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Performance limitation and the role of core temperature when wearing light-weight workwear under moderate thermal conditions

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ABSTRACT

The objective of this investigation was to achieve an understanding about the relationship between heat stress and performance limitation when wearing a two-layerfire-resistant light-weight workwear (full-clothed ensemble) compared to an one-layer short sports gear (semi-clothed ensemble) in an exhaustive, stressful situation under moderate thermal condition (25 °C). Ten well trained male subjects performed a strenuous walking protocol with both clothing ensembles until exhaustion occurred in a climatic chamber. Wearing workwear reduced the endurance performance by 10% ($p=0.007$) and the evaporation by 21% ($p=0.003$), caused a more pronounced rise in core temperature during submaximal walking (0.7 ± 0.3 vs. 1.2 ± 0.4 °C; $p \leq 0.001$) and from start till exhaustion (1.4 ± 0.3 vs. 1.8 ± 0.5 °C; $p=0.008$), accelerated sweat loss (13 ± 2 vs. 15 ± 3 g min^{-1}; $p=0.007$), and led to a significant higher heart rate at the end of cool down (103 ± 6 vs. 111 ± 7 bpm; $p=0.004$). Correlation analysis revealed that core temperature development during submaximal walking and evaporation may play important roles for endurance performance. However, a critical core temperature of 40 °C, which is stated to be a crucial factor for central fatigue and performance limitation, was not reached either with the semi-clothed or the full-clothed ensemble (38.3 ± 0.4 vs. 38.4 ± 0.5 °C). Additionally, perceived exertion did not increase to a higher extent parallel with the rising core temperature with workwear which would substantiate the critical core temperature theory. In conclusion, increased heat stress led to cardiovascular exercise limitation rather than central fatigue.

1. Introduction

Physical activities in hot environments cause core and/or skin temperature increments which are associated with limited performances (Cuddy et al., 2014; Nybo and Nielsen, 2001a,b). An increased heat stress can lead to cardiovascular restrictions and central fatigue (González-Alonso et al., 1999). Hyperthermia increases skin blood flow and heart rate, and reduces cardiac output which is attributed to a lager decline in stroke volume. González-Alonso and Calbet (2003) could demonstrate that severe heat stress reduces maximal oxygen uptake (VO_2max) by accelerating the decline in cardiac output and mean arterial blood pressure, thus leading to a decrease in blood flow to active muscles, O_2 delivery, and O_2 uptake. While the mechanisms of heat stress on the cardiovascular system are well documented, mechanisms by which increased heat stress cause central fatigue are rather vague. Studies report a critical core temperature of 40 °C at which physical activity has to be stopped (Armstrong et al., 2010; González-Alonso et al., 1999; Nybo and Nielsen, 2001a, 2001b). It is believed that high core temperature reduces central drive for exercise by influencing the brain's motor control centre (González-Alonso et al., 1999; Nielsen and Nybo, 2003; Nybo and Nielsen, 2001a, 2001b). For example, it was found that voluntary force development during prolonged maximum voluntary contractions was reduced with hyperthermia and that this reduction was clearly associated with decreased central activation (Nybo and Nielsen, 2001a).

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The predominant heat-dissipating thermoregulatory mechanism for the prevention of hyperthermia and its associated physical restrictions during strenuous activities represent the evaporation of sweat (Casa, 1999; Gavin, 2003; Holmér, 2006). Especially humid ambient conditions limit this effective cooling mechanism. The additional use of protective garment can exaggerate the heat-dissipating restriction due to higher thermal and vapour resistance. Wearing protective clothing in hot environments is associated with pronounced elevations in core temperature and performance limitations (Armstrong et al., 2010; Fogarty et al., 2004). However, wearing extra clothing can increase thermal stress, not only in high ambient temperatures but also in moderate thermal conditions (Gavin, 2003; Kenny et al., 1999). Furthermore, the generated thermal stress is much more pronounced and therefore the performance will be limited if additional strenuous activities are executed. Therefore, using a fire-resistant light-weight workwear could also potentially decrease the effect of evaporative heat loss, thus evoking a critical core temperature, and reduce endurance performance during exhaustive work under moderate thermal conditions.

The main objective was to compare the effects of a fire-resistant two-layer light-weight (1287 g) workwear (full-clothed ensemble) and a short sports gear (one-layer, semi-clothed ensemble) on evaporation of sweat, critical core temperature, and endurance performance under moderate thermal condition (25 °C, 50% RH). It was hypothesised that the rate of sweat evaporated and the associated changes of core temperature play a major role in endurance performance and wearing light-weight workwear will induce a significantly higher thermal stress, in turn leading to a lower endurance performance even under moderate thermal condition. This study was executed to achieve a current status about the performance limitation when wearing fire-resistant two-layer workwear in an exhaustive, stressful situation under normothermic condition.

