Original Article

Sweat responses during inactive recovery after high-intensity running in hot, dry and humid conditions

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ABSTRACT

This study investigated the relationship between high (85%) and low (19%) relative humidity (RH) and sweat rate during inactive recovery after high-intensity work in a hot environment (30 °C). Ten male subjects performed two 20-minute run trials at 68 ± 4 % of maximal oxygen consumption (VO_{2max}) followed by 36 minutes of inactive recovery in standing position. Regional sweat rate (RSR) was measured on the forearm and mid-central back by technical absorbent pads, and gross sweat loss was estimated from change in body weight. Core temperature (T_c) and six skin temperatures for calculation of mean skin temperature (T_s) were measured continuously together with heart rate (HR) during running and recovery. Results show that RSR was significantly ($p<0.05$) higher for both arm and back during running and inactive recovery in 85% RH compared to 19% RH. The highest sweat rate was observed on the back during the last five minutes of running in 85% RH (1387 g·m^{-2}·h^{-1}) compared to 19% RH (886 g·m^{-2}·h^{-1}). Gross sweat loss (GSL) was significantly higher in 85% RH (796 ± 414 g·h^{-1}) than 19% RH (489 ± 140 g·h^{-1}) conditions ($p=0.010$). T_c continued to increase for three and seven minutes post-exercise in 19% RH and 85% RH, respectively and T_s was significantly higher in 85% RH than in 19% RH ($p<0.05$). HR was 11 bpm higher after running in 85% RH compared to 19% RH ($p=0.001$). In conclusion, RSR and GSL, as well as HR, T_c and T_s was higher during post-exercise recovery in 30°C and 85% RH than in 30°C and 19% RH. This study emphasises the importance of including the effect of relative humidity in assessment of both exercise and recovery.
Keywords: Heat; Relative humidity; Exercise; Recovery; Technical absorbents.

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INTRODUCTION

Sweating is the main physiological mechanism for heat loss during work at high ambient temperatures (T_a) (Shibasaki et al., 2006; Wyndham et al., 1965) and sweat production and regulation of sweating have been the objects of many studies (Cotter et al., 1995; Havenith et al., 2008a; Machado-Moreira et al., 2008; Nadel et al., 1971; Nadel and Stolwijk, 1973; Smith and Havenith, 2010). Aerobic fitness, acclimation status, environmental conditions, clothing and evaporative efficiency are all important modifiers of sweat production (Candas et al., 1979; Havenith et al., 2008b; Shapiro et al., 1982). Sweat evaporation in a hot environment is highly dependent on the relative humidity (RH), as it relies on the water-vapour pressure gradient between the skin surface and immediate environment. Several studies have been conducted on total sweat loss, or gross sweat loss (GSL), of the whole body under a wide range of conditions and activities. In recent years, differences in regional sweat rates (RSR) have attracted attention as a result of research on clothing design, thermophysiological modelling and thermal manikins (Havenith, 2001; Havenith et al., 2008b; Smith and Havenith, 2010). It is now well established that RSR varies greatly with body location. RSR is the highest on the back along the lumbar spine and is greatly reduced in the extremities (Cotter et al., 1995; Havenith et al., 2008a; Machado-Moreira et al., 2008; Smith et al., 2007). A study by Smith and Havenith (2010) mapped the RSR of the entire body of male athletes during mild exercise and registered the highest sweat rates on the central back and the lowest on the hands and feet.

The sweating response during exercise in humans is determined by changes in thermal and non-thermal factors (Kenny and Journeay, 2010; Shibasaki et al., 2006). Type of exercise training influences sweating response (Amano et al., 2011) and fitness level can significantly affect thermoregulatory functions (Henane et al., 1977). Exercise or work in hot and humid environments is especially challenging for the thermoregulatory capacity of the body (Wendt et al., 2012; Werner, 1988). Maughan et al. (2012) showed a significant decrease in endurance exercise capacity with increasing RH (24%, 40%, 60%, 80%). They also showed a greater whole-body sweat rate as relative humidity increased (Maughan et al., 2012).

The reduced performance in hot humid environments can be linked to less efficient sweat evaporation as the gradient between ambient water vapour pressure and skin hydration decreases (Candas et al., 1979; Wendt et al., 2012). Exercise under hot and humid conditions may therefore exceed the capacity of the evaporative heat loss mechanism, due to the limited capacity of the environment to hold water vapour (Wendt et al., 2012). The decrease in heat loss capacity is further reduced during prolonged sweating, profound sweating or high-humidity conditions due to the effect of hidromeiosis (Candas et al., 1983, 1980). The thermoregulatory responses of passive (assisted loadless pedalling), inactive (no activity) and active (loadless pedalling) on post-exercise recovery in addition to nonthermal effects have been investigated in earlier studies (Carter III et al., 2002; Jay et al., 2008; Journeay et al., 2006, 2004; Wilson, 2004). These studies were performed under thermoneutral conditions from 24 to 25 °C and only two studies have reported RH values (Journeay et al., 2004; 2005).

