Physiological cost and thermal envelope: A novel approach to cycle garment evaluation during a representative protocol

J. Corbett¹, M. J. Barwood², M. J. Tipton¹

¹Department of Sport and Exercise Sciences, University of Portsmouth, Portsmouth, UK, ²Department of Sport and Exercise Sciences, Northumbria University, Newcastle upon Tyne, UK

Corresponding author: Jo Corbett, PhD, Department of Sport and Exercise Sciences, University of Portsmouth, Spinnaker Building, Cambridge Road, Portsmouth PO1 2ER, UK. Tel: +44 0 2392 843084, Fax: +44 0 2392 843620, E-mail: jo.corbett@port.ac.uk

Accepted for publication 9 December 2013

This study aimed to examine thermoregulation in different clothing assemblies during a representative cycling exercise protocol. Six men undertook cycling exercise simulating representative thermal exchange challenges while wearing low (LOW), intermediate (INT1 and INT2), or high (HI) amounts of clothing. Exercise was conducted at 14.5 °C, 46.8% relative humidity and included a “flat” [45 min at 35% peak power output (PPO), wind speed 8.3 m/s], “uphill” (30 min at 55% PPO, wind speed 3.6 m/s), and “downhill” (20 min at 50 W, wind speed 16.7 m/s) stage. Rectal temperature changed with the exercise stage and was independent of clothing assembly. In contrast, an “envelope” was evident for mean body temperature, resulting from differences in mean skin temperature between the LOW and HI conditions. The elevated mean body temperature in HI was associated with increased physiological “cost,” in the form of increased sweat production and heart rate. Physiological cost provides a better index of clothing performance than deep body temperature in the “thermoregulatory zone,” as a consequence sports clothing should attempt to optimize the balance between comfort and reduced physiological cost.

During cycling exercise metabolic heat production varies mainly as a function of power output, which is typically stochastic due to terrain and tactical influences (Jeukendrup, 2002; Vogt et al., 2007). Simultaneously, the avenues for biophysical heat exchange may be affected: alterations in cycling speed will influence convective cooling, as well as evaporative cooling, through effects on the boundary layer around the body. Consequently, multiple thermal exchange scenarios can arise in a single cycling event. For example, during downhill cycling, metabolic heat production may be low (Vogt et al., 2007), whereas convective and evaporative heat losses can increase due to elevated airflow (Saunders et al., 2005). In uphill cycling, metabolic heat production is typically increased (Vogt et al., 2007), whereas lower airflow will decrease heat loss by convection and evaporation (Saunders et al., 2005). This variety of thermal exchange scenarios can make the selection of appropriate clothing for a given cycling event problematic, particularly when opportunities for adding or removing clothing are limited, such as during competition.

Clothing affects biophysical heat exchange by increasing insulation and acting as a barrier to convective and evaporative heat exchange (Berglund & Gonzalez, 1977; Nagata, 1978; Gavin, 2003). However, excessive clothing will lead to increased sweating in an attempt to regulate body temperature. If the clothing acts as a barrier to evaporation this may cause skin wettedness, discomfort (Pascoe et al., 1994), and increased thermal stress (Brownlie et al., 1987); the cooling efficiency of sweating is also reduced when moisture is wicked away from the skin before it evaporates (Havenith et al., 2013). Thus, the ideal clothing for preventing heat loss is that which blocks air movement, but allows the evaporation of water vapor from the skin if sweating occurs (Gavin, 2003). In contrast, clothing for facilitating heat loss should have minimal insulation and pose little resistance to the evaporation of sweat from the skin or convective airflow (Gavin, 2003), while clothing that reflects solar radiation will reduce heat gain from the environment (Nielsen, 1990).

