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An external heating garment improves 2,000 m rowing performance in a cool environment

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Abstract

Purpose. Rowers can be in marshalling areas for up to 20-25 minutes before the start of a race, which likely negates any benefits of an active warm-up, especially in cold environments. It is unknown if using a heated jacket following a standardised rowing warm-up can improve 2,000 m rowing performance. **Methods.** On two separate occasions, ten trained male rowers completed a standardised rowing warm-up, followed by 25 minutes of passive rest before a 2,000 m rowing time-trial (TT) on a rowing ergometer. Throughout the passive rest, participants wore either a standardised tracksuit top (CON) or an externally heated jacket (HEAT). The trials, presented in a randomised, cross-over fashion, were performed in a controlled environment (temperature, 8°C; humidity 50%). Rowing TT performance, core body and mean skin temperature, along with perceptual variables were measured. **Results.** During the 25 minute period, core body temperature increased in HEAT and decreased in CON ($\Delta 0.54 \pm 0.74$ vs. -0.93 ± 1.14°C; $P = 0.02$). Additionally, mean skin temperature (30.22 ± 1.03 vs. 28.86 ± 1.07°C) was higher in HEAT vs. CON ($P < 0.01$). In line with the physiological data, perceptual data confirmed that participants were more comfortable in HEAT vs. CON and subsequently, rowing performance was improved in HEAT compared to CON (433.1 ± 12.7 vs. 437.9 ± 14.4 s, $P = 0.002$). **Conclusion.** Our data demonstrate that an upper body external heating garment, worn following a warm-up, can improve rowing performance in a cool environment.

Introduction

Rowing is a physiological demanding sport due to the recruitment of a large muscle mass and work rates near to rowers' maximal physical capacity[1,2]. Rowers possess large body dimensions and produce among the largest values of any athlete in specific parameters of physical fitness, involving those related to muscular and cardiorespiratory function[3], such that warming-up prior to a rowing race is an integral part of the preparation phase. Generally, after the warm-up period, rowers must be in the marshalling area ~10-15 minutes before the start of a race and transition phases between warm-up and the beginning of a race can be as long as 20 to 25 minutes. It appears that there is an increased risk of a decline in core temperature (T_{core}) with longer transitions[4] and a reduction in this time has been found to attenuate the overall decline in T_{core}, significantly improving performance times[5,6]. However, there is little scope to alter rowing competition schedules by a large margin. Therefore, methods are needed to support rowers in maintaining muscle activation and raised core and muscle temperature during such transition periods. A rise in muscle temperature results in various physiological benefits, including an increased speed of contraction and relaxation of muscle fibres, increased anaerobic metabolic capacity and nerve conduction enhancements in both the peripheral and central nervous system[7]. Therefore, the transition time offers a period for experimental implementation of different strategies to counter the decline in T_{core} and subsequently improve performance.

Recent literature has combined an active warm-up followed by heated tracksuit pants in the marshalling period before a sprint cycling race which improved core and muscle temperature maintenance, along with time trial (TT) performance (~2%)[8]. More specifically, a combination of an active swimming warm-up followed by use of an upper body passive heating device in the "call room", improved maintenance in core and muscle temperature and overall swimming performance to a similar extent[5,9]. However, although those studies observed significant improvements in performance, few studies have determined the physiological outcomes of a passive warm-up during long duration exercise performance (≥5 minutes), this is partly due to the fact that there are detrimental physiological factors which negatively impact performance in such circumstances. Gregson et al.[10] reported that following a passive warm-up which increased T_{core} to 38.0°C, significantly decreased the time to exhaustion at 70% of maximum aerobic capacity. Similarly, the same authors also observed warming-up passively, significantly decreases high-intensity intermittent exercise time to exhaustion at an ambient temperature (21.7°C)[11]. This negative effect on performance is thought to be because of the impaired thermoregulatory mechanisms and/or a decrease in heat storage capacity, resulting in an accelerated accumulation of metabolites and/or an earlier attainment of a high core temperature[10]. However, at a lower ambient temperature (5°C), a significantly higher heat-storage capacity exists compared to standard ambient conditions (18-20°C)[12]. This may delay the onset of a critical core temperature during long duration rowing in cool conditions and seems to provide valid reasoning for a passive heating device to improve core and muscle temperature maintenance, throughout the lengthy transition periods experienced during competitive rowing. The combination of an upper body passive heating device worn throughout the transition period between the warm-up and race may elicit performance enhancing benefits.

