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Thermoregulatory Response to Base-layer Garments During Treadmill Exercise [1]

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Abstract. The purpose of this study was to determine the thermoregulatory response to, perceived comfort and moisture management properties of, base-layer garments during intermittent treadmill exercise in controlled laboratory conditions. Seven males performed an intermittent treadmill protocol whilst wearing a base-layer hot garment, base-layer cold garment, a 100% cotton t-shirt and bare-chested. Environmental temperatures were 20.6 °C ± 0.2 SD (ambient temperature) and 47.5 % ± 7.7 SD (ambient humidity). Mean torso skin temperature, rectal temperature, comfort rating, thermal sensation rating, rating of perceived exertion, garment moisture retention, and garment rate of evaporation were recorded. Garments were examined under a high magnification microscope in order to characterise physical differences. Mean torso skin temperatures post exercise were 28.5 °C ± 0.8 SD, 29.1 °C ± 0.4 SD, 29.8 °C ± 0.8 SD, 29.8 °C ± 0.8 SD for bare-chested, base-layer hot, base-layer cold, and cotton garment conditions respectively. Mean comfort ratings during exercise were 7.8 ± 0.6 SD, 8.1 ± 0.7 SD, 9.2 ± 0.7 SD, and 9.4 ± 0.6 SD for bare-chested, base-layer hot, base-layer cold, and cotton garment exercise conditions respectively. Mean increase in garment mass post exercise was 0.044 kg ± 0.032 SD, 0.052 kg ± 0.029 SD, and 0.066 kg ± 0.043 SD for base-layer hot, base-layer cold, and cotton garment conditions respectively. In conclusion, base-layer garment choice affects the physiological response to intermittent treadmill exercise. Specialist base-layer garments are a superior alternative to 100% cotton t-shirts with respect to desired thermoregulatory response and wearer comfort.

Keywords: Skin Temperature, Core Temperature, Sweating, Exercise, Apparel.

1. Introduction

Clothing construction can significantly alter thermoregulation during exercise, suggesting that the clothing ensemble worn by athletes can significantly affect performance (Gavin, 2003). It is known that exercise increases metabolic activity and that most of the excess energy, which is not converted to work, is released in the muscle as heat (Havenith, 2002). The dissipation of heat through evaporation, conduction, convection, respiration, and radiation help keep the body in thermal balance by maintaining a stable core temperature (Gavin, 2003). Clothing increases thermal insulation, impeding the loss of heat through and reducing moisture vapour transfer from the skin to the environment. A reduction in heat loss causes an increase in sweat rate further increasing the likelihood of dehydration, if fluids are not replaced. "When exercise exceeds one minute, dehydration profoundly impairs physiologic function and compromises optimal ability to train and compete" (McArdle *et al.*, 2005). Advances in textile technology have the potential to enhance thermoregulation and are thus of benefit to the wearer during exercise.

The thermoregulatory response to apparel has been investigated using thermal manikins (Holmér and Nilsson, 1994; McCullough and Zuo, 2003), integrated modelling (Fengzhi and Yi, 2005), mechanical testing (Ying *et al.*, 2004), and human participants (Matthews *et al.*, 1969; Nielson and Endrusick, 1990; Meir *et al.*, 1994; Kulka and Kenney, 2002; Myhre and Muir, 2002; McCullough and Kenney, 2003). Mathews *et al.*, (1969) carried out one of the earliest experiments aiming to characterise the effects of sportswear on human performance. Nine male participants ran at 9.6 km·h^{-1} for 30 minutes on a treadmill wearing 1) shorts only; 2) a football uniform and 3) shorts plus a backpack of equal mass to the uniform. The

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third garment condition was included to examine the physiological effects of the added mass only, whilst keeping a large evaporative surface area. Mathews *et al.*, (1969) found that rectal temperature, skin temperature, heart rate and total body mass loss were lower when exercising in shorts compared to uniform and backpack exercise conditions. Kulka and Kenney (2002) and McCullough and Kenney (2003) also concluded that wearing padding has a negative effect of thermoregulatory response on players. Meir *et al.*, (1994) examined the thermoregulatory response, during treadmill exercise, of ten male participants wearing two game-play rugby league shirts, one alternative lightweight shirt and bare-chested. Each participant was required to run for 50 minutes at a speed calculated to elicit 50% of their maximum oxygen intake. The magnitude of body mass lost was not as great as those in a professional rugby league match, although the changes relative to time were almost identical; $0.02 g \cdot min^{-1}$ compared to 0.03 and $0.02\ g \cdot min^{-1}$ for forwards and backs respectively (Meir *et al.*, 1990). There were no significant differences in peak core temperature between garment conditions. Shirts worn, of the design and construction typical of the era, had a negative effect on thermoregulatory response in warm humid conditions. The alternative lightweight shirt appeared to be more efficient due to its open weave construction and improved wicking capabilities. Myhre and Muir (2002) examined the thermoregulatory response to one- and two-piece tennis uniforms during a 50 minute intermittent treadmill exercise protocol, designed to replicate the demands of competitive tennis. Total mean sweat losses were significantly higher when wearing the one-piece uniform compared to the two-piece uniform. Mean rectal temperature, mean skin temperature and mean maximum heart rate did not show a significant difference between garment conditions. In summary, the thermoregulatory response to sportswear has received considerable attention in recent years. In most cases, mean skin temperature and total weight losses are significantly influenced by garment design whereas core temperature does not appear to be affected. Individual studies have focussed on the demands of one particular sport, replicated in controlled laboratory conditions.

