue. The probe was further secured in place using tape (Transpore, 3M, UK) in order to prevent any unwanted movement within the muscle. Insertion of the probe took approximately 90s following cessation of cycling. The rate of decline in muscle temperature was analysed using an exponential model using the equation:

$$T_m\left(t\right) = T_{end} + e^{\left(\frac{-t}{\tau}\right)} \bullet \left(T_{start} - T_{end}\right) \qquad [1]$$

where T_m = muscle temperature (˚C); T_{end} = muscle temperature at baseline (˚C); T_{start} = muscle temperature at the start of cooling (˚C); e = Euler constant; t = time (s); τ = time constant.

Heart rate, thermal sensation and blood lactate concentration

Heart rate was recorded using a wireless heart rate monitor. Thermal sensation was measured using a 20-point scale (10 maximal hot, 0 neutral -10 maximal cold) (ASHRAE. 1997). Thermal comfort was measured on a 4-point scale (1- comfortable, 4- uncomfortable) (Griffiths and Boyce. 1971). Both thermal sensation and thermal comfort were recorded at 5-minute intervals throughout the trial. Blood lactate concentration was measured from capillary blood samples (5 μl) taken from the fingertip and analysed immediately using an automated analyser (Lactate Pro, Arkray, Japan).

Clothing insulation

Insulation values for the heated pants for the legs and hips and body as a whole were determined using a thermal manikin (Newton, MTNW, Seattle, US) with a uniform skin temperature of 34°C and environmental temperature of 21°C. For dry heat insulation the following equation was used (Havenith. 2009):

$$I_T = \frac{\overline{T}_{sk} - T_a}{\sum (a_i \cdot H_i)} \qquad [2]$$

where a_i = (surface area of segment i)/(total surface area of manikin); I_T = total insulation of complete ensemble including enclosed and surface air layers (m^2.K.W^{-1}); T_a = ambient temperature; $\overline{T}_{sk}$ = mean skin temperature; H_i = heat loss of segment I (W.m^{-2}). When the heating element was inactive, the insulation value was 0.559 m^2.K.W^{-1} (3.6 clo) for the legs and hips in isolation that were covered by the garment. When the heating element was activated, insulation of the legs and hips increased to give a local insulation value of 0.842 m^2.K.W^{-1} (5.4 clo). The insulation value of the control garment was 0.412 m^2.K.W^{-1} (2.7 clo).

Statistics

Power output data were analysed using a one-way ANOVA with a *post-hoc* paired sample t-test. Muscle temperature, TS, TC, T_c, HR data were analysed using two way repeated measures ANOVA (condition x time). Where significant effects were identified, *post-hoc* pairwise comparisons with a Bonferroni correction were conducted. The relationships between variables were assessed using a Pearson product-moment correlation coefficient. The accepted level of significance was $p < 0.05$. Data are presented as mean ± S.D.

Results

There were no order effects of trial completion on any of the dependant variables.
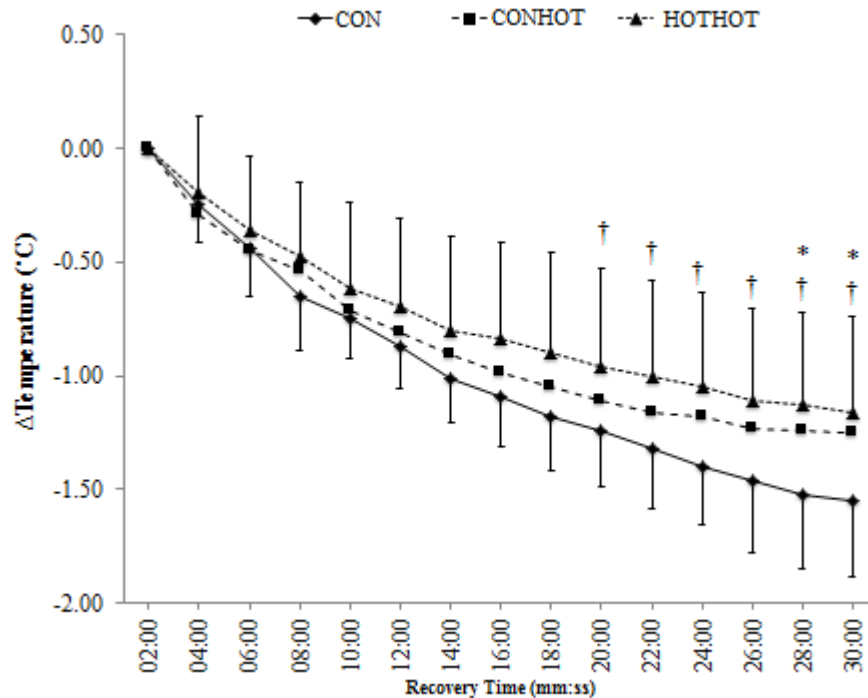
Muscle Temperature