Several studies have investigated the effect of hot and humid conditions on exercise performance. Fewer studies have looked at post-exercise recovery in hot and humid conditions. However, to the authors' knowledge, the effects of high (above 80%) and low RH on post-exercise recovery have not been evaluated. This knowledge may be of importance to ensure optimal evaporation in the development of high-performance clothing and to reduce heat stress for improved athletic performances in high temperature and humidity environments.

The aim of this study was to investigate the relationship between high (85%) and low (19%) RH and sweat rate during inactive recovery after high-intensity exercise in a hot (30 °C) environment. We hypothesised that RSR, GSL, heart rate (HR), mean skin temperature (T_s) and core temperature (T_c), are higher during post-exercise inactive recovery in 85% RH than in 19% RH at 30 °C.

MATERIALS AND METHODS

Participants
Ten healthy young males volunteered to participate in the study. The characteristics (mean and (SD)) of the participants were: age, 23 years (±2); height, 181 cm (±5); weight, 74.4 kg (±11.1); body fat, 11.7% (±3.4) and maximum oxygen consumption (VO_{2max}), 60.3 ml·min^{-1}·kg^{-1} (±7.6) (range 49.4-71.4 ml·min^{-1}·kg^{-1}). All participants were informed about the aim of the study, the test protocol and their rights to terminate their participation at any time in accordance with the Declaration of Helsinki before they provided written consent. The study was approved by the Regional Committee for Medical and Health Research Ethics in Norway.

Procedures
The participants were subjected to one pre-test and two main tests between February and March. The tests were performed in a climatic chamber in the Work Physiology Laboratory of the Department of Health Research at SINTEF.

Pre-tests
All the subjects attended a pre-test session to define VO_{2max}, record their anthropometric data and familiarise themselves with the main test procedures. T_a during the pre-tests was 20.4 ± 0.7 °C and RH was 38 ± 5%. The pre-test measurements were used to determine individual running speeds and the area and placement of sweat pads for the forearm and lower-mid back, used in the main tests.

Main tests
Each subject performed two main tests, one in a high-humidity (85 ± 2% RH) environment and the other in a low-humidity (19 ± 2% RH) environment. T_a was 30°C in each trial. Temperature and RH were measured four times during the test by a hand-held thermostat (Testo 435, Testo, Lenzkirch, Germany); accuracy ± 0.3 °C, ± 2%. Average T_a during the study was calculated from measurements taken after 5 and 20 minutes of running, and 15 and 30 minutes of recovery. The subjects were exposed to the two environments in a counterbalanced order. Each test subject performed the tests at the same time of day, with a minimum of 48 hours between test sessions.

On arrival at the laboratory, the subjects were weighed, before inserting a rectal probe. After dressing in shorts and shoes, six thermistors, a heart-rate recorder and frames for sweat-sampling pads were attached to the forearm and lower back. The main test started with a 20-minute rest at 22.8 ± 0.9°C and 24 ± 3% RH. Sweat sampling pads were applied during the last five minutes of rest and the subjects were asked to evaluate their thermal comfort and sensation. After the initial rest, the subjects moved into the climatic chamber where they started to run on a treadmill (PPS 55 sport-1 climatel, Woodway, Weil am Rhein, Germany) at 68 ± 4% VO_{2max} and 6° incline for 20 minutes. The recovery period lasted for 36 minutes. VO_2 was measured during the first and last five minutes of running. After 15 minutes of running, test subjects stopped to allow sweat-sampling pads to be applied for the final five minutes of the run. Recovery in a standing position started as soon as the running session ended. Sweat sampling pads were changed every five minutes during recovery. The running period, including pad changes was 20 minutes and 17 seconds (±20 seconds). The total recovery period, including pad changes was 35 minutes and 37 seconds (±29

seconds). VO₂ was measured after 15 minutes of recovery. Thermal sensation and comfort were evaluated after five minutes of running, immediately after cessation of running, 10 minutes into the recovery period and immediately after the recovery. The subjects were allowed to drink water ($30.6 \pm 2.1°C$) at five, 15, 20 minutes into the running protocol and 10, 20 and 30 minutes into the recovery period. All water intake was recorded. Body weight was re-measured immediately after the end of the recovery period.

Measurements
Regional sweat rate
Sweat were sampled with a technical absorbent material (Air Laid 2240CW1+, Meditas, Grimsby, United Kingdom), which was fitted into pads for each individual test subject. Sweat sampling pad (hereafter, sweat pad) sizes were calculated following the method of Smith and Havenith (2010), and their areas were estimated using exact measures of pre-cut outlines following the method described by Morris et al. (2013). Eight sweat pads for both arm and back were weighed (Sartorius AG, Göttingen, Germany; accuracy ± 0.01 g), and stored in airtight zip-lock bags before each test. Posterior lower arm and central mid back were chosen as sweat pad locations on the basis of current literature, as they give a good representation of a minimum and maximum sweat rate location (Havenith et al., 2008a; Morris et al., 2013; Smith and Havenith, 2010). In order to ease the application and removal of sweat pads on the arm, these were scaled down by 50% compared to Smith and Havenith (2010). Frames and sweat pads on the back were kept in place by a compression bandage (Comprilan 8 cm x 5 m, 100% cotton, BSN Medical AB, Gothenburg, Sweden) which was wrapped around the abdomen. A-tube compression bandage was used on the right arm (Tubifast 7.5 cm x 1 m, Mölnlycke Health Care, Gothenburg, Sweden).