Although manikins can measure heat flux, it is often difficult to accurately replicate the friction, drag, and cling between layers and against skin that is encountered during exercise, as well as the subsequent impact on the microclimate between the skin and clothes (Pascoe et al., 1994). Manikins also lack the important associated thermoregulatory and perceptual responses. It has also previously been noted that research examining the influence of clothing on thermoregulation has generally failed to investigate high exercise intensities (Gavin, 2003), to mimic the airflow of outdoor conditions (Gavin, 2003), or to employ prolonged and ecologically valid sport-related exercise protocols (Davis & Bishop, 2013).
Evaluating cycle clothing during exercise

Experimental design
Following a preliminary incremental exercise trial for the determination of PPO and VO_{2max}, participants undertook four experimental trials wearing a different clothing assembly on each occasion. The order in which participants undertook the experimental trials was determined using a Latin square. Each participant undertook their exercise trials at the same time of day (± 1 h), with at least 48 h between tests.

Experimental procedure
The preliminary incremental exercise test took place under ambient laboratory conditions, with a fan available to provide cooling if requested by the participant. The participant commenced exercise at a power output of 60 W, which was increased by 30 W/min until the participant could no longer maintain the required power output. The final power achieved at the end of the exercise test was termed the PPO, with the highest VO2 obtained from a Douglas bag collection > 15 s termed the VO_{2max}.

The experimental trials took place in an environmental chamber at an ambient temperature of 14.5 (0.2) °C and relative humidity of 46.8 (2.9)%. During each trial participants undertook an exercise protocol lasting ~2 h, which was designed to simulate a range of representative thermal exchange scenarios. The protocol consisted of (a) 45-min moderate-intensity exercise (35% PPO) with a moderate air speed (8.3 m/s), simulating a “flat” cycling thermal exchange scenario; (b) 30-min high-intensity exercise (55% PPO) with a low air speed (3.6 m/s), simulating an “uphill” cycling thermal exchange scenario; (c) 5-min rest period with no wind, simulating a brief rest period; (d) 20-min low-intensity exercise (50 W) with a high air speed (16.7 m/s), simulating a “downhill” cycling thermal exchange scenario; (e) 5-min rest period with no wind; (f) 10-km self-paced time trial with a moderate air speed (8.3 m/s), to obtain an index of performance.

All exercise trials took place on the participant’s own bicycle, mounted on a Computrainer (Racer Mate, Seattle, Washington, USA) ergometer calibrated in accordance with previously described methods (Davison et al., 2009). During the 10-km time trial, participants completed a virtual racecourse constructed using the Computrainer 3D software (Racer Mate). The distance completed was displayed throughout the time trials, but all other feedback was blinded to the participant. Wind was simulated by use of a 0.5 m industrial fan (Fläkt Woods, Colchester, Essex, UK) positioned at a height of 1.15 m (to center point of fan) and 0.50 m from the center point of the front wheel of the participant’s bicycle. Air speed was measured at a height of 1.40 m and distance of 0.60 m from the fan using an anemometer (Meterman TMA10; Wavetek, San Diego, California, USA).

On each occasion during the experimental tests, participants wore one of the following clothing assemblies: (a) low clothing (LOW) consisting of cycling shorts (74% nylon, 26% elastane); (b) intermediate clothing 1 (INT1) consisting of bib-style cycling shorts (78% nylon, 22% elastane; mesh 82% polyester, 18% elastane) and a short-sleeve cycling jersey (100% polyester; mesh 94% nylon, 6% elastane); (c) intermediate clothing 2 (INT2) consisting of a different set of bib-style cycling shorts (75% polyamide, 22% elastane, 3% carbon fiber) and different short-sleeve cycling jersey (54% polyamide, 36% polyester, 7% elastane, 3% lyocell); (d) high clothing (HI) consisting of INT1 plus a long-sleeve base layer (84% polyester, 16% elastane), cycling trousers (100% nylon, polytetrafluoroethylene membrane; insert 94% nylon, 6% elastane), cycling jacket (100% nylon, polytetrafluoroethylene membrane; insert 94% nylon, 6% elastane), skull cap (100%...
Corbett et al.

polyester polytetrafluoroethylene membrane; insert 87% nylon, 13% elastane). In all of the conditions, the participants also wore the same fingerless gloves, socks, cycling helmet, and cycling shoes. Clothing was fitted in accordance with manufacturers’ guidelines, and the LOW and HI conditions were selected to represent the upper and lower boundaries of clothing assembly that might be worn under the exercise conditions examined. This was performed deliberately to create a reference “envelope” within which to gauge the performance of the other garments.