Accordingly, the purpose of this study was to determine if the use of an externally heated jacket during the transition phase, could improve 2,000 m single scull rowing performance. It was hypothesised that the heated jacket would improve performance in a cool environment by attenuating the decline in body temperature.

Methods

Participants

Ten trained male rowers participated in this study (age, 24.1 ± 2.89 years; stature, 1.85 ± 0.4 m; body mass, 77.61 ± 5.49 kg). The population was defined as a rower who regularly competes in key regional or national tournaments and for the sample studied, rowers competed for 4 ± 2 years and trained 5 ± 1 times a week for a total of 7 ± 3 hours. A sample size of 10 was calculated using a change in mean 2,000 m rowing TT performance, a crossover design in a similar population and the SD of non-tapered performance times (± 23.4 s). A statistical power of 0.8 and the smallest worthwhile improvement in performance of 1%[13] was used (v18 Mini Tab LL, Microsoft, PEN, USA). None of the participants supplemented their diets with any putative ergogenic aid for six months before the start of the study. All participants were explained the experimental procedures, potential benefits, the value of likely findings and associated risks, before providing informed consent to participate. Participants were asked to avoid the consumption of caffeine and alcohol and refrain any vigorous exercise 24 hours before all testing. Participants were also asked to emulate their food consumption during the course of the study. Additionally, foot position and rowing drag on the rowing ergometer remained the same across all visits.

Experimental Design

This study used a within-participant, randomised and counterbalanced experimental design. Each participant was required to visit the environmental chamber (TIS Services, Alton, Hampshire, UK) on three separate occasions, with each session ~7 days apart. Trials were performed at the same time of day (±1 hour) to minimise circadian effects. Before the two experimental sessions participants were familiarised with the exercise protocol and initial measurements were taken (age, stature and body mass). Participants then entered the environmental chamber, with the temperature (8°C) and humidity (50%) controlled to reflect common morning conditions experienced at the start of the competitive UK outdoor rowing season (March). During each visit, participants completed a 10 minute standardised rowing warm-up[14], followed by 25 minutes of passive rest, replicating the time between the completion of a warm-up and the beginning of a race. During the passive rest, participants wore a pair of standardised tracksuit bottoms with a standardised tracksuit top (CON) or, an externally heated jacket (HEAT; Powerlet rapidFIRe Proform Heated Jacket Liner, Warren, MI, USA). Following the passive rest, clothing was removed and a 2,000 m TT was performed on a rowing ergometer (Concept2, Nottingham, UK).

Procedure

Participants arrived at the environmental chamber after consuming a meal typically ~2 hours prior to testing. Upon arrival, following baseline measurements of stature and body mass (Seca Ltd, Birmingham, UK), a calibrated aural thermistor (Grant Instruments, Cambridge, UK), was inserted into the participant's right auditory canal to estimate T_{core}. The thermistor was securely taped into position and insulated with cotton wool[15], before a headband was fitted to maintain placement. Additionally, wired skin thermistors (Grant Instruments) were then attached to the forearm ($T_{Forearm}$), chest (T_{Chest}) and calf (T_{Calf}) for the calculation of mean skin temperature (T_{Sk}; $T_{Sk} = 0.5 \times T_{Chest} + 0.36 \times T_{Calf} + 0.14 \times T_{Forearm}$)[16]. The skin thermistors were placed over the skin and secured in place using an adhesive spray and tape; both aural and skin thermistors, were connected to a data logger (Squirrel SQ2020 Data Logger, Dorset, UK) that sampled data in 10 s epochs. A heart rate (HR) monitor was also fitted (Polar FT1; Polar Electro Oy, Kempele, Finland) prior to entering the chamber.