Sweat rate was measured at 5-minute intervals. The sweat pads took an average of 56 ± 5 seconds to change. They were applied during the last five minutes of the initial rest, running period and every 5 minutes during recovery. These are hereafter referred to as samples 1-8.

RSR ($g \cdot m^{-2} \cdot h^{-1}$) was calculated from Eq. 1, modified from Smith and Havenith (2010).

$$RSR = (60 \cdot \Delta M) \cdot (t \cdot A)^{-1} \qquad (1)$$

where ΔM is the difference in weight of the sweat pad before and after application (g), t is the application time (min), A is the measured area of the sweat pad (m^2).

Gross sweat loss
Subjects were weighed (ID1, Mettler Toledo, Albstadt, Germany; accuracy ± 0.006 kg), before and after each test. GSL was calculated (Eq. 2) from the weight loss of participants (ΔM) and corrected for ingested water (WI) during the test, respiratory water loss (RWL) and metabolic mass loss (MML) (Cheuvront et al., 2002).

$$GSL = \Delta M + WI - RWL - MML \qquad (2)$$

RWL was calculated from respiratory evaporation (E_{res}) by Eq. 3 and converted into RWL by Eq. 4 (Smith and Havenith, 2010).

$$E_{res} = 1.27 \cdot 10^{-3} \cdot MR \cdot \{59.34 + (0.53 \cdot T_a) - (11.69 \cdot P_a)\} \qquad (3)$$

$$RWL = E_{res} \cdot t \cdot 2430^{-1} \qquad (4)$$

where E_{res} is the evaporative heat loss (W), MR is the metabolic rate (W), T_a is the ambient temperature, P_a is the partial water vapour pressure (kPa), t is the duration of the experiment (sec), 2430 is the latent heat of 1g of water (J·g^{-1}). MR were calculated from the simple equation of metabolic rate (Eq. 5) by McIntyre (1980).

$$MR = V_E \cdot (0.2093 - O_e) \tag{5}$$

where V_E is the ventilation rate (L·s^{-1}) and O_e is the fraction of oxygen in the expired air.

MML were calculated using Eq. 6 from Mitchell et al (1972).

$$MML = VO_2 \cdot \{RER \cdot (\rho CO_2 \cdot \rho O_2)\} \tag{6}$$

where VO_2 is the oxygen consumption (L·min^{-1}), RER is the measured respiratory exchange ratio, ρCO_2 and ρO_2 are the densities of carbon dioxide (1.96 g·L^{-1}) and oxygen (1.43 g·L^{-1}).

Oxygen consumption
V_E, VO_2 and O_e were measured with an Oxycon Pro® apparatus (JCAB 5.x, Jaeger, Hoechberg, Germany); accuracy 0.05 L·min^{-1}. Data were registered every 20 seconds during the first and last five minutes of running, and after 15 minutes of recovery.

Heart rate
HR was continuously measured during the initial rest, running and inactive recovery periods by a Polar RS800 HR recorder (Polar Electro Oy, Kempele, Finland; accuracy ± 1 bpm).

Core and skin temperatures
Skin temperatures were measured by skin thermistors (YSI 400, YSI, Yellow Springs, Ohio, USA, ±0.15 °C) at six locations: posterior lower arm, upper arm, chest, back, anterior thigh and anterior calf. T_c was measured using a rectal probe placed 10 cm into the rectum (YSI 400, YSI; ±0.15 °C). Core and skin temperatures were continuously registered at 20-second intervals throughout the test. T_s was calculated according to Teichner (1958).

Body fat
Body fat percentage was measured with a Harpender Skinfold Caliper during the pre-test. Four measurement points were used: musculus biceps brachii, musculus triceps brachii, musculus subscapularis and musculus suprailiacto to estimate body fat percentage according to Durnin and Womersley (1974).

Subjective evaluations
The subjects were asked to evaluate their perceived thermal sensation (PTS) and body comfort during the initial rest, running and inactive recovery period. Questions were modified from Nielsen et al. (1989) and scaled from -5 to 5, where -5 is extremely cold, 0 is neutral and 5 is extremely hot. Subjects were also asked to rate their perception of sweating and skin wittedness. A 15-point Borg scale, on which 6 represents no exertion and 20 is maximal exertion, was used to evaluate rating of perceived exertion (RPE) (Borg, 1985).

