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The effect of thermal insulation pads on heat flux, physical effort and perceived exertion during endurance exercise in cool environments

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Abstract

To determine the effects of thermal insulation pads on clothing surface temperature, physical effort and perceived exertion during endurance exercise in cool environments two different pants (P_{COOL}, P_{INSUL}) were designed: P_{COOL} (Insulation: 0.055 clo) was made of a thin base material while P_{INSUL} (Insulation: 0.131 clo) featured additional insulation pads covering ~30% of its surface, which were placed over the working leg muscles. Two sets of experiments were performed to compare both pants: Study A was completed in 10 active sportsmen who were instructed to run on a treadmill for 45 min at 60% of their maximal running velocity (v_{max}) at 7 °C. In study B, 8 endurance athletes completed the run with 70% v_{max} at 0 °C. Lower and upper body clothing surface temperatures (T_{LB}, T_{UB}), auditory canal temperature, blood lactate, heart rate, subjects´ loss of body mass and perceived exertion were measured. In both studies T_{LB} was found to be lower with P_{INSUL}, reflecting smaller heat loss due to the better thermal insulation. However no significant differences between pants were found for auditory canal temperature, blood lactate, heart rate, subjects´ loss of body mass or perceived exertion. Inserting insulation pads into sports apparel is a practicable approach to limit heat emission from working muscles during endurance exercise in the cold without impairing overall body-heat dissipation. However, under the environmental conditions and exercise intensities tested in this study, the thermal insulation of leg muscles failed to significantly affect parameters reflecting physical effort or perceived exertion.

Keywords: Textiles, Aerobic exercise, Body temperature regulation, Cold temperature

Introduction

Human thermoregulation aims at keeping core temperature at approximately 37 °C and resist thermal fluctuations caused by either endogenous or exogenous factors. Muscular exercise, particularly when performed at vigorous intensity, drastically increases metabolic rate as compared to baseline levels (Jette et al. 1990). Depending on the type of exercise performed, more than 50% of metabolic energy is released as heat (Gonzalez-Alonso et al. 2000; Krustrup et al. 2003) that must be dissipated to the environment to maintain body heat balance. Inadequate heat dissipation results in hyperthermia which limits physical performance especially in endurance-like exercise (Gonzalez-Alonso & Calbet 2003; Nybo 2007, 2009; Tucker et al. 2004). The degree of exercise-induced hyperthermia is largely independent of environmental conditions and directly proportional to the metabolic rate (Nielsen 1938). Sports apparel may also contribute to hyperthermia during physical activity as clothing imposes a barrier for heat exchange with the environment (Gavin 2003). Even in relatively cool environments potentially performance-limiting increases in core temperature may occur if exercise intensity (Ely et al. 2009) and the insulation of the sports apparel worn are sufficiently high (Gavin 2003; Gonzalez et al. 1997).

While systemic increases in body temperature have repeatedly been found to impair endurance performance (Stevens et al. 2016), the functioning of individual skeletal muscles is known to be directly proportional to muscle temperature. Cooling reportedly impairs both the maximal power (Csapo et al. 2017; Drinkwater & Behm 2007) and endurance capacity of skeletal muscles (Bergh & Ekblom 1979; Faulkner et al. 1990; Oksa et al. 2002). In confirmation of the latter, Inoue et al. (2016) recently showed that endurance work performance in a cycle ergometer test was higher when thigh muscle temperature was set to 36 °C as compared to 32 °C.

Sports apparel should therefore meet the competing demands to keep working muscles warm while still facilitating overall heat dissipation to prevent performance-limiting rises in core temperature. In scientific experiments, various attempts have been made to locally influence muscle temperature through warm water immersion (Gray et al. 2006; Sargeant 1987), exposure to hot air (Schlader et al. 2011) or integration of heating/cooling elements (Faulkner et al. 2012; Inoue et al. 2014, 2016). As opposed to these attempts to actively modify muscle temperature, it was decided to reduce heat dissipation through insulation pads that are readily implementable into outdoor sports apparel. Specifically, the goal of this study was to determine the effects of thermal insulation of working muscles on clothing surface temperature and parameters reflecting thermoregulation, physical effort and perceived exertion during endurance exercise in cool environments. Two different combinations of sports apparel were compared: One textile system consisted of a thin shirt and pant to maximize overall heat loss through evaporation of sweat, convection and radiation, whereas the other system featured additional thermal insulation pads placed over the leg muscles with the aim to reduce heat flux from working muscles.