The use of base-layer garments in team sports has become widespread in recent years. Typically worn next to the skin below official team kit, these base-layer garments purport to afford distinct functional properties to the wearer. Manufacturers' claim that the base-layer hot garment keeps the wearer comfortably cool during exercise and is typically worn in hot conditions, whereas the base-layer cold garment aims to keep the wearer comfortably warm during exercise, and is typically worn in cold conditions. Both garments are claimed to reduce moisture retention as a result of good wicking properties. However, to date, the thermoregulatory effects and moisture management properties have yet to be systematically studied.

2. Methods

The thermoregulatory response to a base-layer hot and base-layer cold garment was assessed using an intermittent treadmill protocol and compared to wearing a 100 % cotton t-shirt and when bare-chested. The cotton t-shirt was chosen for comparison as it represents the garment most typically worn during training, recreational exercise or in competition, if a base-layer garment is not available. Garment construction properties were measured using a high magnification microscope to quantify physical differences between garments.

2.1. Garment properties

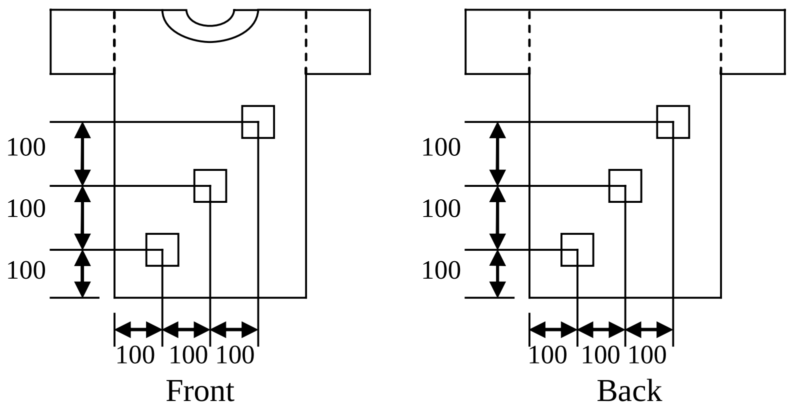

Fig. 1: Areas of shirt examined under high magnification microscope; dimensions in mm.

Garment properties were examined using an optical measurement device (Flash 200 Smartscope, Optical Gaging Products Inc, NY) with x 1 lens. This machine has been calibrated to ± 2.525 microns in the XY direction and ± 3.03 microns in the Z direction (calibration certificate C6401). Standards and equipment have been calibrated using standards traceable to the National Institute of Standards and Technology in accordance with procedures set forth in MIL-STD-45622A, ANSI/ NCSL 2540-1 ISO-10012, as applicable. Six areas were chosen for examination, as shown in Figure 1. These features were illuminated using surface lighting (a 12 V 80 W coaxial, through-the-lens, surface illuminator). The garments were pressed using a steam iron and laid flat, without any visible creases, on the glass base plate. Garment interstices (spaces between the yarns) width and length were measured at x 288 magnification using a box target. Yarn depth was determined by focussing on the uppermost yarn in the centre of the testing area where the height reference was taken as the glass base plate. Yarn width was determined using the diameter of the circle target. The number of wales and courses were determined visually in a 5 mm by 5 mm test sample. Sample sites were selected to ensure that they did not contain the same wales and course threads.

