The determinants of thermal comfort in cool water.

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Abstract

Water-based activities may result in the loss of thermal comfort (TC). We hypothesized that in cooling water, the hands and feet would be responsible. Supine immersions were conducted in up to five clothing conditions (exposing various regions), as well as investigations to determine if a “reference” skin temperature (T_{sk}) distribution in thermoneutral air would help interpret our findings. After 10 minutes in 34.5°C water the temperature was decreased to 19.5°C over 20 minutes; eight resting or exercising volunteers reported when they no longer felt comfortable and which region was responsible. TC, rectal temperature and T_{sk} were measured. Rather than the extremities, the lower back and chest caused the loss of overall TC. At this point, mean (SD) chest T_{sk} was 3.3 [1.7]°C lower than the reference temperature (*P*=0.005), and 3.8 [1.5]°C lower for the back (*P*=0.002). Finger T_{sk} was 3.1 [2.7]°C higher than the reference temperature (*P*=0.037). In cool and cooling water, hands and feet, already adapted to colder air temperatures will not cause discomfort. Contrarily, more discomfort may arise from the chest and lower back, as these regions cool by more than normal. Thus, T_{sk} distribution in thermoneutral air may help understand variations in TC responses across the body.

Keywords: Thermal comfort; Skin temperature; Immersion; Cool water.

INTRODUCTION

Thermal comfort (TC) is an emotional and affective experience which depends on an individual's history and expectation (Leblanc et al. 2003); it is generally defined as the condition of mind expressing satisfaction with the environmental conditions (ASHRAE). In practice, TC refers to the subjective indifference to the environment, and can therefore be characterised by the absence of thermal discomfort.

When a changing or dynamic thermal stimulus is applied to the skin, the frequency of discharge of the thermoreceptors is increased and can reach maximum levels depending on the adapting temperature, which can be defined as the steady state discharge frequency observed at constant temperatures: the faster the rate of change of skin temperature for a given adapting temperature, the greater the dynamic response to cooling up to maximum levels (Hensel, 1981). Humans evolved in, and seek, "comfortable" thermoneutral air or microclimate temperatures of 26-28 °C (Lahr and Foley, 1994). Also, it is believed that the environmental conditions of a working office on a normal day are those under which many modern humans spend most of their time. The skin temperature distribution across the body in such conditions would therefore be the one the most frequently experienced. We believed that the skin temperature distribution of a resting human, in a thermoneutral environment could be the reference upon which subjective thermal responses are based. It was expected that the influence of each body region on overall TC may be driven by local adapting temperatures in such environments.

In cool air environments, it has been reported that TC was lower in hands and feet than elsewhere (Zhang, 2003) and the extremities were the major source of overall thermal discomfort. However, despite extensive investigations in air, the reasons behind the variation between body regions remain unclear. In water, research has focused on the safety aspects of cold water immersions (Golden and Tipton, 2002). Consequently, little is known about TC in cool water where water-sports are undertaken and where maintaining TC becomes more critical as it affects both the behavioural and pleasure responses (Chatonnet and Cabanac, 1965). Without protection, at rest, TC is only achieved in water temperature (T_w) around 35 °C (Craig and Dvorak, 1966). However, in Europe T_w ranges from 10 °C to 25 °C (Météo France Data). Therefore, in these regions, an unprotected individual is likely to experience thermal discomfort during recreational aquatic activities where metabolic heat production is low.

It has been observed that the immersion of humans in cold water (10 °C) was rated more comfortable when the limbs were protected (and trunk exposed) than when the trunk region was protected (and limbs exposed) (Tipton and Golden, 1987). However, in this study hand, feet and forearm pain was reported in the limbs-exposed condition. Therefore, it is difficult to conclude what was responsible for this difference of TC. The effects of different T_{sk} distributions on TC have been investigated in warmer conditions (Wakabayashi et al. 2008), where volunteers immersed in 26 °C water with forearms, hands, lower legs and feet exposed felt more comfortable than when wearing swim briefs only, immersed in 29 °C water. However, this was only noticed when a difference in deep body temperature between the two conditions became apparent. As deep body and skin temperatures contribute equally to TC (Frank et al. 1999), it is not possible to conclude what determined TC. Taken overall, it is unclear which body regions are most important for the maintenance of TC in cool water when skin temperature (T_{sk}) is cooling but deep body temperature remains stable.