It was hypothesized that the pants containing insulation pads would reduce heat flux, promote local rises in temperature and thereby reduce submaximal exercise responses, as reflected by reduced blood lactate levels and lower heart rates. Furthermore, it was assumed that the insulation pads would not hinder overall dissipation of body heat as they covered only a small part of the whole body surface. Therefore no significant differences in auditory canal and upper body clothing surface temperature were expected between clothing systems.

Method

Study design

To test the influence of insulation pads on clothing surface temperature and parameters reflecting thermoregulation, physical effort and perceived exertion two different running pants with (P_{INSUL}) and without insulation pads (P_{COOL}) were designed and tested in

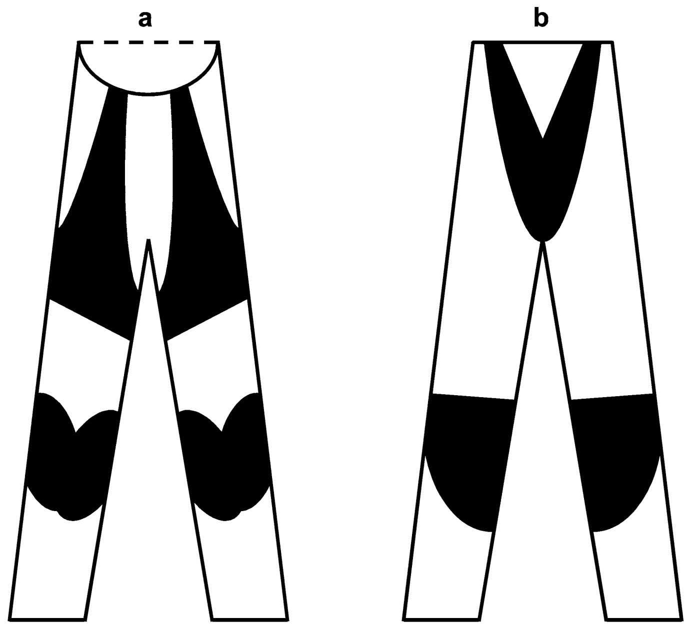

Fig. 1 Schematic image of P_{INSUL} indicating the position of the additional insulation pads placed on the inside at the front (**a**) and rear (**b**) face. The pads were placed to cover the gluteal, knee extensor, ankle dorsi- and plantar flexor muscles and covered ~30% of the surface of P_{INSUL}. P_{COOL} (not pictured) had the same cut and was made of the same base material as P_{INSUL} but was designed without additional insulation pads

two sub-studies: Study A was performed with recreationally active sportsmen who were tested while exercising at moderate intensity under temperate climatic conditions. To reflect the demands in competitive sport, additional experiments were conducted with well-trained endurance athletes exercising in a considerably colder environment (study B).

Apparel

Two different, custom-made running pants (P_{COOL}, P_{INSUL}) were made of identical base fabric and in the same cut. While P_{COOL} was just made of the base material to facilitate heat dissipation, P_{INSUL} featured additional insulating pads as illustrated in Fig. 1 which were sewn in on the inside. The pads were placed to covered the gluteal, knee extensor, ankle dorsi- and plantar flexor muscles and covered ~30% of the surface of P_{INSUL}. The overall insulation of P_{COOL} (size: S) was 0.055 clo while P_{INSUL} (size: S) featured 2.4-times higher insulation (0.131 clo)[1] R_{CT} and further material characteristics of the base fabric and insulation pads are evident from Table 1. The pants were combined with thin long-sleeve shirts composed of the same material as the pants. Pants and shirts were provided in different sizes to guarantee a tight fit. Subjects were also provided with identical thin hats and gloves (100% polyester).