Analysis
HR, T_c and T_s are presented as one-minute running averages, and the last two minutes of each sweat sample interval were used for statistical analyses. RSR are presented for each five-minute sample.

RSR values were $\log_{10}$ transformed to obtain a normalised data distribution as the raw RSR values were skewed. VO_2, V_E, O_e and RER were calculated from the last two minutes of each measurement. In testing the correlation between RSR and local skin temperature, the data were left untransformed. The last two minutes of lower arm and back skin temperatures, i.e. samples two to eight, were used in the correlation analyses.

In our calculations of GSL, the initial resting phase was assumed to have no impact on the total GSL and was not included in the analysis. GSL are calculated for the total testing time (running + inactive recovery). Due to differences in work intensity between running and recovery, metabolic rate (MR) was integrated into a single representative value based on the time weighted averages of each activity, in this case running and recovery (Parsons, 2014, p. 202). The running period accounted for $80 \pm 3\%$ of the total heat production and the recovery period $20 \pm 3\%$ of the total heat production, these values were derived from Parson (2014, p. 194).

The number of subjects differs between parameters, due to loss of data or erroneous measurements during the tests.

Statistical analysis

Normality was assessed by means of Shapiro-Wilk's test ($p > 0.05$) and Q-Q plots, and equality of variances by Levene's test ($p > 0.05$). Outliers and distributions of data were inspected by boxplot or studentized residuals (± 3 SD). If a test showed non-sphericity, a Greenhouse-Geisser adjustment was utilised. Linear and monotonic relationships were assessed by visual inspection of scatterplots.

Two-way repeated measures analysis of variance (ANOVA) was used to examine interactions of the parameters RSR, HR, T_c and T_s between and within 85% RH and 19% RH humidity environments. If statistically significant interactions were found, simple main effects were analysed by Student's t-test for paired samples between environments. Holm-Bonferroni (Holm, 1979) corrections for multiple comparisons were performed as *post hoc* tests.

The Pearson correlation coefficient (r) was calculated for the relationship between GSL and MR, and GSL and VO_{2max}. Due to the presence of outliers, Spearman's rank correlation coefficient (r_s) was calculated for the relationship between GSL and T_s, and RSR and local T_s for both arm and back. Correlations coefficient cut-offs were set to 0.3 to 0.5 for weak, 0.5 to 0.7 for moderate and above 0.7 for strong correlations (Mukaka, 2012).

Differences between the slopes of the regression lines between 85% RH and 19% RH for RSR, HR, T_c and T_s were analysed using Student's t-test for paired samples. The t-test for paired samples was also used to analyse differences in oxygen consumption.

Friedman's test was used to analyse differences in the ratings of PTS and RPE between rest, after 5 and 20 minutes of running, and after 10 and 30 minutes of inactive recovery. Differences in PTS and RPE between 19% RH and 85% RH were analysed with a Wilcoxon signed-rank test. Wilcoxon signed-rank test was used due to the non-parametric nature of the data and the violation of normality.

Data is presented as mean $\pm$ standard deviation (SD), unless otherwise stated. Statistical significance was accepted at $p < 0.05$.

RESULTS

Regional sweat rate

Individual RSR during initial rest ranged between 1 to 17 $g \cdot m^{-2} \cdot h^{-1}$ and did not significantly differ between environments. RSR decreased during recovery in both 85% RH and 19% RH on the back and arm, as shown in Fig. 1. RSR were significantly (p<0.05) higher at all time points on both back and arm during upright inactive recovery in 85% RH compared to 19% RH.
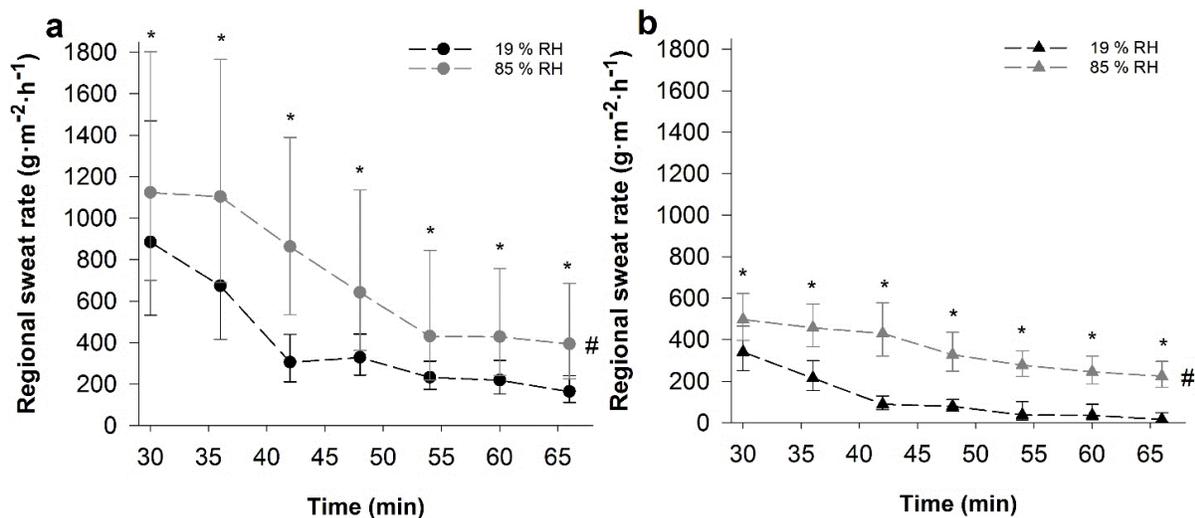