Once participants entered the environmental chamber, they were seated for a 10 minute stabilisation period, during this time participants wore a standardised tracksuit comprising of a zipped-up tracksuit top and trouser bottoms, both consisting of a single layer of nylon material with minimal insulation. Following the stabilisation period, baseline measurements were recorded beginning with a capillary blood sample (20 ml) from the earlobe to measure blood lactate (BLa) using a calibrated, automated system (Biosen 5030, EKF Industrie, Elektronik GmbH, Barleben, Germany). Additionally, T_{core}, T_{Chest}, T_{Calf}, $T_{Forearm}$, and HR were recorded, as well as thermal comfort (TC) and thermal sensation (TS) using visual analogue scales[17]. The number range for both scales was consistent but anchors varied (TC, −3 very uncomfortable, −2 uncomfortable, −1 just uncomfortable, 0 neutral, 1 just comfortable, 2 comfortable, 3 very comfortable; TS, −3 cold, −2 slightly cold, −1 cool, 0 neutral, 1 warm, 2 slightly hot, 3 hot). Participants then completed a standardised 10 minute rowing warm-up using 18-20 strokes per minute[14]. Immediately after the warm-up, participants were seated for 25 minutes simulating the 'marshalling period' between the warm-up and the beginning of a rowing race. Participants wore a long sleeve t-shirt, standardised tracksuit trouser bottoms and CON or HEAT; both jackets' insulations were similar when unheated. The heated jacket (Powerlet rapidFIRe Proform) was chosen because of the optimal coverage of the torso and arms with the heating elements in comparison to other varieties. The key upper body muscle groups (lower deltoids, tricep brachii, pectoralis major and the latissimus dorsi) used for rowing were covered by the heating elements which were powered by 12 V, 10 A power transformers enabling capacity of 105 W. The jacket's stretch panels allowed for optimal heat transfer, as the material is maintained close to the body, thus decreasing convection, whilst allowing movement. The maximum temperature of the heating elements was 50°C but T_{Sk} is known to be lower[5]. The long sleeve t-shirt was worn under the jacket to eliminate the likelihood of burning and ratings of TC and TS were made throughout the entire protocol. Participants were asked to ensure the jacket felt 'comfortable (≤2)' and 'hot (≤3)', if the participant felt 'uncomfortable (≥−2)' the heat stimulus was reduced. As the garment is used for sub-zero conditions, a maximum level of possible heating was not encroached upon. Over the duration of the 25 minute period, all temperature related measurements were recorded every 5 minutes. Following the passive period, tracksuits were removed, and participants performed the 2,000 m rowing TT, replicating the single scull event. Participants were instructed to complete the distance in the fastest possible time and were blinded to feedback. Performance was recorded as the time to completion (s) with HR measured throughout (every 30 s) and BLa measured immediately post.

Data analysis

Data are presented as mean ± SD unless stated otherwise and all data were analysed using GraphPad Prism (v7.04, GraphPad Software, San Diego, CA, USA). Prior to analyses, normality of data was assessed using the Kolmogorov-Smirnov test (v26, SPSS, IBM Cooperation, Armonk, NY, USA). Parameters measured throughout the passive period were analysed using a two-way, repeated-measures ANOVA (Condition [2], time [6]) with multiple comparisons corrected using the Bonferroni method when significant main or interaction effects were observed. Performance data, and the change in BLa, were analysed using a two-tailed, paired T-test. The accepted level of significance was $P < 0.05$. Effect sizes (partial eta squared [η^2]) were determined from the ANOVA (SSeffect/[SSeffect+SSresidual]) and T-test ($t^2[/t^2 + df]$) outputs.

Results

25 minute passive period

No changes were evident in T_{core} at baseline (37.4 ± 0.6 vs. 37.5 ± 0.5°C; P = 0.838) but throughout the passive period there were disparate changes over time ($F_{9,45} = 4.9$, $P < 0.001$), with higher values recorded in HEAT (Δ0.54 ± 0.74°C) compared to CON (Δ−0.93 ± 1.15°C) (condition, $F_{1,5} = 15.5$, $P = 0.011$, $\eta^2 = 0.38$; interaction, $F_{9,45} = 6.8$, $P < 0.001$). Post hoc analyses showed that T_{core} was higher in HEAT at 20 ($P = 0.008$) and 25 mins ($P = 0.001$) (Figure 1A). T_{Sk} also changed over time ($F_{9,45} = 65.1$, $P < 0.001$) and differed between conditions ($F_{1,5} = 25.1$, $P = 0.004$, $\eta^2 = 0.95$; interaction, $F_{9,45} = 4.3$, $P < 0.001$). Specifically, T_{Sk} was higher in HEAT vs. CON at 20 ($P < 0.012$) and 25 mins ($P = 0.013$) (Figure 1B).