The present study investigated the determinants of the loss of TC during water-based activities in cool water. It was hypothesised that the loss of overall TC in cooling water would be due to cooling of the hands and feet: the extremities would be reported responsible for the loss of overall thermal comfort. It was further hypothesised that the regions where skin temperature remains above the "reference" thermoneutral temperature in air would not cause the loss of comfort in cooling water.

METHODS

The study was approved by the University of Portsmouth BioSciences Research Ethics committee and was performed in accordance with the ethical standards of the 1964 Declaration of Helsinki. The participants gave their written informed consent to participate.

Phase One – Thermal comfort of humans immersed at rest in cool water

Volunteers

Eight healthy non-cold habituated males volunteered for the experiment (mean [SD]; Age 23.8 [4.3] yrs; height 1.79 [0.034] m; mass 76.8 [8.7] kg). They were instructed to avoid performing any vigorous physical activity and consuming alcohol for 24 hours prior to each test, and to avoid caffeine and hot food three hours before data collection. During the recruitment process, potential volunteers were excluded in accordance to various medical criteria including cold injuries, peripheral vascular disease, skin thermal insensitivity and any skin conditions (determined by health history questionnaire) or skin disorder such as skin sunburn.

Experimental Design

The experiment was a repeated measures design in which volunteers completed all immersions (on separate days), each in a different clothing condition.

Procedure

Anthropometric measurements were taken. After being equipped with the deep body and skin temperature measuring devices (see below), volunteers donned one of the four clothing assemblies: 1) Swim briefs only, 2) Short wetsuit (to knees and elbows level) with gloves and boots, 3) Long wetsuit only (full coverage wetsuit, to the wrists and ankles), and 4) Long wetsuit with gloves and boots. The wetsuit and accessories were of equivalent thickness (2.5mm), and were as snug as possible. These were composed of neoprene foam and polyamide linings, with a thermal resistance of approximately 0.045 m^2.K/W. The different clothing configurations enabled to alternatively expose or protect key areas and also represented the most commonly used ensembles in water-based activities.

The experiment consisted of four head-out immersions at rest in a rectangular water tank (220 cm x 150 cm x 70 cm); volunteers adopted a supine reclining position in a hammock. The stirred water was initially set at a comfortable temperature of 34.5 °C (Figure 1). After five and nine minutes of immersion volunteers rated their overall and local TC. At the 10th minute T_w was uniformly decreased, over 20 minutes, to 19.5 °C. To do so, a pump injected 100 $L.min^{-1}$ of 12°C water from a cold reservoir into the immersion tank. Throughout the immersions, water temperature was continuously monitored and recorded with three thermistors, attached to the hammock around the head, waist and feet areas. The average cooling rate was relatively linear, at 0.75 $°C.min^{-1}$. As T_w was falling volunteers reported when, overall, they first felt “just uncomfortable” on a categorical scale, and which body region was responsible. By controlling the transition between comfortable and uncomfortable environmental conditions, this protocol enabled us to investigate the physiological determinants of the onset of overall thermal discomfort. From this moment of loss of comfort and until the end of the cooling stage overall and local TC were rated every three minutes. After the water had been cooled to 19.5 °C (minute 30 of immersion) it was maintained at that temperature for up to another 45 minutes to further look at thermal responses to more stressful conditions. Whole body and regional TC were assessed every five minutes during this "stable" stage.