*# indicates a significant change in RSR in 85% RH compared to 19% RH over time, p=0.02. * indicates a significantly higher RSR in 85% RH compared to 19% RH, p<0.05.*

Figure 1. Regional sweat rate (RSR) during the last five minutes of running and the upright recovery period. The upright recovery period starts at 30 minutes into the protocol. (a) RSR on the mid-centre back (n=8) and (b) posterior forearm (n=9). Data are geometric means with asymmetric 95% CI.

RSR showed a weak correlation (r_s=0.351, p=0.014) with local skin temperature on the back during inactive recovery in 19% RH and a moderate correlation (r_s=0.56, p<0.0005) in 85% RH. There was a weak correlation (r_s=0.35, p=0.001) between RSR and local skin temperature on the arm during inactive recovery in 19% RH. RSR in 85% RH showed a moderate correlation (r_s=0.612, p<0.0005) with local skin temperature on the arm during inactive recovery. There were no significant correlations between RSR and local skin temperatures on the back and arm during running.

Gross sweat loss

GSL was significantly higher under 85% RH (796 ± 414 $g \cdot h^{-1}$) than 19% RH (489 ± 140 $g \cdot h^{-1}$) conditions (p=0.010). There was less variation in GSL between individuals (312 to 752 $g \cdot h^{-1}$) in 19% RH compared to 85% RH (308 to 1399 $g \cdot h^{-1}$). There was no significant correlation between GSL and VO_{2max} ($mL \cdot min^{-1} \cdot kg^{-1}$), weight (kg) or body fat (%). GSL correlated positively with individual work intensities, expressed as weighted absolute mean metabolic rate, in both 85% RH (*r*=0.78, p=0.002) and 19% RH (*r*=0.87, p=0.001) (Fig 2). No significant correlation between GSL and T_s was found for either 19% RH or 85% RH (r_s=-0.285, p=0.425 and r_s=0.261, p=0.533).
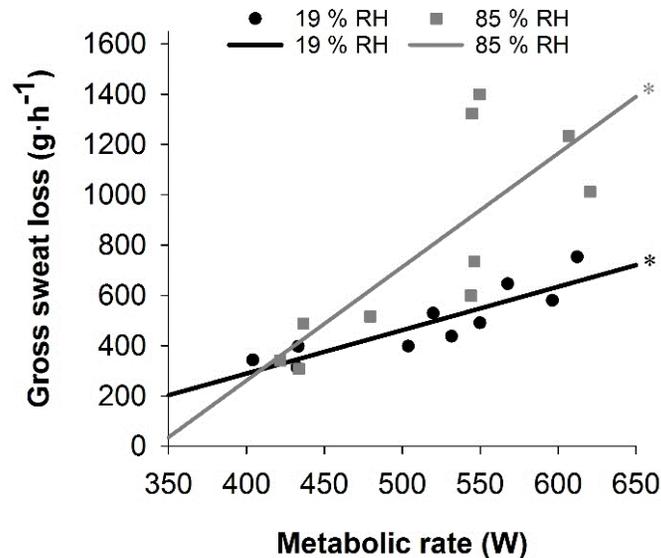
Positive correlations between GSL and metabolic rate observed in both high- (r=0.78, p=0.002) and low-humidity environments (r=0.87, p=0.001).

Figure 2. Gross sweat loss (g·h-1) and weighted absolute mean metabolic rate (W) of subjects in high- (85% RH) and low-humidity (19% RH) environments (n=10).