There were no significant differences in resting T_m between conditions across all depths between conditions after the stabilization period. Nor were there any differences between conditions at each individual depth (table 1).

Table 1 *Baseline muscle temperature (T_m) measured using a solid needle probe for control (CON) warm up in shorts and heat recovery (CONHOT) and combined heated warm up and recovery (HOTHOT) conditions. n=10. All data presented as mean ± S.D*

Table 1: Baseline muscle temperature (T_m) measured using a solid needle probe for control (CONT) warm up in shorts and heat recovery (SHORT) and combined heated warm up and recovery (HEAT) conditions. All data presented as mean ± S.D.

	CONT	SHORT	HEAT
T_m at 1cm (˚C)	35.8 ± 0.4	35.8 ± 0.3	35.8 ± 0.5
T_m at 2cm (˚C)	36.2 ± 0.4	36.3 ± 0.3	36.2 ± 0.3
T_m at 3cm (˚C)	36.4 ± 0.4	36.5 ± 0.4	36.4 ± 0.2
Mean T_m (˚C)	36.1 ± 0.4	36.2 ± 0.4	36.1 ± 0.4

Following the completion of the warm up, there was an increase in T_m of 2-2.4˚C at a depth of 2cm, with no significant differences between conditions (CON 38.1 ± 0.5˚C; CONHOT 38.1 ± 0.3˚C; HOTHOT 38.2 ± 0.5˚C; p=0.87). There were significant effects of condition x time (p<0.05) on muscle temperature during recovery. During recovery, T_m declined exponentially during recovery in CON (T_m(t[minutes])=36.2+ 1.97*$e^{(-t/18.7)}$, r^2=.996) with a time constant of 18.7 minutes, indicating a return to within 5% of the baseline T_m value in around 56 minutes. For both CONHOT (T_m(t[minutes])=36.2+ 1.97*$e^{(-t/23.7)}$, r^2=.944) and HOTHOT (T_m(t[minutes])=36.2+ 1.97*$e^{(-t/29.6)}$, r^2=.971) when analysed as exponential decays, time constants were 24 and 30 minutes respectively, however, as to be expected due to the added heat input the data do not fit the exponential model very well, as T_m appeared to level off for both CONHOT and HOTHOT at a value above the baseline T_m. At the end of 30 minutes, T_m for both CONHOT (36.9 ± 0.3˚C) and HOTHOT (37.0 ± 0.2˚C) was significantly warmer than CON (36.6 ± 0.3˚C, both p<0.01). There was a greater ΔT_m for CON compared to HOTHOT after 20 minutes of recovery (p<0.05, figure 1), and following 28 minutes versus CONHOT (p<0.05). At the end of recovery ΔT_m was less for both CONHOT (-1.2 ± 0.2˚C) and HOTHOT (-1.2 ± 0.4˚C) than the ΔT_m for CON (-1.5 ± 0.3˚C, both p<0.05, figure 1). There were no differences in ΔT_m between HOTHOT and CONHOT at any point.