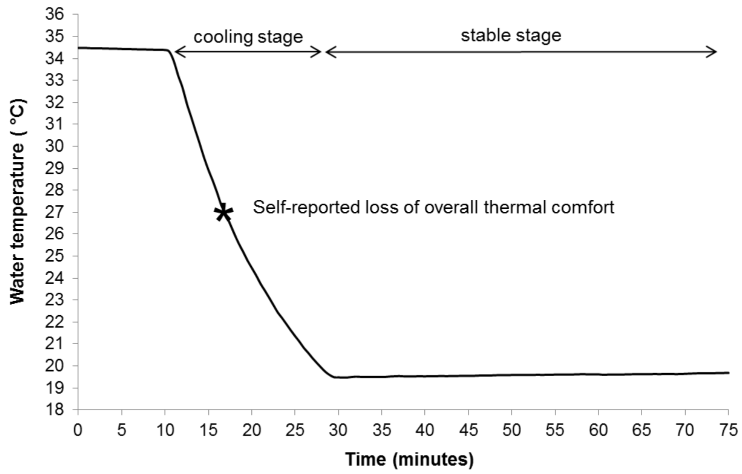


Fig. 1. Graphical time line indicating the average water temperature profile during immersions. The point of loss of thermal comfort on the slope is given as an example.

Measurements

Deep body temperature was measured using a rectal thermistor (Grant Instruments [Cambridge] Ltd., UK) inserted 15 cm beyond the anal sphincter. Firstly, this site is considered to be robust (Tipton, 2006) and it has been shown to be as responsive as other core temperature measurement sites in cooling conditions (Hayward et al. 1984). For the present study, monitoring deep body temperature at the rectum was considered a reasonable choice to provide information related to changes in hypothalamic temperatures. Local T_{sk} was measured with thermistors (Edale Instruments Ltd., UK) attached to selected skin sites on the right side of the body (back of hand, inner forearm, outer upper arm, upper chest, lower back, thigh, calf and top of foot). Rectal temperature (T_{re}) and T_{sk} were continuously recorded on electronic data loggers (Squirrel 1000 and 2040 series meter loggers; Grant Instruments [Cambridge] Ltd., UK) at 30 second intervals. The local T_{sk} were combined to produce a mean skin temperature (T_{msk}) using an adjusted version of Hardy and Du Bois (1938) T_{msk} equation to remove the head T_{sk} which was not immersed. During immersions, volunteers verbally reported their overall and local (hands, forearms, upper arms, chest, lower back, thighs, calves and feet) TC on a categorical scale in front of them (A4 size). It was modified from that originally designed by Zhang (2003), in that volunteers could only choose a TC category amongst those proposed on the scale. The comfort categories were subsequently transformed into numbers for analysis: 0=very uncomfortable, 2=uncomfortable, 4=just uncomfortable, 6=just comfortable, 8=comfortable and 10=very comfortable.

Phase Two – Thermal comfort of humans exercising in cool water

The methods used in *Phase Two* were similar to that in *Phase One;* only differences are described here.

Volunteers

Eight healthy males volunteered for this experiment (mean [SD]; Age 25.1 [4.3] yrs; height 1.77 [0.054] m; mass 68.8 [10.6] kg).

Procedure

The experiment consisted of five head-out immersions, in a supine position, in the same water tank used for *Phase One*. From the 6th to the last minute of immersion, volunteers continuously performed light physical activity, to investigate thermal responses in the situation of recreational scenarios. In each hand, they held a handle attached to a cord. A weight situated outside the immersion facility was attached to each cord. In pace with a metronome, volunteers performed 25 pulling movements per minute with both arms and simultaneously 25 pushing movements with one leg or the other, where a similar weighted system was used. Each of these movements was followed by “returning-into-the-start-position” movements, which involved controlling the weights to the neutral position. The amount of work was standardized across immersions by setting the amplitude of the movements and the mass of the weights and was set during pilot studies so that the measured rate of oxygen consumption was around 0.5 $L.min^{-1}$, equivalent to gentle swimming. This was determined from the analysis of expired gases, using a respiratory face mask. Being in the water, the mass difference between volunteers had no impact on the metabolic rate during exercise in thermoneutral water temperature. Each immersion was completed in a different clothing condition, four of which were identical to those used in *Phase One.* A fifth condition was added: Long wetsuit+gloves+boots+hood. In order to more closely mimic what is likely to happen when a physical activity is undertaken in cool water, throughout the immersions and in all clothing conditions the top of the head (including the forehead, but not the face) was continuously sprayed with water pumped from the immersion tank. T_{sk} and TC on the forehead were measured.