Oxygen consumption and heart rate
During the running period, the exercise intensity was $67 \pm 4\%$ VO_{2max} during the first five minutes and $70 \pm 4\%$ VO_{2max} during the final five minutes in 85% RH. The corresponding values were $67 \pm 3\%$ VO_{2max} and $69 \pm 4\%$ VO_{2max} in 19% RH. No significant differences in oxygen consumption between or within environments were found.
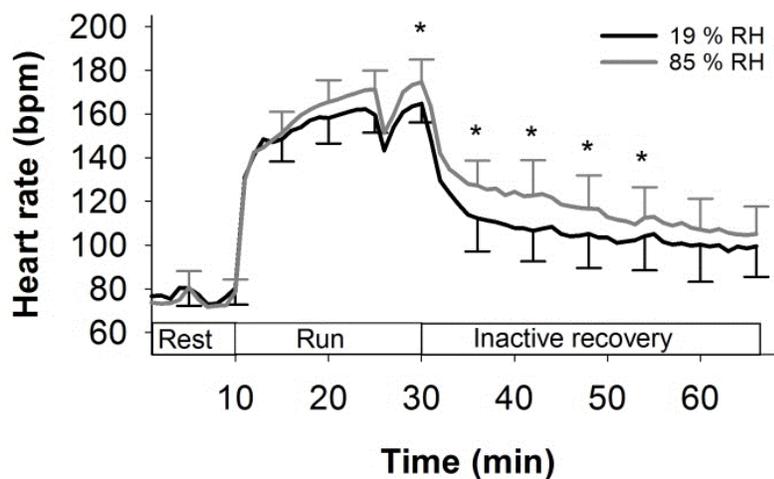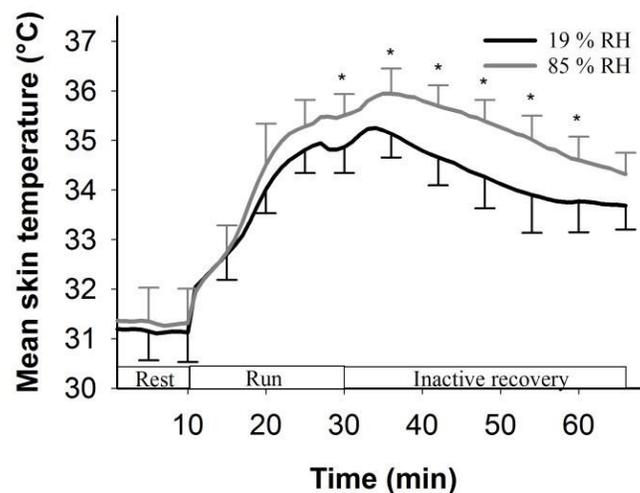

* indicates significant difference in HR between high- and low-humidity conditions (p<0.05). Values are mean ± SD, n=9.

Figure 3. Heart rate (HR) during initial rest, running and upright inactive recovery.

From an average resting value of 76 ± 6 bpm outside the climatic chamber, HR increased to a maximum of 175 ± 11 bpm and 164 ± 10 bpm while running in 85 % RH and 19 % RH respectively. The HR at the end of the 20-minute run under 85% RH environment was significantly higher than in the 19% RH environment (p=0.001). During inactive recovery, HR was also significantly higher under 85% RH compared to the I9% RH conditions (p=0.038) (Fig 3).

Skin temperature

From an average resting value of 31.2 ± 0.6 °C under both ambient conditions, T_s reached 35.4 ± 0.4 °C during exercise in 85% RH and 34.9 ± 0.6 °C in 19% RH. T_s were significantly higher in 85% RH than in 19% RH (p<0.05), except for the last measurement (p=0.135) (Fig. 4). The highest recorded T_s of 35.9 ± 0.5 °C in 85% RH and 35.3 ± 0.5 °C in 19% RH were reached at five and four minutes after exercise respectively. After reaching the highest value, T_s decreased at rates of 0.057 °C and 0.052 °C per minute during upright inactive recovery in 85% RH and 19% RH respectively, and did not differ significantly (p=0.184).

* indicates a significant difference in Ts between high and low humidity (p<0.05). Values are mean ± SD, n=10.

Figure 4. Mean skin temperature (Ts) during initial rest, running and upright inactive recovery.
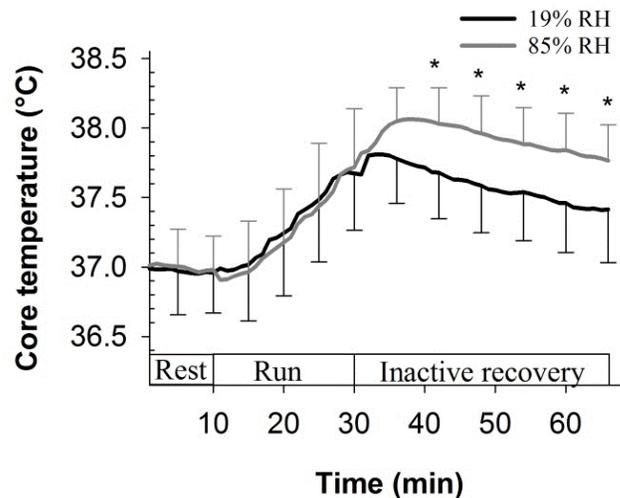
Core temperature

From an average resting value of 37.0 ± 0.3 °C under both ambient conditions, T_c reached 37.7 ± 0.4 °C during exercise in both 19% RH and 85% RH. T_c were significantly higher in 85% RH during the inactive recovery period, except for the last five minutes of running and the first five minutes of recovery (p=0.795 and p=0.085) (Fig. 5). The highest recorded T_c of 37.8 ± 0.3 °C in 19% RH and 38.1 ± 0.3 °C in 85% RH were reached at three and seven minutes after exercise respectively. After reaching its highest values, T_c fell at rates of 0.011 °C and 0.013 °C per minute in 85% RH and 19% RH conditions respectively and did not significantly differ (p=0.490).