[1] Overall insulation of P_{INSUL} was calculated based on the R_{CT} of the base material/insulation pads and the surface area covered by insulation pads.

Table 1 Material characteristics

	Base fabric	Insulation pads
Material composition	94% Polyester, 6% elastane	94% Polyester, 6% elastane
R_{CT} (Km^2/W)	0.0086 ± 0.0007	0.0454 ± 0.0038
Air permeability (mm/s)	1287.6 ± 257.6	42.8 ± 5.4
Density (g/m^2)	80	380
Thickness (mm)	0.47 ± 0.01	2.14 ± 0.02

Material composition and density are according to manufacturer. R_{CT}: Resistance to conductive heat transfer was tested according to ASTM D1518–14; a higher value reflects higher thermal insulation. Air permeability was assessed according to ISO 9237:1995. Thickness was measured according to ASTM D1777–96 (2015) under a compression of 735 Pa

Subjects

Ten male sport students (age: 23 ± 3 y, height: 182 ± 5 cm, weight: 73.4 ± 4.9 kg, body surface area[2]: 2.3 ± 0.1 m^2, Body Mass Index (BMI)[3]: 22 ± 1 kg/m^2) and eight well trained endurance athletes (age: 28 ± 2 y, height: 175 ± 5 cm, weight: 72.7 ± 7.3 kg, body surface area: 1.9 ± 0.1 m^2, BMI: 24 ± 2 kg/m^2) volunteered to participate in studies A and B, respectively. The experiments were approved by the Institutional Review Board of the Department of Sport Science at the University of Innsbruck. Participants were informed about the study purpose and methods involved before giving written consent. Physical readiness to participate was assessed through completion of the Physical Activity Readiness Questionnaire (PARQ) (Adams 1999).

Exercise intervention

To determine their individual maximal running velocity (v_{max}) an incremental and exhaustive treadmill-based test (5% inclination; pulsar, h/p/cosmos, Germany) was completed by all subjects: After warming up for 5 min at 6 km/h, running speed was increased by 1 km/h every minute until subjects aborted the test due to full exhaustion. If the final stage was not completed for 1 min, v_{max} was calculated proportionally.

Then, participants were scheduled for two visits to compare the different running pants in a randomized order. Tests were conducted at the same time of the day and interspersed by a minimum of 48 h of passive recovery. On both testing days, subjects warmed up on the treadmill for 5 min at a freely chosen velocity. Then, participants were instructed to run for 45 min at 5% inclination. Running velocity was set to 60% (study A) and 70% (study B) of v_{max}. All tests were conducted under constant ambient conditions (study A: 7 ± 1 °C and 40 ± 3% relative humidity; study B: 0 ± 1 °C and 40 ± 3% relative humidity) in a climatic chamber (Kältepol, Austria). Light wind (20 km/h) was simulated using a wind machine (TTW 25000 S, Trotec, Germany) positioned next to the treadmill at a 45° angle and facing the subjects. Average running speed was 9.6 ± 0.6 km/h in study A and 11.8 ± 0.8 km/h in study B, respectively.

[2] Body surface area was calculated according to Du Bois & Du Bois (1989).

[3] BMI = body mass (kg)/height $(m)^2$.

Measurements

Measurements were taken after warm-up (t0) and after 15 min (t1), 30 min (t2) and 45 min (t3) of running. Heart rate, blood lactate, auditory canal temperature and perceived exertion were measured at all measuring times whereas body mass measurements as well as thermal images were obtained at t0 and t3 only.