Fig. 1 *Time course of the decline in muscle temperature during recovery measured at a depth of 2cm. n=10. † HOTHOT > CON p<0.05; *CONHOT > CON p<0.05*

Power Output

There was a significant effect of condition on mean power output, and both peak and relative peak power output (all p<0.05, table 2), although 3 of the 10 participants failed to show an improvement in HOTHOT compared to CON, with no detrimental effect observed. For relative peak power output, this equated to an improvement of 11.1 % and 10.6% for CONHOT and HOTHOT respectively vs. CON. There was no difference in peak power output between CONHOT and HOTHOT. In addition, mean power output was greater for both CONHOT (4.4%, p<0.005) and HOTHOT (3.7%, p<0.001) compared to CON (table 2), with both mean power values for CONHOT and HOTHOT representing 47% of the associated peak power output. There was no significant effect on any of the other measured performance variables (table 2). A moderate positive correlation was present between ΔT_m and peak power output (r = 0.36, p<0.05). There was no such relationship between ΔT_m and mean power output (r= 0.26, n=30, p = 0.21).

Table 2 *Peak power output (PPO), relative peak power output (rPPO), mean power output (Mean PO), minimum power output (min power), time to reach peak power output (Time to peak PO), peak cadence (Peak RPM), time to peak cadence and fatigue index for control (CON) warm up in shorts and heat recovery (CONHOT) and combined heated warm up and recovery (HOTHOT) conditions. n=10. All data presented as mean ± S.D.*

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	CON	CONHOT	HOTHOT
PPO (W)	1397 ± 239	1561 ± 258 **	1542 ± 223†
rPPO (W.kg^{-1})	18.9 ± 3.0	21.0 ± 2.2**	20.9 ± 1.8†
Mean PO (W)	703 ± 109	734 ± 126**	729 ± 125†
Min Power (W)	399 ± 88	409 ± 87	439 ± 127
Time to peak PO (s)	1.9 ± 0.5	1.7 ± 0.3	1.7 ± 0.2
Peak cadence (rpm)	121 ± 9	127 ± 9	127 ± 9
Time to peak cadence (s)	2.7 ± 1.3	2.2 ± 0.8	2.7 ± 0.6
Fatigue Index (%)	71.1 ± 6.1	73.6 ± 4.7	71.6 ± 6.8

Significant difference between: † HOTHOT vs. CON ($p<0.05$), ** CONHOT vs. CON $p<0.005$

Blood lactate concentration, core temperature and heart rate

Following warm up, blood lactate concentration increased ($p<0.005$) and was the same in all conditions. During recovery, blood lactate declined in all conditions ($p<0.005$) with no difference between conditions. There was no difference in blood lactate concentration following the 30s maximal sprint test between conditions (table 3). There was no overall effect on core temperature or heart rate (table 3).

Thermal Sensation

Whole body thermal sensation increased ($p<0.05$) towards feeling "warm" for HOTHOT compared to CON from WUP 10 minutes onwards, and remained elevated until the maximal sprint test was completed. There were also differences for CONHOT vs. CON from REC 10 minutes onwards. During recovery, whole body thermal sensation was increased for HOTHOT from REC 5 minutes ($p<0.05$) and CONHOT from REC 10 minutes ($p<0.05$) compared to CON. There were no differences between HOTHOT and CONHOT for whole body thermal sensation during recovery. Thermal sensation of the legs increased ($p<0.05$) towards "warm" and "very warm" for HOTHOT compared to CON from WUP 5 minutes. There was also an increase in thermal sensation of the legs for CONHOT compared to CON from REC 5 minutes.

Thermal Comfort

Whole body thermal comfort changed towards feeling less comfortable for HOTHOT compared to CON from WUP 15 minutes to REC 25 minutes ($p<0.05$). There were no differences in whole body thermal comfort between CONHOT and HOTHOT at any time point. Changes in thermal comfort of the legs towards feeling less comfortable between HOTHOT and CON existed at WUP 10 minutes to REC 30 minutes ($p<0.05$). There was a similar response in CONHOT at REC 5 minutes to REC 30 minutes($p<0.05$). Thermal comfort of the legs was more uncomfortable for HOTHOT vs. CONHOT at WUP 10 minutes ($p<0.05$) and WUP 15 minutes ($p<0.05$).