In terms of the perceptual response, TC changed over time ($F_{9,45} = 9.5$, $P < 0.001$) with responses being higher in HEAT vs. CON ($F_{9,45} = 9.5$, $P < 0.001$, $\eta^2 = 0.70$), however, no interaction effect was evident ($F_{9,45} = 2.1$, $P = 0.053$). Within condition effects for TC showed that every time point throughout the intervention was increased in HEAT (all $P < 0.0001$ vs. pre), whilst in CON, values were only different from pre at 5 ($P < 0.001$) and 10 ($P = 0.001$) mins. TS also changed over time ($F_{9,45} = 2.2$, $P = 0.037$) with responses being higher in HEAT vs. CON ($F_{1,5} = 15.9$, $P = 0.011$, $\eta^2 = 0.42$; interaction, $F_{9,45} = 7.2$, $P < 0.001$). Specifically, TS was higher in HEAT at 10 ($P = 0.003$), 15 ($P = 0.003$), 20 ($P < 0.001$) and 25 mins ($P < 0.001$). Within condition effects for TS showed that every time point throughout the intervention was increased in HEAT (all $P < 0.0001$ vs. pre), whilst in CON, values were only different from pre at 5 ($P = 0.003$), 10 ($P = 0.048$) and 15 ($P = 0.020$) mins (Table 1).

TT performance

Rowing performance was faster in HEAT vs. CON (433.1 ± 12.7 vs. 437.9 ± 14.4 s, Δ1.1%, $t = 4.3$, $P = 0.002$, $\eta^2 = 0.92$; Figure 2). No differences were observed in maximum HR (180 ± 6.7 vs. 178 ± 9 bpm; $t = 1.07$, $P = 0.311$) or the change in BLa (Δ10.27 ± 1.68 vs. 9.77 ± 2.24 mmol·L; $t = 1.08$, $P = 0.306$).

Discussion

The main aim of the present investigation was to understand the effect of using an external heating garment prior to rowing performance in a cool environment. The results show that core and mean skin temperature were higher when using a heated jacket and this led to a faster (1.1%) 2,000 m rowing performance. These data are in line with other investigations which have used thermal interventions in the time prior to exercise performance, akin to that of a holding area during competition. Thus, the present study supports the use of a heated jacket by competitive rowers to maintain core temperature prior to competition, in order to improve performance, particularly when ambient temperatures are low.

Relevance to rowing performance

This study addresses a period of time that should be viewed as an opportunity for applied sport and exercise science practitioners. To the authors' knowledge there is no present literature that has investigated the effects of passive heating protocols used in the time between the end of an active warm-up and the beginning of rowing performance. Such a timeframe was adopted to replicate the marshalling area where rowers wait before a race, which similar to swimming, is known to be an area insufficient to perform exercise[4,5]. Using the heated garment led to an improvement in 2,000 m rowing performance by 1.1%, a magnitude which is deemed important as improvements in performance of as little as 1% can increase the likelihood of positioning higher in a rowing race[13]. The improvement in rowing performance is similar to what has been seen previously in swimming (1.01%)[5] and is likely driven by the higher core and skin temperature (Figure 1) and likely muscle temperature achieved when using the jacket[5,8,18]. The heated jacket caused an increase in T_{core}, compared to a decline found when using the standardised tracksuit jacket, with an overall mean difference of 1.47°C. Such an increase in T_{core} before competition, is acknowledged to be a key determinant for endurance/power based events by facilitating increases in muscle fibre conduction velocity and muscle metabolism[19,20]. Furthermore, the ambient temperature is an important factor to be considered. When the heated jacket is used after warming up in a cool environment, body temperature would be relatively lower compared to if the same protocol was implemented in standard ambient conditions (18-20°C)[21]. Thus, in a cooler environment, the time to reach a critical T_{core} would be delayed and performance improves, however, at a standard ambient temperature, the use of a heated jacket might raise T_{core} to critical levels and potentially reduce capacity for exercise performance. In line with the physiological data, ratings of thermal comfort and sensation improved when using the heated jacket (Table 1), suggesting that participants felt more comfortable in this trial. Indeed, being warm causes widespread changes in the central nervous system[22] and increases perceptions of readiness to perform[23]. Thus, enhanced rowing performance with the heated jacket, likely stemmed from changes in physiological and psychological components.