Phase Three – Skin temperature distribution in thermoneutral air environments

Volunteers and experimental design

Six volunteers who took part in *Phase Two* were recruited for this third phase (mean [SD]; Age 25.8 [4.7] yrs; height 1.76 [0.058] m; mass 68.7 [10.1] kg). This phase included the assessment of each volunteer’s skin temperature in air, on two separate occasions.

Procedure

The air in the experimental chamber was set: 26 °C or, on another occasion, 21 °C; relative humidity was set at 60%. The maximum air movement in the chamber was measured at 0.25 $m.s^{-1}$. For the 21 °C condition, volunteers wore their own clothes, as if they were working in their office on a normal day. This consisted of casual shoes, socks, underwear, a pair of jeans and long sleeve shirt. In the 26 °C condition, volunteers only wore swim briefs. On both occasions, they stayed seated for an hour during which they were asked to report any thermal discomfort. At the end of the hour, volunteers were asked to immediately stand up and, in the 21 °C condition, take their clothes off as quickly as possible (keeping their underwear on). Whole body infrared pictures were immediately taken with volunteers facing an infra-red camera, and then turning their back to it. This protocol aimed at providing two types of thermoneutral and thermally comfortable skin temperature distributions.

Measurements

Whole body surface temperatures were measured at the end of the exposure using a thermal imaging camera (A320 series, ThermaCAM™, FLIR systems, Kent, UK). Sites of interest were selected to represent regions where skin thermistors where applied in the immersion phase of the study.

Data analyses

Before analysis, it was confirmed that the data met the assumptions of normality, and sphericity. One-way repeated measures ANOVA were conducted at chosen time-points (point of loss of thermal comfort during the cooling stage, and later, into the stable cold stage). Further tests used the Bonferroni post-hoc test. In *Phase three*, for each skin site, and within each volunteer, the temperature obtained in 21 °C air and the one collected in 26 °C air were averaged to produce a "reference" T_{sk} in an average thermoneutral air environment. Paired samples t-tests were then conducted to compare the calculated reference T_{sk} to that when TC was lost during immersion. A P value <0.05 was considered statistically significant. Means are reported as mean (SD).

RESULTS

Phase 1: Thermal comfort of humans immersed at rest in cool water

<u>General observations</u>

Mean skin temperature in the *Swim briefs* condition and local T_{sk} of non-protected regions closely followed that of T_w (Fig. 2). Overall, the type of wetsuit did not seem to influence the absolute change in T_{re} (Fig. 3). Towards the end of the immersions, some volunteers reported being too (thermally) uncomfortable to continue, and decided to stop the experiment. Only four volunteers reached the end of the immersion (75 minutes) in *Swim briefs*, seven in *Short wetsuit+gloves+boots*, six in *Long wetsuit*, and seven in *Long wetsuit+gloves+boots*. More details are provided in Figures 2 and 3.

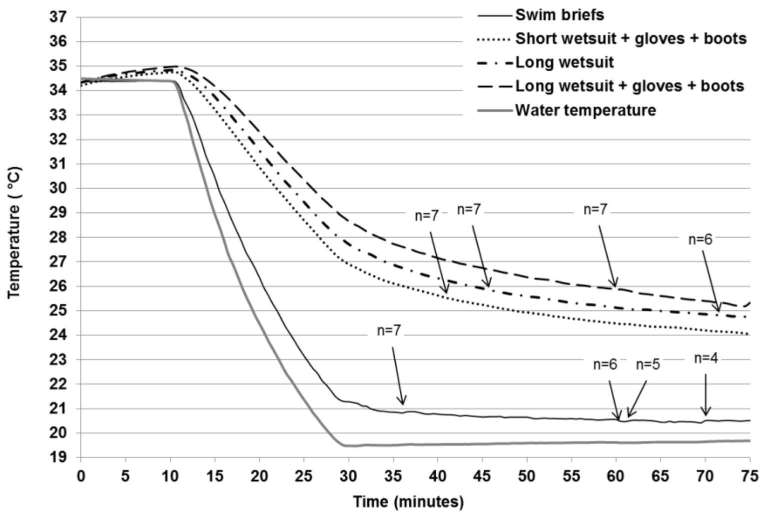


Fig. 2. Average T_{msk} during immersion in the different clothing conditions (*n*=8 initially).