2.2. Participants

Following attainment of informed consent and in accordance with generic clearance from Loughborough University's ethical advisory committee, seven participants completed the study (24 yrs ± 3 SD, 1.84 m ± 0.06 SD, and 83.6 kg ± 8.2 SD). The participants visited the laboratory on four occasions separated by 48 hours. A pre-exercise hydration protocol was followed that included an overnight fast, 500 ml of water before retiring to bed and 500 ml of water following the first urination on waking (Sawka *et al.*, 1992). No further fluids were consumed during the test. Consumption of caffeine and alcohol were also avoided for at least 12 hours prior to exercise (Danel *et al.*, 2001; Quinlan, 1997). Participants refrained from strenuous exercise for at least 12 hours prior to the tests. Participants also refrained from using antiperspirants and were recently showered. The protocol was completed at the same time of day to eliminate circadian rhythm effects (Havenith, 2002; Waterhouse *et al.*, 1999). During testing participants wore either a plain t-shirt (Canterbury of NZ; 100% cotton), a base-layer hot garment (Canterbury of NZ; 85% polyester, 15% elastane), a base-layer cold garment (Canterbury of NZ; 65% nylon, 21% polyester, 14% lycra) or exercised bare-chested. Garments were chosen according to the manufacturer's sizing charts and the order of garment condition testing sequence was controlled, to reduce the likelihood of any order effect. Participants were instructed to wear the same shorts, socks and footwear on each occasion. Mean skin temperatures were recorded pre-acclimatisation (PrA), post-acclimatisation (PoA), mid-exercise (ME), and at the end of exercise (EE) for the unclothed torso (back and front,) using an infrared imaging camera (FLIR Systems, Thermovision Series A20M; accuracy ± 2 % of reading). Infrared emissivity was set at 0.98. Mean skin temperature range at EE was measured by subtracting the minimum from the maximum values. A fan was used to create a fixed airflow (circa 3 $m{\cdot}s^{-1}$) across the front of the torso during active portions of the trial only i.e. no airflow was present during the infrared image capture. Comfort rating (Bedford, 1936), thermal sensation rating (ASHRAE, 1966) and rating of perceived exertion (RPE; Borg, 1982) measures were recorded every 5 minutes. In this experiment thermal comfort was defined as "that condition of mind which expresses satisfaction with the thermal environment" ASHRAE (1966) in Parsons (2003). Ambient humidity and temperature were recorded every 5 minutes using a humidity and temperature meter (Vaisala HMI 31; humidity accuracy ± 0.6 % and temperature accuracy ± 0.3 °C at 20° C). A rectal probe was inserted 100 mm beyond the anal sphincter as indicated by a gauze bung (Meir *et al.*, 1994) and rectal temperature logged, as an indicator of core temperature, every 30 seconds (Squirrel Logger SQ800, Grant Instruments Ltd, UK; temperature accuracy ± 0.1 % of reading). The mass of the trial garment and kit (towel, shoes, shorts, and underwear) were established pre- and immediately post-testing using precision scales (Mettler Toledo SB8001; mass accuracy ± 2 g) to quantify garment moisture retention during exercise. Following the completion of the test, garments were hung, using a coat hanger, in the laboratory and garment mass was recorded every 5 minutes for a total of 45 minutes to establish rate of evaporation.

After a 10 minute preparation period, where the participant changed into their kit and inserted the rectal probe, the participant assumed a standing position upon the rails of a treadmill (RFE International Ltd, TR1) and the first infrared image was recorded (image PoA). The participant then donned one of the three garments (or remained without a garment in the bare-chested condition) and stood motionless, in the absence of airflow, for a further 10 minute acclimatisation period. At the end of this period a second infrared image was taken (image PrA). A treadmill protocol based on Drust *et al.* (2000) was then administrated for a total period of 47 minutes 10 seconds, depicted in Figure 2. The protocol of Drust *et al.*, (2000) was designed to be consistent with the aerobic demands of soccer. The activity pattern distribution was repeated in this study.

However, due to the speed limitations of the treadmill available, sprinting activities were not included. Instead the protocol was divided into 1 minute intervals of walking, jogging and cruising phases at 6, 12 and 15 km·h^{-1} respectively.

At the end of the first 23 minute exercise period, a 70 second rest was implemented followed by a second bout of identical exercise. Two further infrared images were taken; one 30 seconds into the 70 second rest period (image ME) and another at the end of exercise (image EE). In total four images were obtained; in all cases moisture was removed from the skin using a towel, immediately prior to the recording of the images. All image data were transferred to infrared imaging software (ThermaCAM Researcher Pro 2.8) for analysis. Each infrared image was analysed using a constant area polygon positioned over the front/back area of the torso, equivalent to the area covered by the garment. The mean, maximum and minimum temperatures of this area were recorded for each capture.

Data is presented as mean ± standard deviation (SD) unless otherwise stated. Analysis was by Student's paired t-test. Differences between and within garment conditions were considered significant where P < 0.05.