Table 3 *Core temperature (T_c), heart rate (HR) and blood lactate concentration (BLa⁻) for control (CON) warm up in shorts and heat recovery (CONHOT) and heated warm up and recovery (HOTHOT) conditions, following warm up (15 WUP), after 30 minutes passive recovery (30 REC) and immediately following the maximal sprint test (POST WIN). n=10. All data presented as mean ± S.D*

	WUP 15 min			REC 30 min			POST WIN		
	CON	CONHOT	HOTHOT	CON	CONHOT	HOTHOT	CON	CONHOT	HOTHOT
T_C (°C)	37.1 ± 0.4	37.5 ± 0.2	37.4 ± 0.2	37.2 ± 0.3	37.2 ± 0.2	37.3 ± 0.3	37.1 ± 0.3	37.2 ± 0.2	37.2 ± 0.2
HR (b.p.m)	121 ± 17	120 ± 20	129 ± 18	72 ± 19	73 ± 16	79 ± 9	159 ± 9	163 ± 13	163 ± 8
BLa⁻ (mmol.L⁻¹)	8.6 ± 2.3	9.0 ± 3.2	8.2 ± 3.3	2.9 ± 1.2	3.0 ± 1.5	2.7 ± 1.3	8.2 ± 1.7	9.3 ± 2.8	9.0 ± 2.3

Discussion

The main finding of the present study demonstrates that there were no additional physiological or performance benefits to wearing the heated garment during both the active warm up and recovery period, compared to those achieved when worn during recovery alone: T_m was the same after the warm up for both the CONHOT and the HOTHOT conditions. The use of a heated garment during the warm up and/or recovery periods resulted in a T_m that was approximately 0.5˚C warmer following 30 minutes of recovery compared to not using any such garment. In both CONHOT and HOTHOT, this resulted in improvements of ~11% in relative peak power output and ~4% in mean power output during the maximal sprint test. As T_m following the warm up was the same regardless of whether passive heating was provided during the warm-up or not, there was no additional benefit of this intervention on sprint performance. Therefore, we are unable to accept our initial hypothesis that the use of passive heating during an active warm up will lead to additional gains in T_m over and above that of an active warm up alone and subsequently further improve sprint cycling performance. In addition, we were able to demonstrate that following completion of an intermittent, sprint based warm up activity, muscle temperature declines exponentially on exercise cessation, when no form of passive external heating is implemented, and that this exponential decay is attenuated with passive heating.

Muscle Temperature

It is well established that one of the primary functions of a warm up prior to power or sprint based activities is to increase muscle temperature (Asmussen and Boje 1945; Faulkner et al. 2013; Sargeant 1987). The present data demonstrate that during post warm up recovery, an additional T_m drop at a depth of 2cm of just 0.3˚C is capable of impairing sprint performance and that it is possible to reduce this drop by using an electrically heated trouser during warm up and recovery or recovery alone. It is likely that maintenance of more superficial muscle temperature has a greater impact on power output. Presumably it is the more superficial tissue that will be most susceptible to environmental heat exchange, and therefore temperature mediated alterations in contractile function and performance. In support of this, we have previously shown that at a depth of 1cm, T_m was 0.4˚C warmer than when measured at 2cm following 30 minutes recovery using a similar passive heating garment (Faulkner et al. 2013), with comparable temperatures and power outputs as reported here. These results confirm the

finding of previous research (Asmussen and Boje 1945; Faulkner et al. 2013; Kilduff et al. 2012; Sargeant. 1987), demonstrating that changes in muscle temperature can have a large impact on the ability to generate the maximum power output.

However, despite the effectiveness of HOTHOT and CONHOT in reducing the drop in T_m, there was still a significant drop in muscle temperature over the course of the recovery period. Based on heat transfer analysis (Havenith, 2001), this is likely to be due to the lower central blood temperature entering the leg (T_c is lower than T_m) during recovery and secondly, the effect of peripheral blood cooling as it reaches the lower leg, and in particular the foot, thus cooling the muscles of the thigh as it returns towards the heart. Despite this remaining drop, T_m in HOTHOT is still 0.5˚C warmer than when no passive heating was used, and this difference is shown to lead to better performance. However, as we only measured T_m at a depth of 2cm, it is not possible to show any potential differences in the T_m gradient throughout the muscle at different depths. Our previous data demonstrate that at more superficial depths, there is a larger effect of the passive heating garment on maintaining muscle temperature (Faulkner et al. 2013). Furthermore, it is possible that the probe insertion may affect blood circulation (Anderson et al. 1994) and local inflammation (Stenken et al. 2010), however, although the probe insertion may affect local blood creating a possible artifact, this would be present in all conditions, and the blood flow increase due to exercise will be magnitudes higher, limiting any impact of such an artifact.