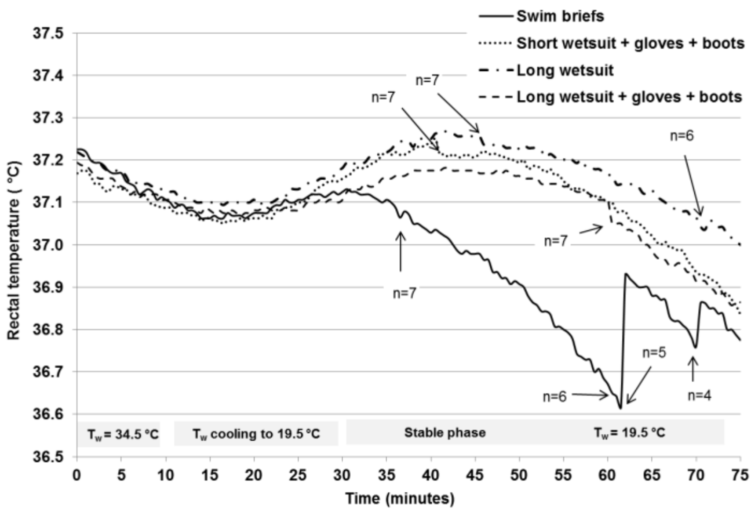


Fig. 3. Mean rectal temperature during the immersion (*n*=8 initially).

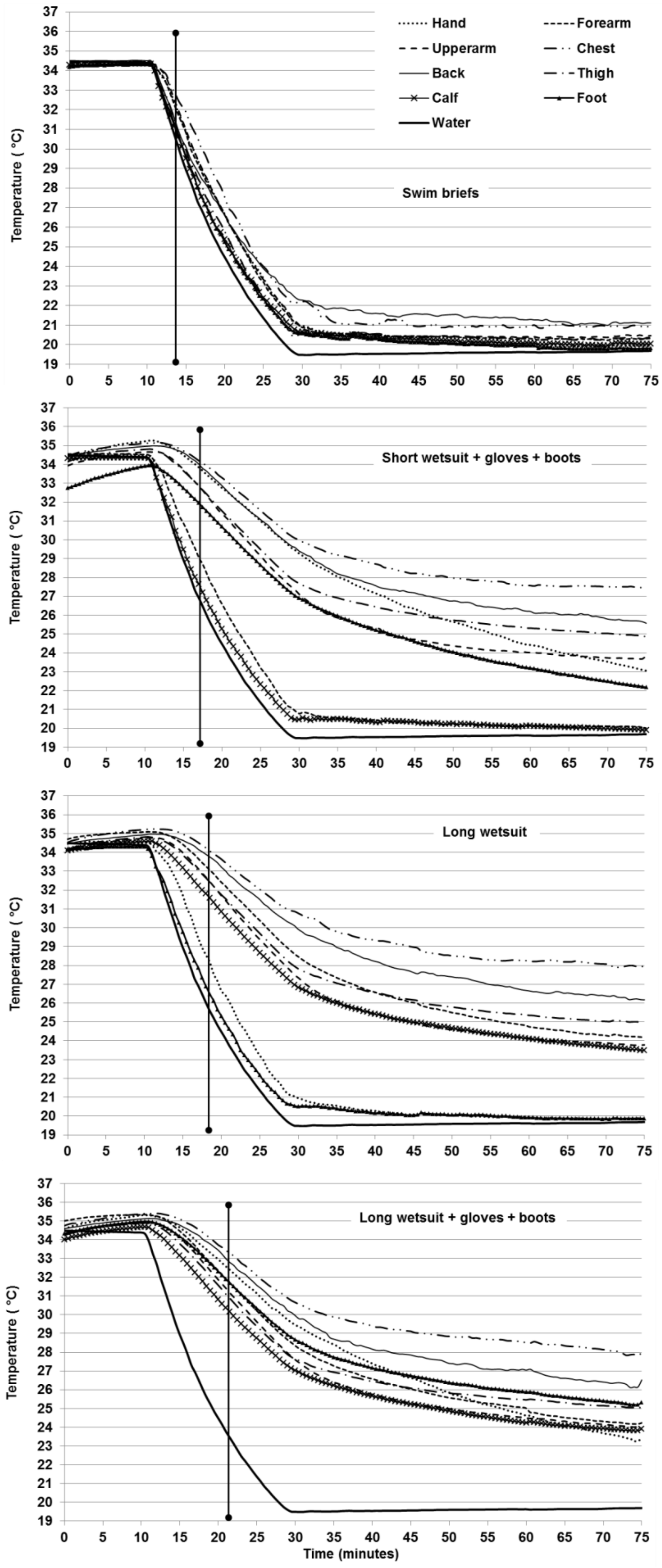
When volunteers reported no longer being comfortable during the cooling stage, T_{re} had dropped by an average of less than 0.05 °C in all clothing conditions, whereas T_{msk} had cooled by a minimum of 0.62 °C, and a maximum of 6.69 °C, across all 32 immersions (Table 1).