Skin Temperature

Wearing the heated jacket during 25 minutes of passive rest following the active warm-up increased T_{sk} on average by ~1.37°C compared to the control condition. Although the present study did not directly measure muscle temperature, it is likely that it would have increased, at least to some extent, when using the heated jacket[8,24]. It should be noted that the skin temperature measurement sites in the present study were located on the upper (chest and forearm) and lower body (calf), such that the use of an equation to estimate measure muscle temperature[25] is invalid. These sites were selected to capture the thermal effects of the heated jacket. Yet, the procedural difficulties associated with directly measuring muscle temperature at these sites, such as avoiding the circulatory anatomy, may make recording muscle temperature at the upper body more difficult. Taken together, the increased T_{sk} and T_{core} clearly demonstrates that the participants were hotter when using the heated jacket and we speculate this maintained the temperature of underlying muscle. Given that a muscle temperature difference of ~0.3°C is known to alter performance[8], increases in upper body temperature with use of the heated jacket, in part, likely explains the positive effect on subsequent rowing performance.

Most of the positive properties of warming-up have been accredited to mechanisms relating to temperature regulation[26]. The relationship between muscle function and temperature is well recognised[27-29], thus the maintenance of an increased muscle temperature from a warm-up is essential for attaining an optimal performance. Increased temperature improves performance due to a number of factors, including the change in the force-velocity relationship, increased transmission rate of nerve impulses, decreased stiffness of joints and muscles and increased high energy phosphate degradation, glycolgenolysis and glycolysis[26]. Additionally, due to the likely improved muscle temperature when using the heated jacket, would suggest muscle-fibre conduction velocity is increased and is a potential mechanism contributing to the enhancement in performance[27]. Heightened muscle temperatures have also been related to rise of myosin adenosine triphosphatase activity, improving the rate of ATP turnover and calcium sequestration by the sarcoplasmic reticulum[30,31]. Collectively, these physiological variations confirm why an increased power output is reached and could be linked to higher muscle temperatures. As power output is a key influence in rowing performance, responsible for the ability to produce driving force, it is essential that temperature is upheld throughout the transition period prior to competition[14].

Presently, there is no technique available to assist thermal maintenance during rowing competitions. Therefore, rowers potentially compete with sub optimal thermal profiles, as warm-ups are generally completed from anywhere between 20-25 minutes prior to racing. This is far from the optimal recommendation of between 5-10 minutes between cessation of warm-up and a race[26]. However, because of competition time constraints and the absence of warm-up facilities in marshalling areas, improving warm-up time is not possible. Durations which are longer than the optimal time to compete, would result in a disadvantageous thermal profile, which we speculate to be the primary variable for enhancement when using the heated jacket in the present study. We show that the absence of a thermal manipulation leads to the muscle contractile properties generating less powerful and slower contractions, as indicated by our slower performance times in the control condition[28,32]. Consequently, rowers might start a race in a sub optimal physical condition, thereby reducing possibilities of accomplishing a peak performance. Historically, research has suggested that females experience higher cardiovascular or thermal strain compared to men during exercise in the heat[33], which would have implications for passive heating protocols. Such differences were related to group variations in body size, fitness and environmental conditions. However, more recent evidence suggests that across most activities and environments, it does not appear that young, healthy women are at any disadvantage when exercising in the heat compared to men of similar age, fitness and overall health[34], making the present findings applicable to female rowers also. It should be noted, however, that fluctuations in T_{core} across the menstrual cycle[35,36] could affect thermoregulation and potentially the effectiveness of a passive heating protocol. Nonetheless, our data suggest that an active warm-up, combined with a passive heating protocol, can offset such attenuations in temperature during the transition period and significantly improve 2,000 m rowing performance in a cool environment.

Limitations

The method of T_{core} assessment in the present study has been shown to be confounded by convection and inaccuracies at higher temperatures, in comparison to other methods[37]. Despite this, we are confident in the data presented. Temperatures were never deemed to be ‘high’ and disparate responses are reported, thus, if a more accurate method was used, differences would have likely been more pronounced. Furthermore, showing a change with aural temperature, demonstrates the strength of the hyperthermic stimulus generated by the jacket. Furthermore, we measured responses during a passive period, so heating and cooling is not going to be profoundly influenced by convection (i.e. no body movement) or large changes in blood circulation to the muscles under the heating jacket, which would happen if they were exercising. Thus, it is most likely that conductive heating and cooling was elicited during the intervention period. To address some of these points, further research is required to determine the optimal strategy for passive heating protocols, including the location of the heating elements embodied into a garment, garment temperature, the muscle groups that are studied, the effect of a more harsh environment including wind (convection) and the length of time garments should be worn.