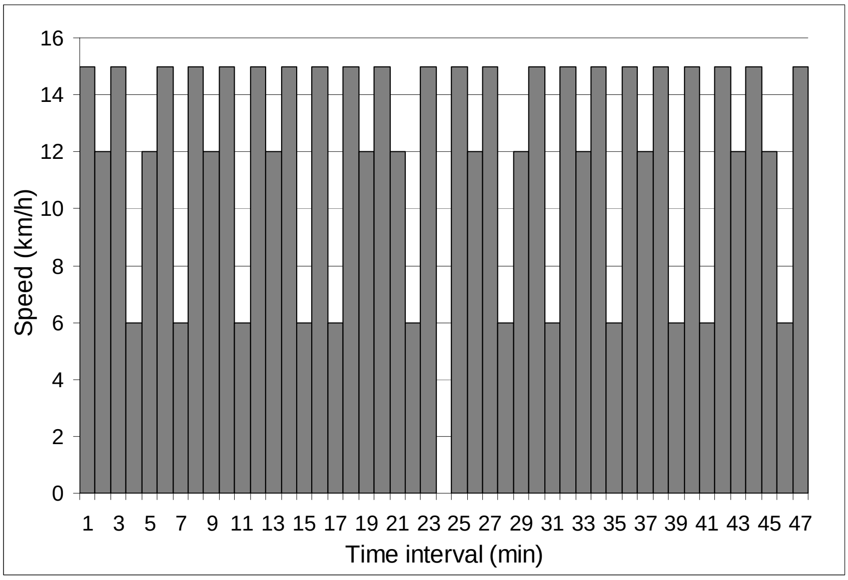

Fig. 2: Graphical representation of the treadmill protocol

3. Results

3.1. Garment physical data

Results indicate significant physical differences between garments. Mean data averaged from all six points are shown in Table 1 and images of one 5 mm by 5 mm sample from each garment are shown in Figure 3.

Table 1: Garment physical properties

Shirt	**Yarn Height (mm)**	**Yarn Width (mm)**	**Number of Wales**	**Number of Courses**	**Interstice Length (mm)**	**Interstice Width (mm)**
Base-layer hot						
Mean	0.652	0.174	9	21	0.169	0.077
SD	0.022	0.010	0	0	0.041	0.010
Base-layer cold						
Mean	1.003	0.216	8	15	0.066	0.033
SD	0.069	0.018	0	0	0.014	0.005
Cotton						
Mean	1.188	0.309	7	9	0.105	0.058
SD	0.119	0.024	0	0	0.021	0.013

Yarn height of the cotton garment was significantly higher than the base-layer hot garment (P < 0.0005) and base-layer cold garment (P < 0.05). Yarn height was also significant higher in the base-layer cold than base-layer hot garment ($P < 0.00005$). Yarn width was significant larger in the cotton garment than base-layer hot ($P < 0.0001$) and base-layer cold garment ($P < 0.001$) which, in turn, was significantly larger than base-layer hot garment ($P < 0.00005$). Interstice length and width in the base-layer hot garment were significantly larger than base-layer cold garment ($P < 0.005$ and $P < 0.0005$) and cotton garment ($P < 0.05$ and $P < 0.05$). Interstice length and width in the cotton garment were also significantly larger than base-layer cold garment ($P < 0.01$ and $P < 0.01$). Garment masses pre-exercise were 0.135 kg ± 0.011 SD, 0.162 kg ± 0.013 SD, 0.207 kg ± 0.004 SD for base-layer hot, base-layer cold, and cotton respectively.

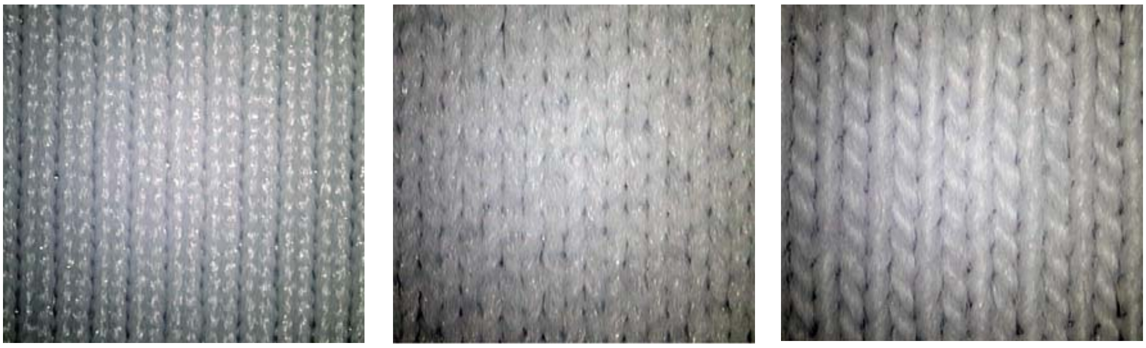

Fig. 3: Base-layer hot, base-layer cold and cotton images at x 35 magnification.

3.2. Thermoregulatory response

Thermoregulatory testing was completed in cool conditions, as defined by Havenith (2001). Mean ambient temperature and humidity were 20.6 °C ± 0.2 SD and 47.5 % ± 7.7 SD respectively. Results, in Table 2, show that mean torso skin temperatures, across all garment conditions, were similar post-acclimatisation and tend towards 31.4 °C for the bare-chested and base-layer garment conditions and 31.9 °C for the cotton condition. Mean torso skin temperatures recorded during the bare-chested condition, at both ME and EE, were lower than all other garment conditions; significantly in comparison to the base-layer cold (ME; $P < 0.0005$ and EE; $P < 0.001$) and cotton garment conditions (ME; $P < 0.0001$ and EE; $P < 0.0005$). Mean torso skin temperatures when wearing the base-layer hot garment fall between that of the bare-chested and base-layer cold garment conditions at both ME and EE and were significantly lower than cotton at both points (ME; $P < 0.05$ and EE; $P < 0.05$) and base-layer cold garment at EE ($P < 0.05$). When wearing the base-layer cold garment, mean skin temperatures are between that of the base-layer hot and cotton condition at ME but were similar to cotton at EE. Mean torso skin temperatures were significantly lower than cotton garment condition at ME only ($P < 0.05$).