Measurements

**Preliminary incremental exercise trial**

During the preliminary test, power output was controlled using the Computrainer control panel, and consecutive 60-s expired gas collections were obtained using the Douglas bag method. Expired gases were analyzed to determine gas fractions and volumes using a gas analyzer (Servomex PLC, Crowborough, East Sussex, UK) calibrated using gases of known concentration and dry gas meter (Harvard Apparatus Ltd., Edenbridge, Kent, UK), respectively.

**Experimental trials**

Deep body temperature was measured using a thermistor (Grant Instruments, Cambridge, UK) self-inserted in the rectum, 15 cm beyond the anal sphincter (Squirrel Data Logger; Grant Instruments). Skin temperature (Tsk) was measured using thermistors (DS18B20-T-3, MSR Electronics GmbH, Henggart, Switzerland) attached to the skin by a single piece of Tegaderm™ (3M, St. Paul, MN, USA) tape at six sites on the right side of the participant at chest, back, bicep, forearm, thigh, and calf. Deep body temperature and skin temperatures were recorded every 60 s throughout experimental trials using an MSR data logger (MSR12; MSR Electronics GmbH). Ambient conditions were measured using a Wet Bulb Globe Temperature weather station (Grant Instruments). Mean body temperature was determined according to Colin et al. (1971) and mean skin temperature using Ramanathan (1964). Throughout the experimental trial participants wore a heart rate monitor (Polar RS800; Polar Electro Oy, Kempele, Finland), which recorded heart rate every 15 s. Fluid intake and pre and post nacket (following towel drying) and clothed body weights (OHAUS Corporation, Parsippany, NJ, USA) were used to estimate total sweat production. Local sweat rate was determined using a ventilated capsule positioned on the forehead under the cycling helmet (Q-Sweat quantiative sweat measurement system, model 1.0; WR Medical Electronics, Co., Maplewood, Minnesota, USA). To provide an index of peripheral blood flow, a laser Doppler probe (Moor Instruments, Axminster, UK) was lightly taped to the right index finger, with data corrected against a biological zero taken at the start of each trial by inflating a blood pressure cuff to 250 mmHg to momentarily occlude the brachial artery. Five minutes before the end of each exercise stage of the experimental trial, a 60-s expired gas collection was obtained and analyzed to determine the rate of oxygen uptake (VO2). Rating of perceived exertion (RPE; Borg, 1982) and perceptual measures of thermal comfort and thermal sensation (Zhang, 2003) were obtained at 5-min intervals throughout the trials.

**Data analyses**

Data are presented as mean (SD) unless otherwise stated. Where data are available at 60-s intervals (i.e., deep body temperature, mean body temperature, mean skin temperature, heart rate) they were averaged for each participant over the final 5 min of each of the exercise stages of the experimental protocol, i.e., final 5 min of the 45-min flat stage, final 5 min of the 30-min uphill stage, final 5 min of the 20-min downhill stage for comparisons. Where data are reported at 5-min intervals (i.e., RPE, thermal comfort, thermal sensation), the final data point recorded for each exercise stage was used for analysis. Between-group differences were determined by Friedman’s test, with significant differences examined post hoc using the Wilcoxon signed-rank test. The alpha value was set a priori at 0.05.