2. Materials and methods

2.1. Subjects

Ten healthy well trained male students volunteered to participate in this study (age: 25.6 ± 4.8 years; body mass: 73 ± 5.6 kg; body surface area: 1.93 ± 0.1 m^2; height: 1.81 ± 0.05 m; physical activity: 9.1 ± 5.2 h × wk^{-1}). Physical activity of 9 hours per week means that participants were not untrained and performed regular endurance sports (e.g. running, cycling, and ball sports). Participants provided written informed consent, and the study was approved by the Institutional Review Board and the Ethical Commission of the University of Innsbruck.

2.2. Study design and garment specifications

Each subject completed the following test procedure two times. First, participants wore a one-layer traditional short sports gear composed of a t-shirt (163 g) and shorts (179 g). Second, after a resting period of at least three days they wore a fire-resistant two-layerlight-weight workwear system composed of long sleeved and full legged underwear (surface weight: 222 g m^{-2}; fabric thickness: 0.94 mm; thermal resistance: 0.047 $m^2K\,W^{-1}$; water vapour resistance: 4.43 $m^2Pa\,W^{-1}$; water vapour permeability index: 0.64; moisture absorbency potential: 0.62 g m^{-2}; weight: 464 g) in combination with an aramid overall (surface weight: 263 g m^{-2}; fabric thickness: 0.56 mm; thermal resistance: 0.022 m^2 K W^{-1}; water vapour resistance: 3.48 m^2 Pa W^{-1}; water vapour permeability index: 0.38; moisture absorbency potential: 2.3 g m^{-2}; weight: 823 g). The fire-resistant light-weight clothing system (1287 g) was closely fitting and corresponded to a clothing system used, for instance, by welders, fire brigade, military, and police. Underwear and outerwear was comprised of flame resistant aramid fibres. Aramid fibres are synthetic fibres (Aromatic amide) which are commonly used in protective garments. During both tests, to simulate a real life scenario and to increase the work load, participants wore a 9 kg weight belt representing additional working equipment (e.g. breathing apparatus, helmet, gloves, welding gun, fire distinguisher etc.).

2.3. Test protocol

The test protocol was based on pre-investigations which demonstrate that a strenuous, stressful working situation with an additional load (wearing of working equipment) lasting for a minimum of 30 minutes is required. After a warm-up of 10 min, participants walked for 34 min on a treadmill (pulsar, h/p/cosmos, Germany) at a speed of 6 km/h and an inclination of 11%. Afterwards, if exhaustion did not occur, the inclination was increased by 2% every 7 min. The subsequent cool down phase lasted, once again, for 10 min. All tests were performed at 25 °C ambient temperature (T_a) with 50% relative humidity (P_a = 1.583 kPa) in the climatic chamber (Kältepol, Austria) of the Centre of Technology of Ski and Alpine Sport at the Department of Sport Science of the University of Innsbruck (Austria).

2.4. Measurements

2.4.1. Time to exhaustion, heart rate, and perceived exertion

Time to exhaustion reflected the main parameter of endurance performance. Heart rate (wear link + transmitter w.i.n.d, Polar, Finland) was used in parallel with the treadmill software (para graphics, h/p/cosmos, Germany) to monitor and record the performance of the test subjects. Perceived exertion was evaluated with the Borg scale (6–20, from no exertion at all to maximal exertion) (Borg, 1998).

2.4.2. Temperature, Humidity, and comfort

Infra-red ear thermometry (Thermoscan IRT 4520, Braun, Germany) was used to determine core temperature (T_{core} in °C) (Burtscher et al., 2012). This measuring method was chosen because it is non-invasive, fast, and near to the thermoregulatory centre. A thermo sensor (SHT 15, Sensirion, Switzerland) connected with a data logger measured the temperature and relative humidity of the microclimate between skin and underwear at the chest in the range of the pectoralis major (T_{chest} in °C, RH_{chest} in %). Data of T_{chest} and RH_{chest} were used for calculating absolute humidity underneath the first garment layer. Thermography records were made (VarioCam high resolution, Infratec, Germany) for determining the surface temperature of the overall and shirt in the back area. Thermal comfort sensation was estimated using a 7-point Likert scale from 3 to −3 respectively from very comfortable to very uncomfortable (Fukazawa and Havenith, 2009).

2.4.3. Weight parameters

Weight measurements (DS150K1, Kern, Germany) were conducted; at the start of warm-up, walking protocol, cool down, and at the end of the whole test allowing for determination of sweat evaporation during load (e in g), whole body weight loss (sweat production, SP in g), and sweat residue (SR in g). Sweat evaporation during load was calculated by the difference between the fully equipped body weight measurement at the start and end of the walking protocol. Sweat production was estimated from the difference of the weight measurements which were made in underwear at the start and the end of the whole test. Weight loss due to humidifying inspired air was neglected in this calculation. Sweat