Table 1. Mean (SD) changes in mean skin (T_{msk}) and rectal (T_{re}) temperatures between the end of immersion period in 34.5 °C water (minute 10) and the moment when loss of overall thermal comfort was reported during the cooling stage (*n*=8). Note: * represent significant differences between the *Swim briefs* and the *Long wetsuit+gloves+boots* conditions. * *P*<0.05 (*n*=8).

	Swim briefs	**Short wetsuit + gloves + boots**	**Long wetsuit**	**Long wetsuit + gloves + boots**
ΔT_{msk} (°C)	-3.03 (1.67)	-2.29 (1.41)	-2.42 (1.44)	-3.20 (2.23)
ΔT_{re} (°C)	-0.038 (0.035)	-0.025 (0.027)	-0.025 (0.027)	-0.019 (0.026)

T_w (°C)	30.0 (2.0)	27.7 (2.9)	26.5 (2.8)	24.2 (3.8)
Time (min)	14.1 (1.9)	16.6 (3.2)	18.1 (3.6)	21.5 (6.3)*

A one way repeated-measures ANOVA revealed no significant differences, when comparing the changes in T_{msk} or T_{re}, between the clothing conditions. The same analysis was conducted to compare absolute times to loss of overall thermal comfort between the four clothing conditions. The mean (SD) time to loss of comfort in the *Swim briefs* condition (14.1 [1.89] minutes) was significantly shorter than that in the *Long wetsuit+gloves+boots* condition (21.5 [6.9] minutes), P=0.028. No other significant difference was found. Figure 3 shows the average water and local skin temperatures during immersion. The moment when volunteers verbally reported no longer being thermally comfortable is indicated with a vertical line. This loss of overall thermal comfort occurred early in the immersion. Consequently, at that point, local skin temperatures were relatively high, as indicated by the intersection of the vertical line with the individual temperatures for each region.



Hand
Forearm
Upperarm
Chest
Back
Thigh
Calf
Foot
Water
Swim briefs
Short wetsuit + gloves + boots
Long wetsuit
Long wetsuit + gloves + boots
Temperature (°C)
Time (minutes)

Fig. 4. Average water and local skin temperatures during immersion in the different clothing conditions (*n*=8 initially). The vertical line indicates the average time of loss of overall thermal comfort (*n*=8).

Region(s) responsible for the loss of overall thermal comfort in cool water, at rest

The lower back was reported to be responsible for the loss of overall TC more frequently than any other region, in all conditions (Fig. 5).

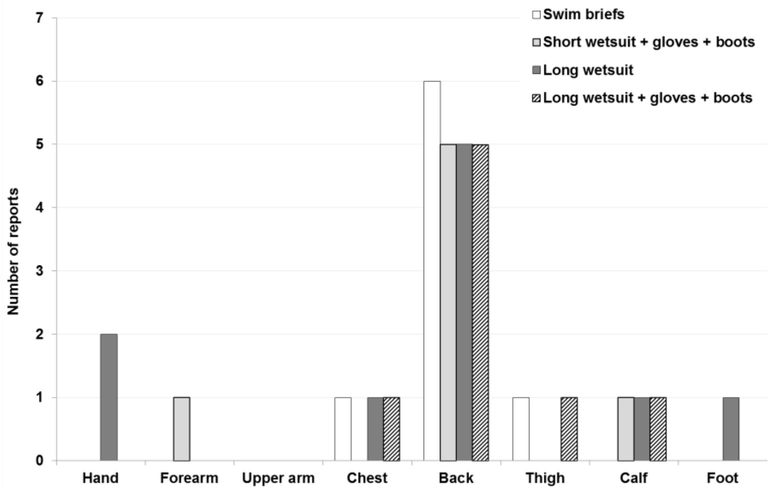


Fig. 5. Number of times when the different body regions were reported responsible for the loss of overall thermal comfort in cooling water, in four clothing conditions (*n*=8).