Table 2: Mean (°C) ± 1SD skin (torso) and core temperatures for each garment condition; mean of all participants.

	Bare-chested	**Base-layer hot**	**Base-layer cold**	**Cotton**
Mean skin temp. (PrA)	31.6 ± 0.7	30.8 ± 0.9	31.2 ± 0.7	31.5 ± 1.2
Mean skin temp. (PoA)	31.4 ± 0.5	31.3 ± 0.9	31.4 ± 0.6	31.9 ± 0.7
Mean skin temp. (ME)	$^{a,\,d}$ 28.7 ± 0.8	^{e} 28.9 ± 0.8	^{e} 29.4 ± 0.9	29.7 ± 1.0
Mean skin temp. (EE)	$^{b,\,d}$ 28.5 ± 0.8	$^{c,\,e}$ 29.1 ± 0.4	29.8 ± 0.8	29.8 ± 0.8

Significantly lower than base-layer cold, ^{a} $p < 0.0005$, ^{b} $p < 0.001$,
^{c} $p < 0.05$
Significantly lower than cotton, ^{d} $p < 0.0005$, ^{e} $p < 0.05$

The mean maximum and mean minimum torso skin temperatures and mean skin temperature range at EE are shown in Figure 4, for all garment conditions. Again the bare-chested condition exhibits the lowest mean skin temperatures. However, both the mean maximum skin temperatures and mean skin temperature range exhibit a different trend than the overall mean torso skin temperatures in Table 2. Maximum skin temperatures were 32.5 °C ± 0.8 SD, 33.4 °C ± 0.4 SD, 33.7 °C ± 0.7 SD, 33.2 °C ± 0.9 SD for bare-chested, base-layer hot, base-layer cold and cotton garment conditions respectively. Mean maximum skin temperatures were highest when wearing a base-layer cold garment; significantly so when compared to bare-chested and cotton ($P < 0.0005$ and $P < 0.05$ respectively). Mean maximum torso skin temperatures when bare-chested were also significantly lower than base-layer hot and cotton ($P < 0.05$ and $P < 0.005$ respectively). Mean skin temperature range values were lowest when wearing cotton but similar between the other garment conditions. Values were 10.1 °C ± 2.9 SD, 10.2 °C ± 2.0 SD, 10.0 °C ± 1.7 SD, 8.4 °C ± 3.3 SD for bare-chested, base-layer hot, base-layer cold and cotton garment conditions respectively. Mean minimum skin temperatures show a similar trend to mean torso skin temperatures where values were lowest when bare-chested (22.5 °C ± 2.6 SD) followed by base-layer hot (23.1 °C ± 1.8 SD), base-layer cold (23.8 °C ± 1.5 SD), and cotton (24.7 °C ± 2.8 SD). Mean minimum skin temperatures were significantly lower during the base-layer hot condition compared to the cotton condition ($P < 0.05$). These differences are highlighted in Figure 5 which shows the front torso thermographs of one participant at EE after exercising in each of the garment conditions.

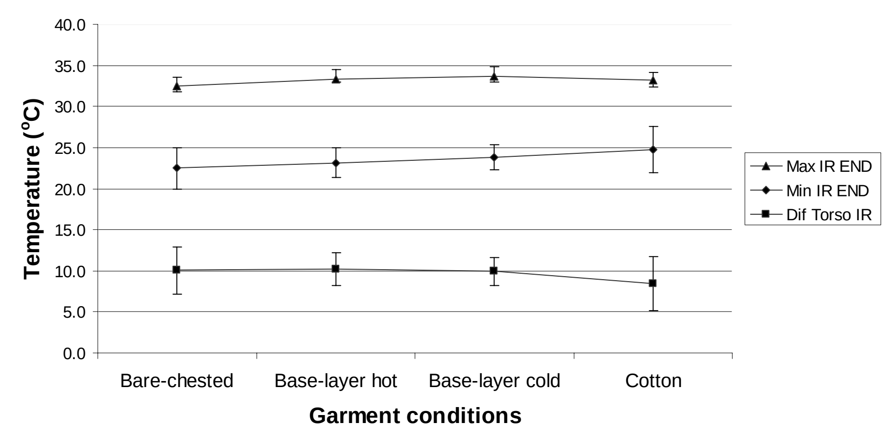

Fig. 4: Mean maximum and mean minimum skin temperatures at end-exercise point.