Subjective evaluation

Perceived thermal sensation (PTS) was higher during initial rest (p=0.046) and after 20 minutes of running (p=0.007) in 85% RH compared to 19% RH. The higher score in skin wittedness was significant for both the running and recovery periods in 85% RH (p=0.014 and p=0.014) compared to 19% RH (p=0.004 and

p=0.011). Perceived exertion (RPE) was rated at 15 in 85% RH and 14 in 19% RH after 20 minutes of running (p<0.0005). There were no significant differences in RPE between conditions during initial rest and inactive recovery.

* indicates significant difference in Tc between high and low humidity (p<0.05). Values are mean ± SD, n=10.

Figure 5. Core temperature (Tc) during initial rest, running and upright inactive recovery.

DISCUSSION

The main findings of this laboratory study that simulated periods of high work intensities followed by inactive recovery in 85% RH or 19% RH conditions supported our hypotheses that high humidity would lead to a higher thermal stress and affect thermal sensation and comfort negatively, compared to low humidity conditions. Several studies show that exercise intensity and ambient temperature affect both regional and total sweat rate during exercise (Cheuvront et al., 2002; Galloway and Maughan, 1997; Havenith and Middendorp, 1990; Kondo et al., 1998; Smith and Havenith, 2010; Sparks et al., 2005). In our study, exercise intensity and T_a did not differ between the two environmental conditions, so the significant differences in RSR and GSL would result from the differences in the humidity of the environments.

RSR in young males are significantly higher in 85% RH than in 19% RH conditions. Our findings of high RSR on the central mid-back and low RSR on the posterior forearm is in accordance with the well-documented variation in distribution of sweating (Cotter et al., 1995; Hertzman, 1957; Kuno, 1956). Recent studies by Smith et al. (2007), Havenith et al. (2008a; upper body), Machadi-Morerira et al. (2008) and Smith and Havenith (2010) are also in accordance with the variation in sweat production in our sample population for both posterior forearm and mid-central back location. These findings show that there is no uniform sweat rate for the whole body and that large variation between individuals exists; in fact, sweat rates are largely dependent on location of measurement and individual characteristics.

The effects of post-exercise recovery on cardiovascular, thermal and sweat rate responses during active, inactive and passive recovery modes have been well documented in previous studies (Carter III et al., 2002; Jay et al., 2008; Journeay et al., 2005, 2004; Wilson, 2004). In our study, upright inactive recovery was chosen as mode of recovery to simulate work situations in which sitting would not be possible. Sweat rate during upright recovery may be modified by baroreceptors (Carter III et al., 2002; Wilson, 2004) but such an

effect was not considered to be important in the testing of our hypotheses. All of the above studies on post-exercise recovery were performed at 24-25 °C in either unreported or RH of 55% (Journeay et al., 2004) or 30% (Jay et al., 2008). To our knowledge, no studies have been performed on post-exercise sweat rate under conditions of high T_a (30 °C) and 85% RH. Candas et al. (1983) described the effect of hot humid environments on sweating in resting men, and showed that sweat rate rose for one hour before starting to decline due to the effect of skin wittedness (hidromeiosis). During profound sweating the skin becomes hydrated and swells, which induces a decline in sweating (Candas et al., 1983, 1979; Gonzalez et al., 1974; Nadel and Stolwijk, 1973). RSR in our study did not seem to be affected by hidromeiosis. This can be attributed to the high absorption capacity of the technical absorbent pads used to measure sweat production. Instead, our results indicate delayed onset of the fall in sweat rate in an 85% RH compared to a 19% RH environment. This corresponds well with the continued increase in T_c measured during the first seven minutes of inactive recovery in 85% RH.

Our findings also show weak to strong correlations between RSR and local skin temperature during inactive recovery under both 85% RH and 19% RH conditions, but no correlation between RSR and local skin temperature during running. The classical study by Nadel et al. (1971) emphasises the importance of local skin temperature for sweat rate. A relationship between RSR and local skin temperature during exercise, as had been suggested by Nadel et al (1971), was not evident in the studies of Bothorel et al. (1991), Cotter et al. (1995) and Smith and Havenith (2010).

GSL was higher when subjects were exposed to 85% RH than to 19% RH, and showed a positive correlation with metabolic rate. This is explained by the reduced effect of evaporation due to the diminished water vapour gradient between the skin and the ambient environment under conditions of high humidity, and were in accordance with earlier studies (Maughan et al., 2012; Niwa and Nakayama, 1978; Shapiro et al., 1982). They show that GSL increased in a high humidity environment compared to a low humidity environment. The shorter duration of physical work in our study compared to the studies by Shapiro et al. (1982) and Maughan et al. (2012) explains our lower GSL values. Nevertheless, there was a highly significant correlation between GSL and metabolic rate under both environmental conditions, which is in accordance with the results of Smith and Havenith (2010).