Practical applications

The present study supports the use of a heated jacket by competitive rowers to maintain a thermal profile prior to competition, in order to improve performance particularly when ambient temperatures are low. The findings reported here may be applicable to sports that experience delays post warm-up, in particular events which are frequently performed in low ambient temperatures.

Conclusion

This study demonstrates that after an active warm-up, 25 minutes of passive rest with the application of an externally heated jacket, leads to a significant and relevant enhancement in 2,000 m single scull rowing performance in a cool environment. This study presents the first practical application of heated garments in rowing and longer duration performance in low ambient temperatures. These data offer rowers a protocol to maintain body temperature throughout the unavoidable delay from the end of an active warm-up to the start of a race. The findings reported here may be applicable to sports that experience delays post warm-up and in particular, events which are frequently performed in cool environments.

References

1. Baudouin A, Hawkins D. Investigation of biomechanical factors affecting rowing performance. *J Biomech.* 2004;37(7):969-976.
2. Buckeridge EM, Bull AM, McGregor AH. Biomechanical determinants of elite rowing technique and performance. *Scand J Med Sci Sports.* 2015;25(2):e176-183.
3. Hagerman FC. Applied physiology of rowing. *Sports medicine.* 1984;1(4):303-326.
4. West DJ, Dietzig BM, Bracken RM, et al. Influence of post-warm-up recovery time on swim performance in international swimmers. *J Med Sport.* 2013;16(2):172-176.
5. Wilkins E, Havenith G. External heating garments used post-warm-up improve upper body power and elite sprint swimming performance. *J Sports Eng Tech.* 2017;231(2):91 - 101.
6. Zochowski T, Johnson E, Sleivert GG. Effects of varying post-warm-up recovery time on 200-m time-trial swim performance. *Int J Sports Physiol Perf.* 2007;2(2):201-211.
7. Mohr M, Krustrup P, Nybo L, Nielsen JJ, Bangsbo J. Muscle temperature and sprint performance during soccer matches--beneficial effect of re-warm-up at half-time. *Scand J Med Sci Sport.* 2004;14(3):156-162.
8. Faulkner SH, Ferguson RA, Hodder SG, Havenith G. External muscle heating during warm-up does not provide added performance benefit above external heating in the recovery period alone. *Eur J Appl Physiol.* 2013;113(11):2713-2721.
9. McGowan CJ, Pyne DB, Thompson KG, Rattray B. Warm-Up Strategies for Sport and Exercise: Mechanisms and Applications. *Sports Med.* 2015;45(11):1523-1546.
10. Gregson WA, Drust B, Batterham A, Cable NT. The effects of pre-warming on the metabolic and thermoregulatory responses to prolonged submaximal exercise in moderate ambient temperatures. *Eur J Appl Physiol.* 2002;86(6):526-533.
11. Gregson WA, Batterham A, Drust B, Cable NT. The influence of pre-warming on the physiological responses to prolonged intermittent exercise. *J Sports Sci.* 2005;23(5):455-464.
12. Kruk B, Pekkarinen H, Manninen K, Hanninen O. Comparison in men of physiological responses to exercise of increasing intensity at low and moderate ambient temperatures. *Eur J Appl Physiol.* 1991;62(5):353-357.
13. Driller MW, Fell JW, Gregory JR, Shing CM, Williams AD. The effects of high-intensity interval training in well-trained rowers. *Int J Sports Physiol Perf.* 2009;4(1):110-121.
14. Huang C, Nesser T, Edwards J, E. Strength and Power Determinants of Rowing Performance. *J Exer Physiol On.* 2007;10(4):43-50.
15. Barwood MJ, Corbett J, White DK. Spraying with 0.20% L-menthol does not enhance 5 km running performance in the heat in untrained runners. *J Sports Med Phys Fit.* 2014;54(5):595-604.
16. Burton AC. Human Calorimetry: II. The Average Temperature of the Tissues of the Body: Three Figures. *J Nutr.* 1935;9(3):261-280.
17. Gagge AP, Stolwijk JA, Hardy JD. Comfort and thermal sensations and associated physiological responses at various ambient temperatures. *Environ Res.* 1967;1(1):1-20.

18. McGowan CJ, Thompson KG, Pyne DB, Raglin JS, Rattray B. Heated jackets and dryland-based activation exercises used as additional warm-ups during transition enhance sprint swimming performance. *J Sci Med Sport.* 2016;19(4):354-358.