Clothing surface temperatures and auditory canal temperature were determined as representative measures of body surface and core temperature. Thermal images were recorded from the upper and lower body (Vario Cam High Resolution, Infratec, Germany) with subjects wearing the test apparel. Average clothing surface temperatures were separately calculated in areas coinciding with the anterior and posterior aspect of legs and upper body using custom-made Labview routines (National Instruments, USA) (Fournet et al. 2015). As both pants (P_{INSUL}, P_{COOL}) and the long-sleeve shirts were composed of the same material and tight fit, temperature values calculated on the basis of thermal images of the clothing surface can be directly compared without the need to adjust results for differences in material compositions (emission coefficient was assumed to be $\varepsilon = 0.9$) (Maldague 2012; Pastore & Kiekens 2000). Since the temperatures measured on the anterior and posterior side were found to be largely congruent, the average of these two values was calculated for further analysis. According to Burtscher et al. (2012) auditory canal temperature was measured in the left ear using a thermometer, which was kept under ambient temperature conditions between measurements (ThermoScan IRT 4520, Braun, Germany). During the protocol, ears were covered with a cap to prevent potential bias resulting from cooling of the outer auditory canal.

Blood lactate, heart rate and subjects´ loss of body mass were measured as parameters reflecting physical effort. For blood lactate concentration, capillary blood samples were drawn from the earlobe (Double determination; EKF Biosen 5040, Germany). Heart rate was measured via chest strap (Polar Electro, Finland). To estimate the loss of water due to sweating and respiration, the subjects were weighed in underwear before and after running using a high-precision scale (Kern DS 150K1, Kern & Sohn GmbH, Germany), and the average of five consecutive measurements was considered for further analyses (Agache et al. 2004). In addition, Borg's scale (6 = no exertion; 20 = maximal exertion) was used to inquire perceived exertion (Borg 1982).

Statistical analyses

Factorial ANOVAs with repeated measurements were used to determine the influence of the factors *pant* and *time* on blood lactate, heart rate, auditory canal temperature, clothing surface temperature, subjects´ loss of body mass and perceived exertion. *Pant* × *time* interaction effects were non-significant for all variables, so the respective results are omitted for improved clarity. In cases where Mauchly's test indicated a violation of the assumption of sphericity, degrees of freedom were corrected by the Greenhouse–Geisser procedure. Values are reported as mean values ± standard deviation (SD). Differences were considered significant at $p \leq 0.05$. SPSS Statistics Version 21 (IBM, USA) was used for all statistical calculations.

Results

Lower body clothing surface temperature

In study A (Fig. 2a) lower body clothing surface temperatures (T_{LB}) ($F(1, 9) = 14.138$, $p = 0.004$) were significantly lower for P_{INSUL} compared to P_{COOL} indicating a lower heat flux with P_{INSUL}. T_{LB} did not change significantly over time ($F(1, 9) = 2.855$, $p = 0.125$). Also in study B (Fig. 2b), T_{LB} showed significantly lower values for P_{INSUL} ($F(1, 7) = 11{,}531$, $p = 0.012$). Reflecting the colder conditions in the climatic chamber during study B, T_{LB} dropped significantly during the exercise intervention ($F(1, 7) = 9.664$, $p = 0.017$).

Upper body clothing surface temperature

In study A (Fig. 3a), upper body clothing surface temperature (T_{UB}) revealed no significant differences between apparel systems ($F(1, 9) = 0.488$, $p = 0.503$) but decreased significantly from t0 to t3 ($F(1, 9) = 25.877$, $p = 0.001$). Analogously in study B