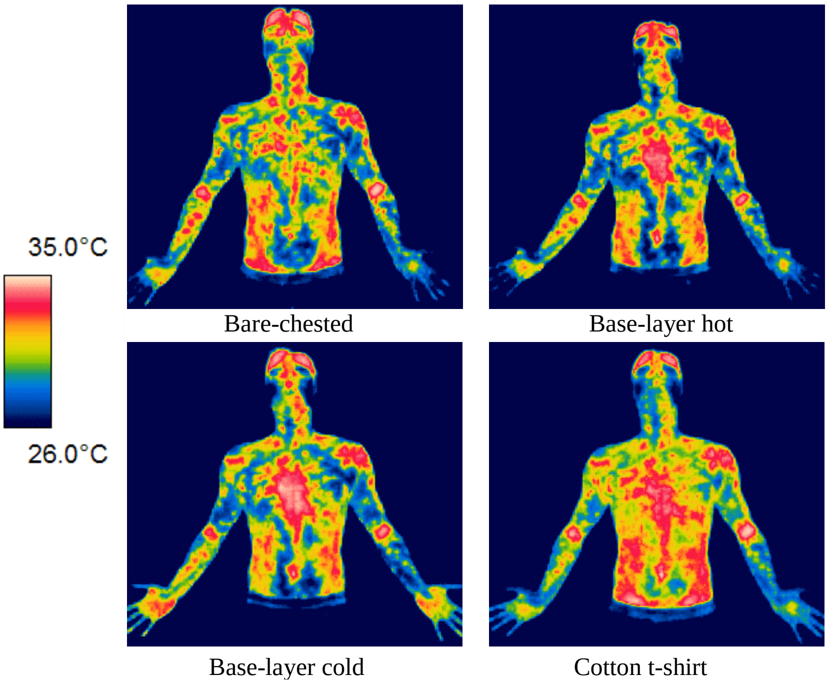

Fig. 5: Front torso thermographs of one participant at the end-exercise point for each garment condition.

Mean core temperatures increased significantly due to exercise in all conditions ($P < 0.000005$ for all garment conditions). Mean core temperature traces during exercise for each garment condition are shown in Figure 6. Mean and maximum core temperatures were significantly lower when bare-chested than cotton ($P < 0.05$ and $P < 0.05$ for mean and maximum respectively) but not between the other garment conditions.

Mean values were 37.9 °C ± 0.3 SD, 37.9 °C ± 0.3 SD, 37.9 °C ± 0.1 SD, 38.0 °C ± 0.3 SD for bare-chested, base-layer hot, base-layer cold and cotton respectively. Maximum core temperatures were 38.4 °C ± 0.3 SD, 38.5 °C ± 0.2 SD, 38.5 °C ± 0.2 SD, 38.6 °C ± 0.3 SD for bare-chested, base-layer hot, base-layer cold and cotton respectively. Minimum core temperatures were similar throughout measured at 36.9 °C ± 0.3 SD, 37.1 °C ± 0.4 SD, 37.0 °C ± 0.1 SD, 37.1 °C ± 0.3 SD for bare-chested, base-layer hot, base-layer cold and cotton respectively.

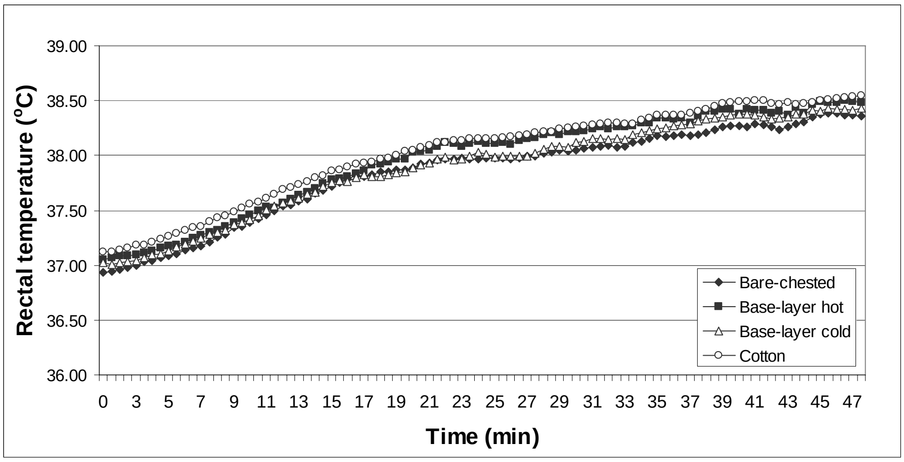

Fig. 6: Mean core temperatures for all garment conditions (time zero was after 10 minutes of habituation)

Comfort, thermal sensation and RPE data obtained during exercise are shown in Figure 7. Mean comfort ratings were 7.8 ± 0.6 SD, 8.1 ± 0.7 SD, 9.2 ± 0.7 SD, and 9.4 ± 0.6 SD for bare-chested, base-layer hot, base-layer cold, and cotton garment conditions respectively. Bare-chested and base-layer hot were significantly more comfortable than base-layer cold ($P < 0.005$ and $P < 0.01$ respectively) and cotton ($P < 0.01$ and $P < 0.05$ respectively). Mean sensation ratings were 7.8 ± 0.9 SD, 8.3 ± 0.6 SD, 9.5 ± 0.8 SD, and 9.7 ± 0.7 SD for bare-chested, base-layer hot, base-layer cold, and cotton garment conditions respectively. Bare-chested and base-layer hot were significantly more comfortable than base-layer cold ($P < 0.005$; $P < 0.01$ respectively) and cotton ($P < 0.005$; and $P < 0.05$ respectively). Mean RPE values were 11.6 ± 1.2 SD, 11.9 ± 1.2 SD, 11.5 ± 1.4 SD, and 11.8 ± 1.2 SD for bare-chested, base-layer hot, base-layer cold, and cotton garment conditions respectively. There were no significant differences between garment conditions.