**Results**

**Thermal measures**

There were no significant differences between clothing conditions in rectal temperature at any of the comparison points throughout the exercise trials (Fig. 1(a)). In general, rectal temperature rose toward a plateau throughout the first 45 min of exercise, with a further increase occurring during the subsequent 30-min uphill exercise stage. During the 20-min simulated downhill cycling stage, a reduction in rectal temperature was observed. In contrast, significant differences in mean skin temperature were evident between all of the clothing assemblies at comparison point 1 and comparison point 3. At the second comparison point, mean skin temperature was not different between INT1 vs INT2 and LOW vs INT2, but was different between all other conditions (Fig. 1(b)). Significant differences in mean body temperature were evident at comparison point 1 and comparison point 3 between all conditions except INT1 vs INT2. At comparison point 2, differences in mean body temperature were evident between all conditions except INT1 vs INT2 and LOW vs INT2 (Fig. 1(c)). Across the experimental protocol a clear thermal envelope was evident for mean skin temperature and mean body temperature, the upper and lower boundaries of which were defined by the HI and LOW clothing conditions, respectively.

Site-specific chest and back temperature data are presented together in Fig. 1(d), with significant differences between conditions denoted accordingly. Chest temperature was different between all conditions at each comparison point, with the exception of H1 vs INT2 at the third comparison point. INT1 chest temperature was lower than INT2 at each comparison point, although both were positioned within the boundaries of the thermal envelope defined by HI and LOW. Back temperatures were similar between INT1 and INT2 across the exercise protocol, and a clear thermal envelope was defined by the HI and LOW conditions. However, back temperature in INT1 and INT2 approached the upper end of the thermal envelope at the second comparison point.

**Physiological measures**

A significant effect of clothing condition on heart rate was evident at the second comparison point, with heart rate being higher in the HI condition than in either the LOW condition or INT2 (Fig. 2). Between-condition differences in heart rate at the other comparisons points were not statistically significant. Significant differences
in forehead sweat rate were evident between LOW vs HI and HI vs INT1 at comparison point 1 (Fig. 3). Sweat rate was increased at the second comparison point, but was not different between conditions, suggesting that the peak local sweating rate had been achieved in all conditions. At the third comparison point, differences in sweat rate were evident between each condition with the exception of INT1 vs INT2 and LOW vs INT1. Total sweat production was 0.35 (0.06), 0.43 (0.05), 0.42 (0.06), and 0.71 (0.06) L/h for LOW, INT1, INT2, and HI, respectively, and was different between all clothing conditions with the exception of INT1 and INT2. In contrast, no significant differences were evident in the rate of oxygen uptake, or fingertip blood flow, at any of the comparison points. Mean power output sustained during the 10-km performance trial was 272 (15), 265 (18), 266 (20), and 259 (27) W for LOW, INT1, INT2, and HI, respectively, and was not significantly different between clothing conditions.

Fig. 1. (a) Mean rectal temperature during the representative cycle test. (b) Average mean skin temperature during the representative cycle test. (c) Average mean body temperature during the representative cycle test. (d) Mean chest and back skin temperature during the representative cycle test. Letters denote significant difference: \( a = \) LOW vs HI, \( b = \) LOW vs INT1, \( c = \) LOW vs INT2, \( d = \) HI vs INT1, \( e = \) HI vs INT2, \( f = \) INT1 vs INT2. Bold letters refer to back skin temperature only. Gray shaded areas denote comparison points. Standard deviations are omitted for clarity.

Fig. 2. Mean heart rate during the representative cycle test. \( a = \) difference LOW vs HI, \( e = \) difference HI vs INT2. Gray shaded areas denote comparison points. Standard deviations are omitted for clarity.

Fig. 3. Forehead sweat rates during the representative cycle test. \( a = \) difference LOW vs HI, \( c = \) difference LOW vs INT2, \( d = \) difference HI vs INT1, \( e = \) difference HI vs INT2. Gray shaded areas denote comparison points. Standard deviations are omitted for clarity.
Corbett et al.