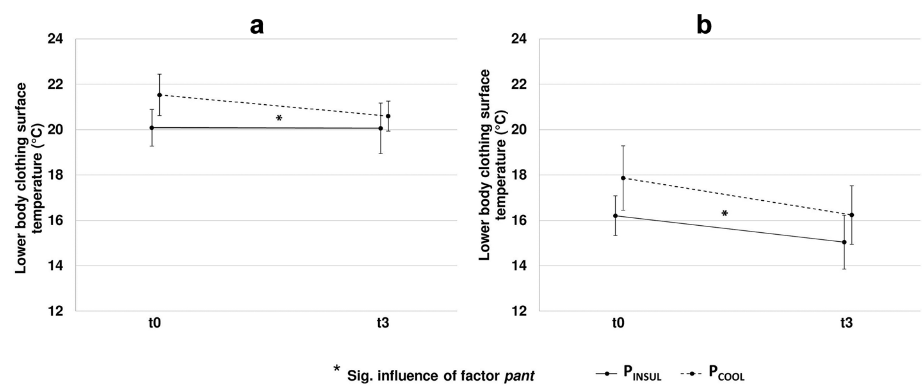

Fig. 2 Lower body clothing surface temperature (T_{LB}) as measured after warm-up (t0) and after 45 min (t3) of running while subjects were wearing the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants in studies A (**a**) and B (**b**). Significantly lower T_{LB} were found for P_{INSUL} ($p < 0.05$) in study A and B indicating a lower heat flux with P_{INSUL} compared to P_{COOL}. A significant effect of *time* ($p < 0.05$) was found in study B. Note: Asterisk indicates significant differences ($p < 0.05$) between P_{INSUL} and P_{COOL}

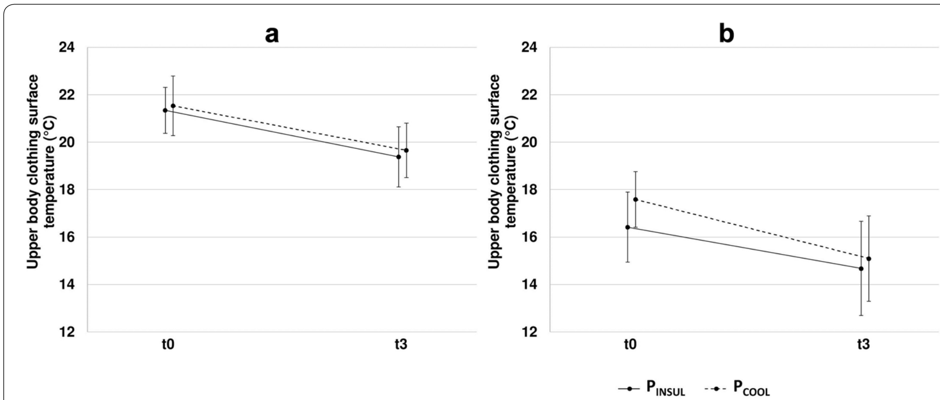

Fig. 3 Upper body clothing surface temperature (T_{UB}) as measured after warm-up (t0) and after 45 min (t3) of running while subjects were wearing the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants in studies A (**a**) and B (**b**). No significant differences were found between P_{INSUL} and P_{COOL}. Factor *time* was significant in study A and B ($p < 0.05$)

(Fig. 3b), the influence of *pant* on T_{UB} (F(1,7) = 1.989, p = 0.201) was non-significant whereas a significant effect of *time* was found for T_{UB} (F(1,7) = 12,245, p = 0.010).

Auditory canal temperature

In study A, auditory canal temperature (Fig. 4a) was neither significantly affected by *pant* F(1, 9) = 0.371, p = 0.558) nor *time* (F(3, 27) = 1.382, p = 0.270).

Just like in study A, the effect of *pant* (F(1, 7) = 0.192, p = 0.674) on auditory canal temperature was not significant in study B (Fig. 4b). However, a significant drop in auditory canal temperature was observed over time (F(3, 21) = 7.504, p = 0.001).

Parameters reflecting physical effort

In study A (Fig. 5a) no significant difference between blood lactate levels was found between P_{INSUL} and P_{COOL} (F(1, 9) = 0.612, p = 0.454). In response to the exercise, blood lactate increased at the start of the exercise and then stabilized (F(1.064, 9.579) = 27.564, p < 0.001) at higher levels.

Just as in study A, the effect of *pant* (F(1, 7) = 0.050, p = 0.830) on blood lactate levels was not significant in study B (Fig. 5b). Blood lactate increased compared to initial levels and then stabilized during exercise (F(1.292, 9.045) = 29.263, p < 0.001).