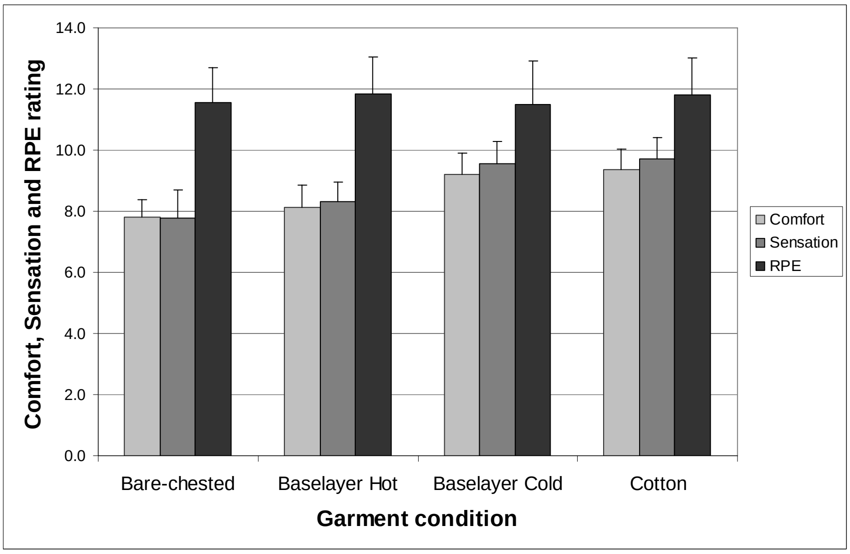

Fig. 7: Mean comfort, sensation and RPE ratings; mean from all participants.

Kit and garment mass increased in all garment conditions due to moisture retention. Mean garment mass increases were 0.044 kg ± 0.032 SD, 0.052 kg ± 0.029 SD, and 0.066 kg ± 0.043 SD for base-layer hot, base-layer cold, and cotton garment conditions respectively. The base-layer hot garment retained significantly lower amounts of moisture than the cotton garment ($P < 0.05$). There were no significant differences between the other garment conditions. Total mean kit (including garment) moisture uptake was 0.073 kg ± 0.033 SD, 0.073 kg ± 0.035 SD, 0.086 kg ± 0.035 SD, and 0.071 kg ± 0.039 SD for bare-chested, base-layer hot, base-layer cold and cotton garment conditions respectively. The bare-chested condition retained significantly lower amounts of moisture in the overall kit assembly than base-layer cold ($P < 0.05$). There were no significant differences between the other garment conditions. Rate of evaporation for the garment conditions post- exercise were 0.028 $L\cdot hr^{-1}$ ± 0.015 SD, 0.035 $L\cdot hr^{-1}$ ± 0.012 SD, and 0.040 $L\cdot hr^{-1}$ ± 0.013 SD for base-layer hot, base-layer cold, and cotton garment conditions respectively. The base-layer hot garment evaporates significantly more moisture than the base-layer cold ($P < 0.05$) and cotton ($P < 0.05$) garments respectively, whilst hanging in controlled laboratory conditions for 45 minutes.

4. Discussion

The results obtained suggest that the functionality of the various garments tested differ; with the bare-chested and base-layer hot garments resulting in lower mean skin temperatures than the base-layer cold and cotton garments. These differences can be explained, at least partially, by comparing the garments' physical properties to the thermophysical results. The base-layer garments studied were constructed to allow increased moisture vapour transfer with added wicking characteristics. More wales and courses suggest a larger number of interstices. Mean skin temperature will reduce with increased air-flow, due to a larger number of interstices of greater area, as forced convection by air-flow is known to increase the removal of heat from the body to the atmosphere (Houdas and Ring, 1982). Reduced thickness may increase the wicking transfer rate of perspiration from the skin to the garment surface, as distance travelled through capillary flow is less. Increases in garment thickness also increase insulation and decrease the rate of moisture vapour transfer due to the added entrapped air (Havenith, 2002). Cotton fibres are also known to have a higher absorbency; swelling when saturated. An increase in fibre diameter, due to swelling, will decrease interstice size, reducing the moisture vapour transfer rate consequently increasing microclimate humidity (Nielson, 1986) and moisture concentration. An increase in microclimate moisture concentration will reduce the rate of evaporative heat loss (Havenith, 2002) and increase feelings of discomfort (Ueda, *et al.*, 2006). However, the rate of heat conduction from the skin to the atmosphere will increase due to the higher conductivity of a saturated garment. The thermal insulation of clothing is also reduced when wearing wet clothing in cool environments (Gavin, 2003). It is recognised, though, that the rate of conduction heat losses are significantly smaller than that of convection during exercise in cool conditions (Havenith, 2002). This intricate mechanism of heat evaporation, conduction and retention explains the minor differences seen between garment conditions.