A correlation analysis was performed between overall and local TC votes reported during the first 30 minutes of the immersion. The highest correlation coefficients were found between the overall TC votes and the TC votes for the lower back, in most clothing conditions (Table 2). The table also reveals that across conditions, the lowest coefficients were found for the hands and feet.

Table 2. R² values of the best trend lines found between the overall and the local thermal comfort votes during the cooling stage of the immersion (*n*=8).

	Swim briefs	Short wetsuit + gloves + boots	Long wetsuit	Long wetsuit + gloves + boots	Across conditions
Back	0.96	0.86	0.88	0.97	**0.92**
Chest	0.94	0.84	0.68	0.87	**0.83**
Forearm	0.85	0.85	0.83	0.76	**0.82**
Thigh	0.85	0.84	0.67	0.72	**0.77**
Upper arm	0.91	0.67	0.54	0.91	**0.76**
Calf	0.82	0.75	0.72	0.66	**0.74**
Hand	0.82	0.57	0.85	0.63	**0.71**
Foot	0.83	0.55	0.90	0.53	**0.70**

Thermal comfort during the stable cold stage (T_W at 19.5 °C)

Overall TC scores reported at the 35th, 40th, and 45th minute of immersion were averaged. The mean (SD) comfort vote after prolonged immersion in 19.5 °C water was significantly higher in the *Long wetsuit+gloves+boots* condition (2.28 [1.71]) than that in the *Long wetsuit* condition (1.62 [1.38]), *P*=0.038. The overall thermal comfort profiles are presented in Figure 6, and reveal that high levels of discomfort were rapidly reached in cold water.

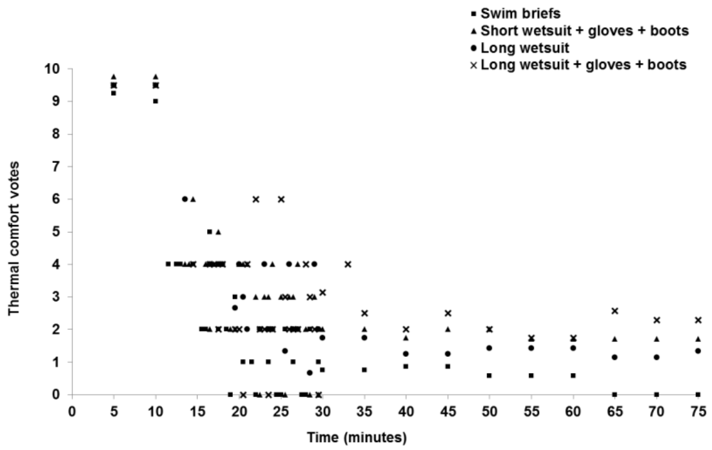


Fig. 6. Mean overall thermal comfort during imersion, in four clothing conditions (*n*=8 initially). Note: 0 = Very uncomfortable, 10 = Very comfortable.

Phase 2 - Thermal comfort of humans exercising in cool water

General observations

Figure 7 and Figure 8 show T_{msk} and local T_{sk} during immersions. The mean T_{re} are presented in Figure 9. The same patterns as for *Phase One* were observed.