Perceptual measures

The RPE was not different between the clothing conditions during the first two comparison points, but was significantly higher in INT2 than LOW at the third comparison point. Thermal sensation data indicated that participants felt significantly warmer in HI than in LOW, INT1, or INT2 at the first comparison point. At the second comparison point, participants felt significantly hotter in HI than in LOW or INT2, and also in INT1 and INT2 than in LOW. At the third comparison point, participants felt significantly warmer in HI than in LOW, INT1, or INT2. Finally, there were no significant between-condition differences in thermal comfort at the first or third comparison point, although participants felt significantly less comfortable in HI than in LOW, INT1 or INT2 at the second comparison point.

Discussion

The ultimate validation of any clothing assembly relies on testing with humans under the actual conditions of intended use (Pascoe et al., 1994). The present study is the first to employ a prolonged and ecologically valid sports-related exercise protocol to evaluate the performance of different cycle garment assemblies during exercise in a range of representative thermal exchange scenarios, which mimic the airflow of outdoor conditions. In all clothing assembly conditions, the rectal temperature response was independent of the clothing worn. Rectal temperature increased throughout the flat cycling exercise stage, with a further increase during the uphill exercise stage, prior to a reduction during the downhill exercise stage. This finding is consistent with other studies that have shown that the temperature at which deep body temperature is regulated during exercise is primarily related to the relative exercise intensity (Nielsen, 1938; Lind, 1963; Saltin & Hermansen, 1966; Gant et al., 2004). In contrast, mean skin temperature, and consequently mean body temperature, was influenced by the clothing assembly. In each instance the mean skin and mean body temperature was highest in the HI condition and lowest in LOW, with INT1 and INT2 positioned toward the lower end of the thermal envelope. Because work output was identical between each of the exercise conditions (except during the TT), these differences must result solely from alterations in heat loss capacity as a consequence of the different clothing assemblies. The boundaries of the thermal envelope defined by the LOW and HI condition should be a useful reference for clothing manufacturers by providing an indication of the realistic limits for heat loss and heat retention that are possible for each exercise stage via alterations in garment assembly selection, or design.

The site-specific temperature data from the chest and back are useful in illustrating the non-uniform nature of the torso skin temperature during cycling exercise in an environment where a representative air velocity is provided. Although not examined statistically, an elevated back temperature relative to chest temperature was particularly evident at the higher air velocities in INT1, INT2, and LOW conditions (comparison points 1 and 3). In addition, it is interesting to note that the back temperature in INT1 and INT2 conditions approached the upper limit of the thermal envelope for back temperature (e.g., HI condition) at the second comparison point. We believe that these site-specific data are useful for two reasons: first, they demonstrate the importance of using a representative air velocity when examining the performance of sporting garments; failure to do so will lead to an inaccurate representation of the skin : clothing microclimate during exercise, and will diminish heat loss to the environment (Saunders et al., 2005). Second, the observation that back temperature in the INT1 and INT2 conditions approached the upper (HI) limit of the thermal envelope at the second comparison point implies that increased back ventilation may be a beneficial design feature for these assemblies in this thermal exchange scenario.

Sweat production was influenced by the clothing assembly worn, and differences in local sweat rates were evident at the first and third comparison points. However, local sweat rates were not different between conditions at the second comparison point, possibly indicating that the peak local sweating rate had been reached. Nevertheless, heart rate was elevated in HI relative to INT2 and LOW at the second comparison point. Presumably, these augmented effector responses with increased amounts of clothing occurred as a consequence of the elevated mean skin temperature and mean body temperature, in order to facilitate heat loss, and as such, demonstrate the increased physiological cost associated with regulating deep body temperature while wearing different garment assemblies. It is well established that sweat losses of ~2% body weight can result in significant impairments in performance (Cheuvront et al., 2003), whereas an elevated heart rate during submaximal exercise at a fixed intensity is indicative of increased physiological strain. However, there was no significant difference in 10-km time trial (TT) performance between the clothing conditions in the present investigation, although, numerically, the trends for performance times were consistent with the differences in mean body and mean skin temperature. This indicates that the increased physiological cost was tolerated by the trained cyclists participating in this study, although the participant numbers used in the present study will have impact upon the ability to detect a statistically significant difference; it remains to be confirmed whether a statistically significant effect would have been evident with a larger number of participants, or if the increased physiological cost would have been tolerated by less well-trained participants, or during exercise in a warmer exercise environment. Nevertheless, it would appear logical to suggest that garments intended for use in sports
performance should be designed to achieve the best thermal response at minimum physiological cost. In most prolonged exercise activities, during which participants must remain in the thermoregulatory zone (i.e., able to thermoregulate), it will be the physiological cost of thermoregulating, rather than body temperature per se that will be the most illuminating measure of clothing performance.