19. Gray SR, De Vito G, Nimmo MA, Farina D, Ferguson RA. 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 Reg Int Comp Physiol.* 2006;290(2):R376-382.

20. Gray SR, Soderlund K, Watson M, Ferguson RA. Skeletal muscle ATP turnover and single fibre ATP and PCr content during intense exercise at different muscle temperatures in humans. *Eur J Physiol.* 2011;462(6):885-893.

21. Marino FE. Methods, advantages, and limitations of body cooling for exercise performance. *Brit J Sports Med.* 2002;36(2):89-94.

22. Lowry CA, Lightman SL, Nutt DJ. That warm fuzzy feeling: brain serotonergic neurons and the regulation of emotion. *J Psychopharmacol.* 2009;23(4):392-400.

23. Yanci J, Iturri J, Castillo D, Pardeiro M, Nakamura FY. Influence of warm-up duration on perceived exertion and subsequent physical performance of soccer players. *Biol Sport.* 2019;36(2):125-131.

24. Raccuglia M, Lloyd A, Filingeri D, Faulkner SH, Hodder S, Havenith G. Post-warm-up muscle temperature maintenance: blood flow contribution and external heating optimisation. *Eur J Appl Physiol.* 2016;116(2):395-404.

25. de Ruiter CJ, Jones DA, Sargeant AJ, de Haan A. Temperature effect on the rates of isometric force development and relaxation in the fresh and fatigued human adductor pollicis muscle. *Exp Physiol.* 1999;84(6):1137-1150.

26. Bishop D. Warm up II: performance changes following active warm up and how to structure the warm up. *Sports Med.* 2003;33(7):483-498.

27. Bergh U, Ekblom B. Influence of muscle temperature on maximal muscle strength and power output in human skeletal muscles. *Acta Physiologica.* 1979;107(1):33-37.

28. Davies CT, Mecrow IK, White MJ. Contractile properties of the human triceps surae with some observations on the effects of temperature and exercise. *Eur J Appl Physiol.* 1982;49(2):255-269.

29. Sargeant AJ. Effect of muscle temperature on leg extension force and short-term power output in humans. *Eur J Appl Physiol.* 1987;56(6):693-698.

30. Racinais S, Oksa J. Temperature and neuromuscular function. *Scand J Med Sci Sports.* 2010;20 Suppl 3:1-18.

31. Stein RB, Gordon T, Shriver J. Temperature dependence of mammalian muscle contractions and ATPase activities. *Biophys J.* 1982;40(2):97-107.

32. De Ruiter CJ, De Haan A. Temperature effect on the force/velocity relationship of the fresh and fatigued human adductor pollicis muscle. *Eur J Physiol.* 2000;440(1):163-170.

33. Charkoudian N, Stachenfeld NS. Reproductive hormone influences on thermoregulation in women. *Compr Physiol.* 2014;4(2):793-804.

34. Charkoudian N, Stachenfeld N. Sex hormone effects on autonomic mechanisms of thermoregulation in humans. *Auton Neurosci.* 2016;196:75-80.

35. Harvey O, Crockett HE. Individual differences in temperature changes of women during the course of the menstrual cycle. *Hum Biol.* 1932;4:453 - 468.

36. Stephenson LA, Kolka MA. Thermoregulation in women. *Exerc Sport Sci Rev.* 1993;21:231-262.

37. Huggins R, Glaviano N, Negishi N, Casa DJ, Hertel J. Comparison of rectal and aural core body temperature thermometry in hyperthermic, exercising individuals: a meta-analysis. *J Ath Trg.* 2012;47(3):329-338.

Table & Figure Legends

Table 1. Thermal comfort and thermal sensation at baseline and throughout the 25 minute intervention period.