In study A (Fig. 6a), no significant effects on heart rate were found for the factor *pant* (F(1, 9) = 4.896, p = 0.055). Heart rate increased during the running intervention,

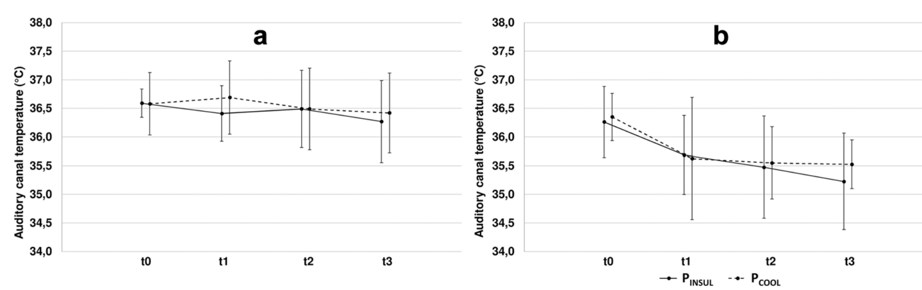

Fig. 4 Auditory canal temperature as measured after warm-up (t0) and after 15 min (t1), 30 min (t2) and 45 min (t3) of running for the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants worn in studies A (**a**) and B (**b**). No significant differences were found between P_{INSUL} and P_{COOL} but factor *time* was significant in study B (p < 0.05)

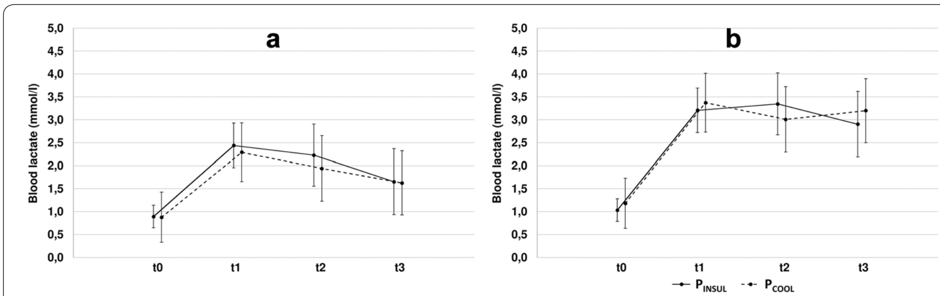

Fig. 5 Blood lactate levels as measured after warm-up (t0) and after 15 min (t1), 30 min (t2) and 45 min (t3) of running while wearing the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants in studies A (**a**) and B (**b**). No significant differences were found between P_{INSUL} and P_{COOL} but factor *time* was significant in study A and B (p < 0.05)

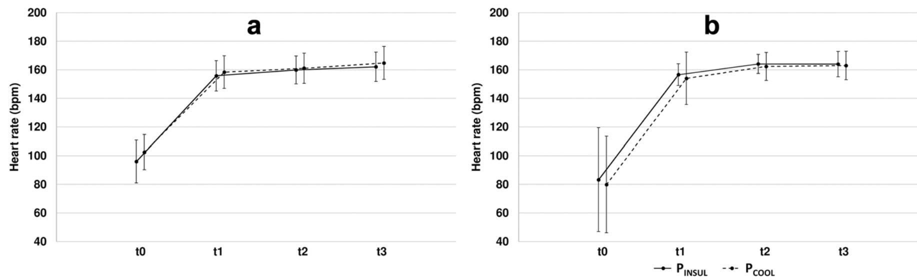

Fig. 6 Heart rate as measured after warm-up (t0) and after 15 min (t1), 30 min (t2) and 45 min (t3) of running for the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants in studies A (**a**) and B (**b**). No significant differences were found between P_{INSUL} and P_{COOL} but factor time was significant in study A and B ($p < 0.05$)

with all follow-up measures being significantly greater as compared to t0 ($F(1.120, 10.076) = 237.294$, $p < 0.001$).