Differences in thermal sensation between clothing conditions were evident at each of the comparison points, indicating that the clothing assemblies were sufficiently different to induce significant perceptual differences. In contrast, there was no difference in thermal comfort between conditions at the first and third comparison points, although thermal comfort was significantly lower in the HI condition than in the other conditions at the end of the uphill exercise stage. The observation that participants generally remained comfortable and that there were no between-condition differences in thermal comfort during the first and third stage suggests that the range of clothing assemblies selected were realistic under these conditions. Taken together these findings emphasize the complex nature of thermal comfort perception, which may remain relatively constant (comparison points 1 and 3) in the presence of a variety of whole-body thermal sensations. Interestingly, the RPE did not differ between groups at the point at which a significant difference in thermal comfort was detected. This would imply that thermal comfort is not an important factor determining perception of exertion, or that there is a lag in the relationship between thermal comfort and RPE. It should be noted that RPE was higher in INT2 than LOW at the third comparison point, although we question the practical significance of this finding. Further research is required to understand the nature of the factors influencing thermal and effort perception under the non-uniform and dynamic exercise conditions employed in the present study, and frequently encountered outside of the laboratory environment.

In summary, the representative cycle exercise protocol employed in this study enabled cycle garment performance to be evaluated across a range of different thermal scenarios, in a single exercise test. Rectal temperature remained in the thermoregulatory zone and changed concomitant with the intensity of exercise and was independent of the clothing assembly. In contrast, a clear thermal envelope was evident for mean body temperature, which resulted from differences in mean skin temperature as a consequence of the various garment assemblies used. Thus, future studies examining clothing performance during exercise within the thermoregulatory zone should not use deep body temperature as the sole index of thermal performance. The elevated mean body tempera-

Evaluating cycle clothing during exercise

Perspective

There have been calls for studies examining the influence of clothing on thermoregulation to employ prolonged, ecologically relevant, sports-related exercise protocols including high exercise intensities and mimicking the airflow of outdoor conditions (Gavin, 2003; Davis & Bishop, 2013). This study used a novel protocol to examine thermoregulatory and physiological responses during prolonged cycling exercise in representative thermal exchange challenges, with different cycle clothing assemblies; the concepts of physiological cost and thermal envelope have been introduced. During most prolonged exercise activities athletes remain in the thermoregulatory zone; we proposed the magnitude of thermoeffector responses necessary to maintain the regulated deep body temperature (i.e., physiological cost), rather than body temperature per se as an index of clothing performance. Differences in physiological cost were evident between clothing assemblies in the absence of change in deep body temperature. Thermal envelope refers to boundary thermal profiles elicited by clothing assemblies toward the upper and lower end of those that might be worn under given environmental conditions. This envelope in mean body temperature was demonstrated in this study and might represent a useful approach for providing an indication of the realistic limits for heat loss and heat retention possible via alterations in garment assembly selection or design.

Key words: Environmental physiology, clothing, temperature.

Acknowledgements

The authors would like to acknowledge the technical assistance provided by Geoff Long, Alex Ouzounoglou, and Nicola Ferguson.
References

Berglund LG, Gonzalez RR. Evaporation of sweat from sedentary man in humid environments. J Appl Physiol 1977: 42 (5): 767–772.

Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 1982: 14 (5): 377–381.