There is only limited evidence detailing the post exercise muscle temperature response in humans. The data which does exist tends to show a transient decline in T_m following exercise termination (Aikas et al. 1962; Allsop et al. 1991; Faulkner et al. 2013; Kenny et al. 2002; Kenny et al. 2003; Saltin et al. 1970; Saltin et al. 1972). In rats, T_m has previously been shown to follow an exponential decline immediately following moderate exercise cessation, with resting temperatures reached within 60 minutes (Brooks et al. 1971). In the limited number of similar experiments on humans, T_m has been shown to decline immediately post exercise, with a ~1-2˚C drop occurring within 30-40 minutes post exercise (Allsop et al. 1991; Kenny et al. 2003), which is similar to the decline reported here. There are however, some discrepancies in the exact nature of this decline. Some authors report that upon exercise termination, there is still a gradual increase in T_m which can continue for up to 10 minutes before T_m begins to drop (Aikas et al. 1962; Kenny et al. 2002), whereas others report an immediate decline in T_m

(Allsop et al. 1991; Kenny et al. 2003; Saltin et al. 1970). It is possible that the differences reported are due to different protocols used between studies, e.g. leg extensions (Kenny et al. 2002; Kenny et al. 2003) continual cycling (Aikas et al. 1962; Allsop et al. 1991; Saltin et al. 1970) or even variations in environmental conditions. Saltin et al., (Saltin et al. 1968) suggest that cooler conditions will have a greater effect on reducing muscle tissue temperature following exercise. They report that in warmer ambient temperatures, the rate of T_m decline following exercise appears to be slower than is evident in cooler conditions (Saltin et al. 1970). It is to be expected that the increase in the thermal gradient between the muscle and surrounding ambient air, results in a faster temperature decline via increased heat transfer in cooler ambient conditions; however, one would expect the time constant of the decline to be the same. In the present study, the heating elements are designed to reach a maximum of 40˚C. This implies the thermal gradient between 'environment' and muscle is reversed compared to the CON condition, in favour of air to body heat transfer, resulting in elevated T_m following 30 minutes of recovery. As metabolic heat produced during the warm-up itself was able to raise T_m to 38˚C, for there to be an additional benefit in HOTHOT, the heating capacity of the elements used would have to be much warmer than the 40˚C they are able to achieve. This might explain why no additional benefit was found for HOTHOT compared to CONHOT or CON on post warm up T_m. However, if passive external heating in excess of 40˚C was used, then there would be a danger of exceeding both the pain (Hardy et al. 1951; Hardy et al. 1952) and skin burn (45 ± 1.7˚C) (Hardy. 1956) thresholds.

Power Output

The elevation in T_m when passive heating was used as part of an active warm up and recovery or in recovery alone, resulted in a mean improvement of 11.1%, 10.6% and 4.1% in peak, relative and mean power output respectively, confirming our previous findings on use of recovery heating alone (Faulkner et al. 2013). What is of particular importance to sprint performance is the novel finding that both heated conditions resulted in similar improvements in mean power output throughout the course of the maximal sprint test. Given that this is analogous to speed, this is a key finding when applying the current data to sprint cycling, and indicates that with the use of the heated pants an athlete will be able to sustain a higher average speed over the course of a sprint effort. To our knowledge, this has not been reported previously. These data add to the growing body of literature, demonstrating a clear

temperature dependence of skeletal muscle power generating capability and the importance for power based performance.

Limitations

One potential limitation of the present study that should be acknowledged is the potential for the differing measures of T_m used to have an effect on the reliability and accuracy of the measurements taken. However, we believe that we have minimized this potential as we have successfully demonstrated comparable temperatures at the measured depths to those achieved in our previously published study (Faulkner et al. 2013) and the same investigator was responsible for muscle temperature measurement and probe insertion on all occasions. Further, as the indwelling probe took in the region of 90s to be inserted on completion of the warm up, it is possible that the present data is a conservative reflection of the drop in T_m, particularly given the rapid exponential decline in Tm as the onset of the recovery phase. It would however not have been possible to insert the probe prior to the warm up and for it to remain *in situ* throughout, as there would be a significant risk of the probe breaking, when exposed to very high sheer stress during the maximal sprints. Although using ultrasound to place the probe could have minimized this risk, the potential for it to break could not entirely be removed, hence the use of the method reported.