Also in study B (Fig. 6b), the effect of *pant* on heart rate ($F(1, 7) = 0.661$, $p = 0.443$) was non-significant ($F(3, 21) = 0.043$, $p = 0.988$). Heart rate increased from t0 to t1 and then stabilized, revealing a significant effect of *time* ($F(1.118, 8.318) = 53.496$, $p < 0.001$).

Body mass loss

In study A, subjects' body mass decreased significantly from t0 to t3 by 646 ± 107 g with P_{INSUL} and 645 ± 133 g with P_{COOL} ($F(1, 9) = 330.435$, $p < 0.001$), but no significant differences were found between pants ($F(1, 9) = 0.075$, $p = 0.791$).

Comparable losses in body mass (P_{INSUL}: 644 ± 182 g, P_{COOL}: 680 ± 170 g) were observed in study B. As in study A, no statistical effects were found between pants ($F(1, 7) = 0.013$, $p = 0.911$) but the effect of *time* was significant ($F(1, 7) = 104.178$, $p < 0.001$).

Perceived exertion

Perceived exertion as measured with the Borg scale is shown in Fig. 7a, b. As for the parameters reflecting physical effort, the differences between pants ($F(1, 9) = 0.438$, $p = 0.525$) failed to reach statistical significance in study A. Perceived exertion increased

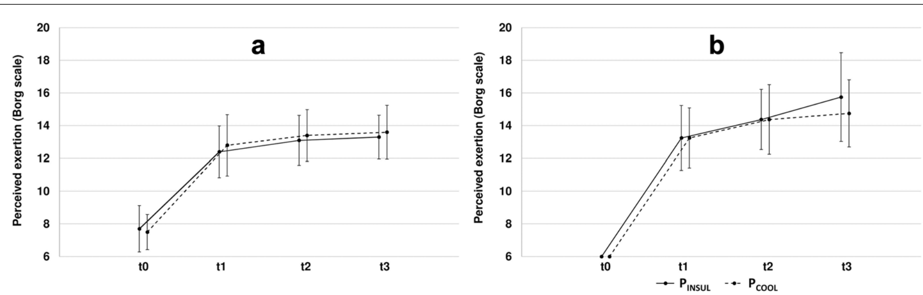

Fig. 7 Perceived exertion as measured after warm-up (t0) and after 15 min (t1), 30 min (t2) and 45 min (t3) of running with the Borg scale for the thermally insulating (P_{INSUL}) and non-insulating (P_{COOL}) pants in studies A (**a**) and B (**b**). No significant differences were found between P_{INSUL} and P_{COOL} but factor time was significant in study A and B ($p < 0.05$)

with both pants during the protocol reflecting a significant influence of *time* ($F(3, 27) = 229.550$, $p < 0.001$).

A similar time course of perceived exertion was found in study B. No significant differences between P_{INSUL} and P_{COOL} ($F(1, 7) = 0.538$, $p = 0.487$) were found, but the effect of *time* was significant ($F(1.262, 8.832) = 129.561$, $p < 0.001$).

Discussion

The aim of this application-oriented study was to determine the effects of thermal insulation pads placed over working leg muscles on clothing surface temperature and parameters reflecting thermoregulation, physical effort and perceived exertion during endurance exercise in cool environments. In agreement with the hypothesis, significantly lower T_{LB} for P_{INSUL} compared to P_{COOL} were found, confirming the insulation effect of the additional pads. Furthermore, no significant differences in T_{UB} and auditory canal temperature were found, which confirms the assumption that the additional insulation pads would not impair thermoregulation during exercise. However, no significant differences in parameters reflecting physical effort or perceived exertion between P_{INSUL} and P_{COOL} were found.

The rationale to test insulation pads placed over working muscles with the aim to improve endurance performance in cool environments was that cold ambient conditions may lead to a drop in muscle temperature (Parkin et al. 1999). This may be of functional importance since cold muscles show impaired performance (Bennett 1985; Bottinelli et al. 1996; Drinkwater & Behm 2007). To counter the expected decreases in muscle temperature, simple insulation pads were used which, unlike active cooling or warming devices (Faulkner et al. 2012; Gray et al. 2006; Inoue et al. 2014, 2016; Sargeant 1987; Schlader et al. 2011), do not require energy supply and could be easily integrated into sports apparel in real-life scenarios.