Brownie L, Mekjavic I, Bannister E. Thermoregulation in athletic racing apparel. Ann Physiol Anthropol 1987: 6 (3): 145–155.

Cheuvront SN, Carter R, Sawka MN. Fluid balance and endurance exercise performance. Curr Sports Med Rep 2003: 2 (4): 202–208.

Colin J, Timbal J, Houdas Y, Boutelier C, Guieu JD. Computation of mean body temperature from rectal and skin temperatures. J Appl Physiol 1971: 31 (3): 484–489.

Davis JK, Bishop PA. Impact of clothing on exercise in the heat. Sports Med 2013: 43: 695–706.

Davison RCR, Corbett J, Ansley L. Influence of temperature and protocol on the calibration of the Computrainer electromagnetically-braked cycling ergometer. Int Sports Med J 2009: 10: 66–76.

Gant N, Williams C, King J, Hodge BJ. Thermoregulatory responses to exercise: relative versus absolute intensity. J Sports Sci 2004: 22 (11–12): 1083–1090.

Gavin TP. Clothing and thermoregulation during exercise. Sports Med 2003: 33 (13): 941–947.

Gonzalez RR, McLellan TM, Withey WR, Chang SK, Pandolf KB. Heat strain models applicable for protective clothing systems: comparison of core temperature response. J Appl Physiol 1997: 83 (3): 1017–1032.

González-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. J Appl Physiol 1999: 86 (3): 1032–1039.

Haldane JC. The influence of high air temperatures. J Hyg (Lond) 1905: 5 (4): 494–513.

Havenith G, Bröde P, den Hartog E, Kuklane K, Holmér I, Rossi RM, Richards M, Farnworth B, Wang X. Evaporative cooling: effective latent heat of evaporation in relation to evaporation distance from skin. J Appl Physiol 2013: 114 (6): 778–785.

Jeukendrup AE. Power output. In: Jeukendrup AE, ed. High performance cycling. Champaign, IL: Human Kinetics, 2002: 69–77.

Lind AR. A physiological criterion for setting thermal limits for everyday work. J Appl Physiol 1963: 18 (1): 51–56.

Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. Am J Physiol 1998: 275 (1 Pt 2): R129–R134.

Nagata H. Evaporative heat loss and clothing. J Hum Ergol (Tokyo) 1978: 7 (2): 169–175.

Nielsen B. Solar heat load: heat balance during exercise in clothed subjects. Eur J Appl Physiol Occup Physiol 1990: 60 (8): 452–456.

Pascoe DD, Shanley LA, Smith EW. Clothing and exercise I: biophysics of heat transfer between then individual clothing and the environment. Sports Med 1994: 18 (1): 38–54.

Ramanathan NL. A new weighting system for mean surface temperature of the human body. J Appl Physiol 1964: 19 (3): 531–533.

Saltin B, Hermansen L. Esophageal, rectal, and muscle temperature during exercise. J Appl Physiol 1966: 21 (6): 1757–1762.

Saunders AG, Dugas JP, Tucker R, Lambert MI, Noakes TD. The effects of different air velocities on heat storage and body temperature in humans cycling in a hot humid environment. Acta Physiol Scand 2005: 183 (3): 241–255.

Schlader ZJ, Simmons SE, Stannard SR, Mündel T. Exercise modality modulates body temperature regulation during exercise in uncompensable heat stress. Eur J Appl Physiol 2011: 111 (5): 757–766.

Tipton MJ. Thermal stress and survival. In: Rainford DJ, Gradwell DP, eds. Ernsting’s aviation medicine. 4th edn. London: Hodder Arnold, 2006: 213–229.

Vogt S, Schumacher YO, Blum A, Roecker K, Dickhuth HH, Schmid A, Heinrich L. Cycling power output produced during flat and mountain stages in the Giro d’Italia: a case study. J Sports Sci 2007: 25 (12): 1299–1305.

Zhang H. Human thermal sensation and comfort in transient and non-uniform thermal environments. PhD thesis, University of California, Berkley, CA. 2003.