We cannot determine the exact depth of the temperature probe during recovery, based on previous data, it was estimated to be approximately 2cm beyond the muscle fascia. We report that for a T_m elevation of ~0.5˚C following recovery with external passive heating compared to when no heating is used, that there is an improvement in relative peak power output of 10.6%. This represents a greater improvement in power output than has previously been reported per ˚C rise in T_m at a depth of 3cm (Bergh and Ekblom. 1979; Sargeant. 1987), suggesting that T_m elevations in the more superficial muscle tissue may be a key determinant of muscle power output during short burst activity. Nevertheless, we cannot conclude that this is all down to the alteration in T_m at the onset of the maximal sprint test, as for obvious reasons, we were unable to completely blind participants to the experimental condition, although they were blind to our hypothesis. Therefore, there may be an additional benefit brought about by improved perception of "readiness" and this may be why we see a larger rise in power per ˚C than has previously been reported.

Practical Application

The present data demonstrate that using passive heating as part of a pre-race or mid event strategy to maintain muscle temperature is capable of improving sprint/power related performance measures. Based on the results of this and our previous study (Faulkner et al. 2013), a similar intervention was used by the British track cycling team at the London Olympics during the sprint events in which Team GB achieved a number of gold medals and World Records (Cycling Weekly, 2012).

It may be of particular importance to realize that T_m appears to decline immediately upon exercise cessation and as little a decline in muscle temperature as 0.3°C may be critical to maintaining performance. Therefore even where delays between exercise bouts, or between warm up completion and competition are relatively short, using passive external heating to maintain T_m may be of benefit to the subsequent performance. However, our data suggest that adding this heating during the 15 minute warm up did not provide any significant additional benefit. It should also be noted that the heated clothing interventions studied are unlikely to raise muscle temperature substantially when used without active warm-up.

Conclusion

This experiment has been successful in demonstrating that the use of a heating garment during a warm up and the following recovery does not convey an additional benefit to either T_m or any measures of sprint cycling performance, over and above what is achieved when the same garment is used during recovery alone. Furthermore, these data show that when no additional heating is applied post warm up during a period of inactivity, muscle temperature declines exponentially, with the rate of decline attenuated in both CONHOT and HOTHOT. These data add further weight to the argument that sprint and power athletes should use some form of passive heating in between competitive performance exercise bouts when T_m will decline due to limited activity.

Acknowledgements

References

Aikas E, Karvonen MJ, Piironen P, Ruosteenoja R (1962) Intramuscular, rectal and oesophageal temperature during exercise. Acta Physiol Scand 54:36-70

Allsop P, Jorfeldt L, Rutberg H, Lennmarken C, Hall GM (1991) Delayed recovery of muscle pH after short duration, high intensity exercise in malignant hyperthermia susceptible subjects. Br J Anaesth 66:541-545

Anderson C, Andersson T, Wardell K (1994) Changes in skin circulation after insertion of a microdialysis probe visualized by laser Doppler perfusion imaging. J Invest Dermatol. 102:807–811

ASHRAE (1997) *Thermal comfort. ASHRAE handbook of fundamentals.* . In: Anonymous , Atlanta, USA

Asmussen E, Boje O (1945) Body temperature and capacity for work. Acta Physiol Scand 10:1-22

Bar-Or O. The Wingate anaerobic test. An update on methodology, reliability and validity. Sports Med. 1987;4(6):381–94

Bergh U, Ekblom B (1979) Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. Acta Physiol Scand 107:33-37

Brooks GA, Hittelman KJ, Faulkner JA, Beyer RE (1971) Tissue temperatures and whole-animal oxygen consumption after exercise. Am J Physiol 221:427-431