Our results show a significant difference between the GSL regression lines of 85% RH and 19% RH. This indicates increased sweat loss in relation to work rate in 85% RH compared to 19% RH conditions. This effect can once again be attributed to the reduced efficiency of evaporation on the skin in high humidity conditions. In order to take the differences in heat production between running and upright recovery into account, we adjusted metabolic rate to the total heat production to obtain an estimate of absolute metabolic rate during the test session. We did not measure the weight change between running and inactive recovery in this study. It was therefore impossible to calculate separate GSL values for running and inactive recovery, which might have highlighted the change in sweat rate from running to recovery.

We observed a significant increase in HR at the end of the running period and during the first 24 minutes of recovery in 85% RH compared to 19% RH. A high HR in a hot environment is explained by a redistribution of blood to the periphery as a thermoregulatory response. This reduces the central blood volume, which in turn reduces stroke volume and leads to increased HR (Galloway and Maughan, 1997; González-Alonso et al., 2000; Montain et al., 1996; Rowell et al., 1966). In our study, T_a was kept at 30 °C in both 85% RH and 19% RH conditions. Nevertheless, a significantly higher HR was measured under the 85% RH conditions during inactive recovery, which can be explained by the significant elevation in T_c during the same period in 85% RH (Bergh and Ekblom, 1979; Kenney, 2008; Rowell, 1974). However, the higher HR during running in

85% RH cannot be explained by an elevation in T_c, since no significant differences in T_c during running were found between the two conditions. This is explained by the rise in T_s due to reduced evaporative efficiency in high humidity, which is also described in the reviews by Rowell (1974) and González-Alonso et al. (2008).

There was a significant 0.5 °C higher T_s at the end of the running period, and T_s were significantly elevated during most of the recovery period in 85% RH compared to 19% RH in our study. Increased skin blood flow in the heat results in an increased volume of warm blood in the periphery (González-Alonso et al., 2008; Rowell, 1974). This is an important mechanism for keeping skin temperature higher than the surrounding air and thus maintaining the evaporative and conductive temperature gradient between skin and air (Alber-Wallerström and Holmér, 1985; Havenith et al., 2013; Webb, 1995). The effect of the increased skin blood flow to maintain the evaporative temperature gradient is reduced in high humidity conditions, as the gradient between ambient water vapour pressure and skin hydration decreases (Candas et al., 1979; Wendt et al., 2012). Our study found no differences in the rate of decrease in T_s (0.05 °C per minute) during inactive recovery after the highest measured T_s in 85% RH and 19% RH conditions. Heat transfer between the skin and surrounding environment can explain the lack of difference between the rates of decrease in T_s. In our study, the T_a of 30 °C displayed no significant differences in heat loss between 85% RH and 19% RH conditions. The similar rates of cooling in T_s and T_c, and the similar decline in RSR between inactive recovery in 85% RH and 19% RH supports this statement.

T_c rose from 37.0 °C during initial rest to 37.7 °C during running in both 85% RH and 19% RH conditions and did not differ significantly. It is observed that during work, rectal temperatures are independent of environmental temperatures between 5 and 30 °C (Nielsen and Nielsen, 1962), but is dependent on the intensity of exercise (Saltin et al., 1968). Maughan et al. (2012) tested exercise capacity in men during cycling at 70% VO_{2max} at 30 °C under four different humidity conditions and, as in our study, did not find any significant difference between T_c in low and high humidity after 20 minutes of exercise. In our study T_c continued to increase during the inactive recovery period and reached a peak of 38.1 °C after seven minutes of inactive recovery in 85% RH, and a peak of 37.8 °C after three minutes in 19% RH. That the peak rectal temperature is reached several minutes after the stop of the exercise may be explained by the measuring site. The temperature of this area shows a slow response to changes in the body heat content due to low blood flow rate. Also, the area has a high degree of thermal inertia due to its relatively large mass (Gunga et al., 2008; Taylor et al., 2014).

Most of the studies discussed in this article have used RH values around 50%, and there are differences in measurement sites, exercise intensities and durations, recovery modes and durations, and it is therefore hard to conclude about the effect of one single parameter. However, it is likely that RH may have an effect on the prolonged increase in T_c and delayed fall in RSR as observed in our study.

CONCLUSIONS

Regional sweat rate, gross sweat loss, heart rate, skin and core temperatures, was higher during post-exercise recovery in a high humidity (85% RH) than a low humidity (19% RH) environment at 30 °C. This identifies the importance of relative humidity at high environmental temperature for thermal sensation and comfort and physiological responses during inactive recovery after high-intensity activities. This study emphasises the importance of including the effect of relative humidity in assessment of both exercise and recovery, to ensure optimal evaporation in the development of high-performance clothing and to reduce heat stress for improved athletic performances in high temperature and humidity environments.

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