Mean maximum skin temperatures were lowest when bare-chested and highest when wearing a base-layer cold garment. The higher conductive heat loss due to the saturated cotton garment may explain this difference. However due to the increased sweat evaporative qualities of the base-layer garments, mean torso skin temperature was lower overall. Mean minimum skin temperatures were lowest when bare-chested, followed by the base-layer hot condition, then the base-layer cold condition and highest when wearing cotton. This base temperature increase, as highlighted in Figure 5, may explain the overall increase in mean skin temperature values shown across all garment conditions in Table 2. Localised heat spots increase in size at the sternum and near the external oblique muscles of the abdomen creating larger areas of higher temperature. These areas are not in contact with the skin suggesting that evaporation and convection are the main mechanism of heat loss.

A low mean skin temperature suggests a higher rate of total heat transfer from the core to the skin providing the surface area of heat transfer and core-to-skin transfer coefficient remains constant (Houdas and Ring, 1982). A higher rate of heat transfer allows for a more efficient thermoregulatory mechanism. Should the rate of heat transfer decrease it is likely that core temperature would increase more rapidly. In this study there was a significant increase in core temperature due to exercise in all garment conditions. However, as can be seen in Figure 6, core temperature data were similar in all garment conditions. Mean and maximum core temperatures did vary significantly between bare-chested and cotton garment conditions during exercise but there were no significant differences between garment conditions.

Pre-acclimatisation mean skin temperatures vary due to ambient conditions and clothing worn outside the laboratory. A 10 minute acclimatisation period is essential in order to stabilise mean skin temperature prior to exercise (Houdas and Ring, 1982). During exercise the bare-chested condition was most effective at maintaining the lowest skin temperatures, as there are no added layers of insulation or any barriers to the evaporation of moisture. Ideally a 'cooling' garment should offer little resistance to heat transfer and moisture evaporation. A fabric with high wicking capabilities will help in this respect by moving the moisture to its outer surface, dispersing it over the surface area of the garment, improving heat transfer efficiency. The base-layer hot garment performs closest to that of exposed skin and therefore was successful in maintaining a relatively low skin temperature. This may be due in part to it being a more lightweight garment, the inclusion of high wicking fabric and more interstices due to a smaller yarn diameter. The base-layer cold and cotton garments perform similarly in that a higher skin temperature was maintained throughout the garment conditions however the base-layer cold garment retains significantly less moisture than the cotton garment. This was unsurprising given that the base-layer cold garment was constructed from a high wicking fabric improving sweat evaporation.

There are four accepted conditions of comfort: the body must be in heat balance, mean skin temperatures and sweat rates are within required levels of comfort and there are no local discomforts, such as draughts (Parsons, 2000). In general, comfort is related to skin temperature and skin wetness (Havenith, 2002) however Parsons (2003) argues that “thermal comfort is a psychological phenomenon which is not directly related to the physical environment or physiological state”. Newburgh (1968) also states that with the onset of perspiration, skin temperature tends to rise very slowly and as such cannot be a satisfactory index of comfort and discomfort. Validated comfort and thermal sensation rating scales were used as an index of comfort. It can be seen that when bare-chested and when wearing a base-layer hot garment the wearer was significantly more comfortable than when wearing a base-layer cold and cotton garment. This may be due, in part, to the lower garment moisture retention therefore reducing skin wettedness. Un-evaporated sweat, that can cause the garment to stick to the wearer, has been shown to cause warmth discomfort (Parsons, 2002). There were no significant differences in the participant’s rating of perceived exertion between garments.

The mean garment moisture uptake values recorded, including kit mass, show that cotton retained the most moisture, the base-layer hot garment retained least moisture but the difference between pre- and post-trial kit mass was least whilst running bare-chested. The difference in moisture retention of 0.02 kg observed here between garments may significantly affect feelings of comfort.

5. Conclusions

This study has provided insight in to the subtle differences afforded by alternative fabric options on base-layer garments. The base-layer hot garment successfully permits the body to remain cool during the exercise period to a level close to bare-chested. The base-layer cold garment successfully maintains a higher skin temperature whilst permitting moisture transfer and evaporation. It should be noted that further trials are necessary to identify the performance of these garments at different ambient temperatures.

In conclusion, mean skin temperature, comfort and sensation ratings were significantly affected by a person’s choice of garment during intermittent treadmill exercise. Synthetic base-layer garments were more effective than cotton garments at actively reducing moisture retention, whilst maintaining desired skin temperatures.

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