Cycling Weekly (2012) Pendelton's hotpants helped her win gold. IPC Media. http://homepages.lboro.ac.uk/~hugh/pendleton's%20hotpants%20helped%20her%20win%20gold.pdf. Accessed 10 August 2012

De Ruiter CJ, De Haan A (2000) Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. Pflugers Arch 440:163-170

Dotan R, Bar-Or O. Load optimization for the Wingate Anaerobic Test. Eur J Appl Physiol Occup Physiol. 1983;51(3):409–17

Edwards RH, Harris RC, Hultman E, Kaijser L, Koh D, Nordesjo LO (1972) Effect of temperature on muscle energy metabolism and endurance during successive isometric contractions, sustained to fatigue, of the quadriceps muscle in man. J Physiol 220:335-352

Faulkner SH, Ferguson RA, Gerrett N, Hupperets M, Hodder SG, Havenith G (2013) Reducing Muscle Temperature Drop after Warm-up Improves Sprint Cycling Performance. Med Sci Sports Exerc 45:359-365

Gray SR, De Vito G, Nimmo MA, Farina D, Ferguson RA (2006) Skeletal muscle ATP turnover and muscle fiber conduction velocity are elevated at higher muscle temperatures during maximal power output development in humans. Am J Physiol Regul Integr Comp Physiol 290:R376-382

Griffiths ID, Boyce PR (1971) Performance and thermal comfort. Ergonomics 14:457-468

Hajoglou A, Foster C, De Koning JJ, Lucia A, Kernozek TW, Porcari JP (2005) Effect of warm-up on cycle time trial performance. Med Sci Sports Exerc 37:1608-1614

Hardy JD (1956) The nature of pain. J Chronic Dis 4:22-51

Hardy JD, Goodell H, Wolff HG (1952) The influence of skin temperature upon the pain threshold as evoked by thermal radiation. J Nerv Ment Dis 116:359-360

Hardy JD, Goodell H, Wolff HG (1951) The influence of skin temperature upon the pain threshold as evoked by thermal radiation. Science 114:149-150

Havenith G (2009) Laboratory assessment of cold weather clothing. In: Williams J (ed) Textiles for cold weather apparel, Publishing in Textiles: Number 93 edn. Woodhead Publishing Limited, Oxford Cambridge New Delhi

Havenith, G (2001) An individual model of human thermoregulation for the simulation of heat stress response. J Appl Physiol 90:1943-1954

Kenny GP, Reardon FD, Zaleski W, Reardon ML, Haman F, Ducharme MB (2003) Muscle temperature transients before, during, and after exercise measured using an intramuscular multisensor probe. J Appl Physiol 94:2350-2357

Kenny GP, Reardon FD, Ducharme MB, Reardon ML, Zaleski W (2002) Tissue temperature transients in resting contra-lateral leg muscle tissue during isolated knee extension. Can J Appl Physiol 27:535-550

Kilduff LP, West DJ, Williams N, Cook CJ (2012) The influence of passive heat maintenance on lower body power output and repeated sprint performance in professional rugby league players. J Sci Med Sport [Epub ahead of print]

McRae DA, Esrick MA (1993) Changes in electrical impedance of skeletal muscle measured during hyperthermia. Int J Hyperthermia 9:247-61

Racinais S, Blonc S, Hue O (2005) Effects of active warm-up and diurnal increase in temperature on muscular power. Med Sci Sports Exerc 37:2134-2139

Saltin B, Gagge AP, Bergh U, Stolwijk JA (1972) Body temperatures and sweating during exhaustive exercise. J Appl Physiol 32:635-643

Saltin B, Gagge AP, Stolwijk JA (1970) Body temperatures and sweating during thermal transients caused by exercise. J Appl Physiol 28:318-327

Saltin B, Gagge AP, Stolwijk JA (1968) Muscle temperature during submaximal exercise in man. J Appl Physiol 25:679-688

Sargeant AJ (1987) Effect of muscle temperature on leg extension force and short-term power output in humans. Eur J Appl Physiol Occup Physiol 56:693-698

Stenken JA, Church MK, Gill CA, Clough GF (2010) How minimally invasive is microdialysis sampling? A cautionary note for cytokine collection in human skin and other clinical studies. The AAPS Journal 12:73–78