With P_{INSUL}, T_{LB} were significantly lower as compared to P_{COOL}. Lower surface temperatures reflect smaller heat loss due to better thermal insulation (Al-Homoud 2005). During exercise, muscles produce heat with heat production being directly proportional to exercise intensity (Gonzalez-Alonso et al. 2000; Jette et al. 1990). The lower heat emission observed with P_{INSUL} is expected to promote higher local temperatures underneath the insulated areas. However, conclusions about the effects on muscle temperature remain speculative since (highly invasive) direct measurements were precluded in this study. No significant differences in T_{UB} and auditory canal temperature between pants were found, implicating that thermoregulation was not negatively influenced by the additional insulation pads. Studies by Fournet et al. (2015) and Gavin et al. (2001) confirm these results. They showed that neither clothing systems featuring the same overall insulation but varying local insulation, nor small differences in overall clothing insulation have a significant influence on core temperature while exercising at intensities comparable to the ones applied in this study.

The expected differences in muscle temperature notwithstanding, parameters reflecting physical effort and perceived exertion were not significantly different between P_{INSUL} and P_{COOL}. Various factors may explain this result: It is possible that the warming effect of the insulation pads was not large enough to cause significant differences in muscle temperature and, consequently no physiologically relevant differences in physical effort were found. Inoue et al. (2016) induced temperature differences of 4 °C within the muscle to produce a significant effect on endurance performance. It is also possible that, even with the non-insulating P_{COOL}, muscle temperatures did not drop to an extent where performance deficits may be expected (Noakes 2000). While exercise intensities and climatic conditions were deliberately selected to represent typical conditions encountered by recreationally active sportsmen who exercise in a cool environment (study A) or well-trained athletes exercising in a cold environment (study B), lower exercise intensities in combination with colder environmental conditions are expected to result in more drastic decreases in muscle temperature. In future studies the effect of insulation pads should be evaluated in climatic conditions typical for cold-weather endurance sports like cross country skiing where training and competition are often performed in temperatures below − 15 °C (Larsson et al. 1993).

Several methodical limitations of the current study must be considered. Instead of measuring muscle temperature directly, thermography recordings were used to confirm the insulating effect of the additional pads. In future studies direct measures of muscle temperature should be used to directly determine the differences in muscle temperature induced by insulation pads. Additionally, submaximal exercise responses were investigated, i.e., blood lactate, heart rate, auditory canal temperature, loss in body mass and perceived exertion. While representative of physical effort, such measures may not accurately reflect exercise performance capacity. Thus, in future studies, the effect of insulation pads on the outcomes of competition like events or endurance performance tests (e.g. time trails or time to exhaustion) should be investigated.

Conclusions

Insertion of properly positioned insulation pads into sports apparel is a practical approach to limit heat emission from working muscles during endurance exercise in cool environments without impairing overall body-heat dissipation. However, under the environmental conditions and exercise intensities applied in this study, the insulation of working muscles failed to significantly improve parameters reflecting physical effort or perceived exertion. Two reasons might account for that: Either the warming effect of the insulation pads was not large enough to cause significant differences in muscle temperature or muscle temperatures in both pants did not drop to an extent where performance deficits may be expected. Future studies on the benefit of insulation pads should therefore focus on temperature conditions markedly below 0 °C, where a drop in muscle temperature is likely to be larger. Also muscle temperature should be measured directly.

Authors' contributions

SW, RC carried out the data collection, participated in the development and the final editing of the manuscript. MH, HG, WN assisted with writing the manuscript. TW conducted the textile tests and participated in editing of the manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Ethics approval and consent to participate
The study protocol was approved by the Board for Ethical Questions in Science of the University of Innsbruck (38/2015) indicating compliance with the Helsinki Declaration. Participants were informed about the study purpose and methods involved before giving written consent.

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