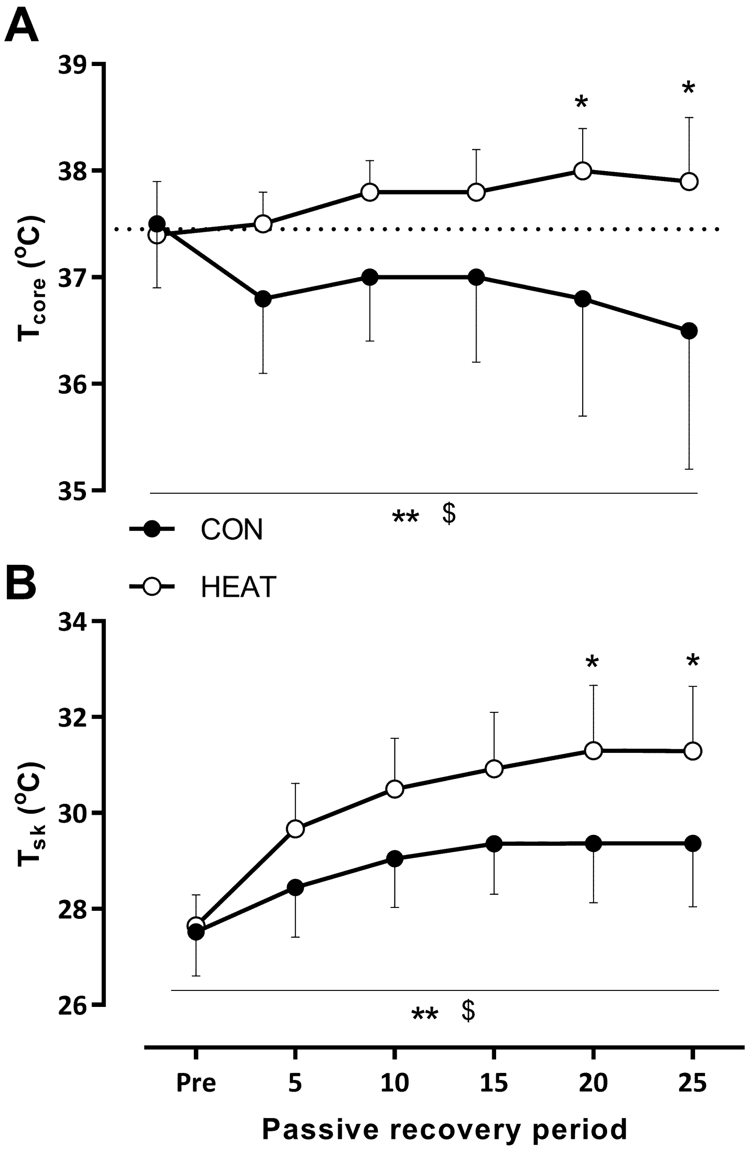
Figure 1. Measurement of core (T_{core}, A) and mean skin temperature (T_{sk}, B) at baseline and throughout the 25 minute intervention period. ** = $P < 0.05$ condition effect, \$ = $P < 0.05$ interaction effect and * = $P < 0.05$ vs. the same time point in CON.

Figure 2. Rowing performance; individual data points are shown as unfilled circles with the adjoining line between conditions and the filled circles represent the mean response in each condition. * = $P = 0.002$ vs. CON.

Table 1. Thermal comfort and thermal sensation at baseline and throughout the 25 minute intervention period.

	Control						Experimental					
Thermal Comfort (TC)												
	Pre	5	10	15	20	25	Pre	5	10	15	20	25
	−1.0 ± 0.7	0.7 ± 0.7*	0.6 ± 0.7*	0.2 ± 0.9	−0.4 ± 1.1	−0.6 ± 1.3	−1.0 ± 0.7	1.5 ± 0.7*	1.9 ± 0.7*	2.0 ± 0.7*	2.0 ± 0.7*	2.0 ± 0.7*
Thermal Sensation (TS)												
	Pre	5	10	15	20	25	Pre	5	10	15	20	25
	−1.5 ± 1.0	0.2 ± 0.6*	−0.1 ± 0.6*	0.0 ± 1.5*	−0.3 ± 1.3	−0.4 ± 1.5	−1.7 ± 0.9	1.3 ± 0.5*	1.6 ± 0.7*#	1.7 ± 0.7*#	1.8 ± 0.6*#	1.8 ± 0.6*#

Visual analogue scale anchors: TC, −3 very uncomfortable, −2 uncomfortable, −1 just uncomfortable, 0 neutral, 1 just comfortable, 2 comfortable, 3 very comfortable; TS, −3 cold, −2 slightly cold, −1 cool, 0 neutral, 1 warm, 2 slightly hot, 3 hot. * $P < 0.05$ vs. Pre; # = $P < 0.05$ vs. CON.


A
39
38
37
36
35
Tcore (°C)
*
*
**
$
CON
HEAT
B
34
32
30
28
26
Tsk (°C)
*
*
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$
Pre
5
10
15
20
25
Passive recovery period