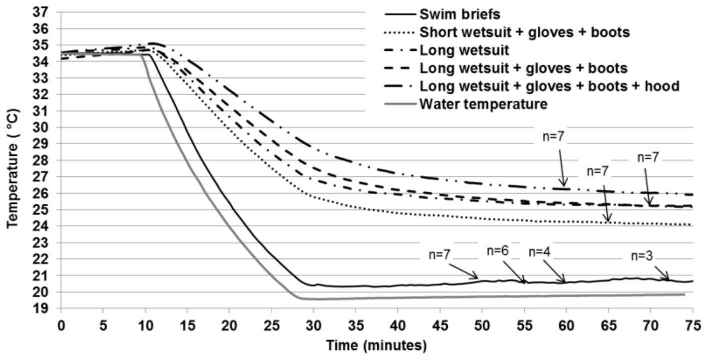


Fig. 7. Average T_{msk} of volunteers exercising in water with different levels of protection (*n*=8 up to the 50th minute).

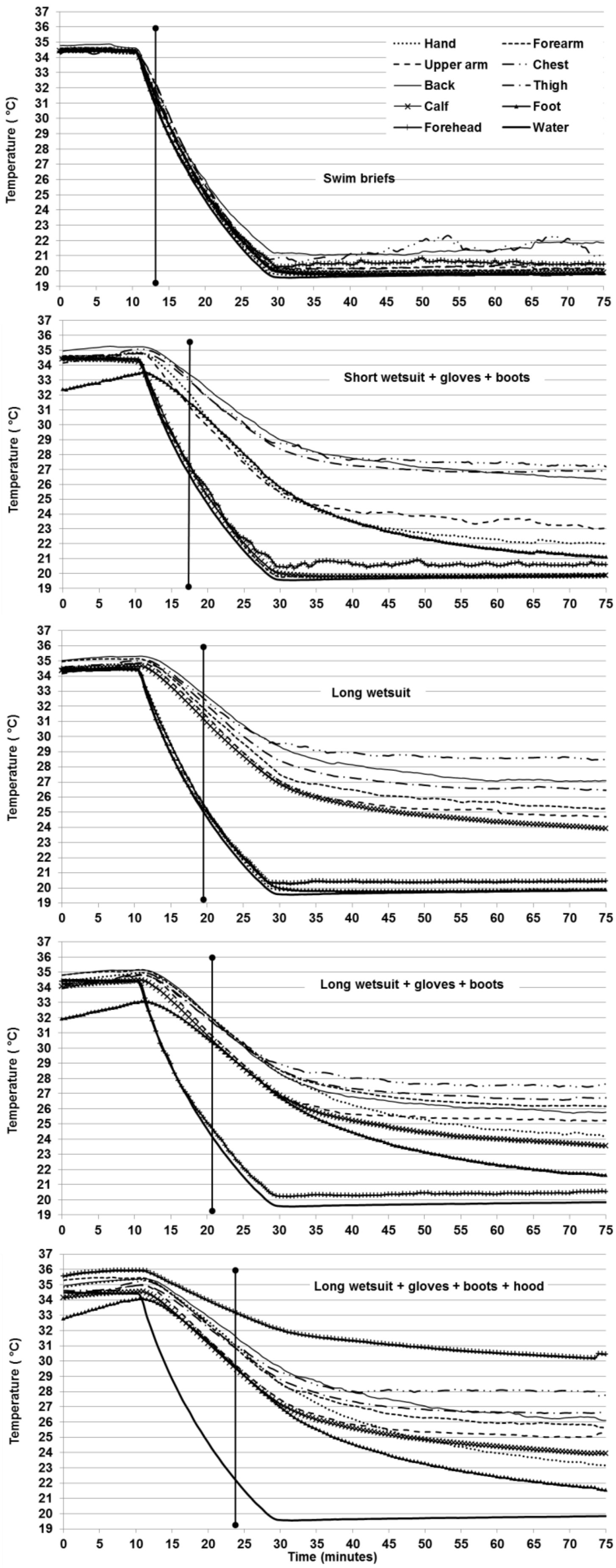

Hand
Forearm
Upper arm
Chest
Back
Thigh
Calf
Foot
Forehead
Water
Swim briefs
Short wetsuit + gloves + boots
Long wetsuit
Long wetsuit + gloves + boots
Long wetsuit + gloves + boots + hood
Temperature (°C)
Time (minutes)

Fig. 8. Average local skin temperatures during exercising immersions in the different clothing conditions (*n*=8 initially). The vertical line indicates the average time of loss of overall thermal comfort (*n*=8).

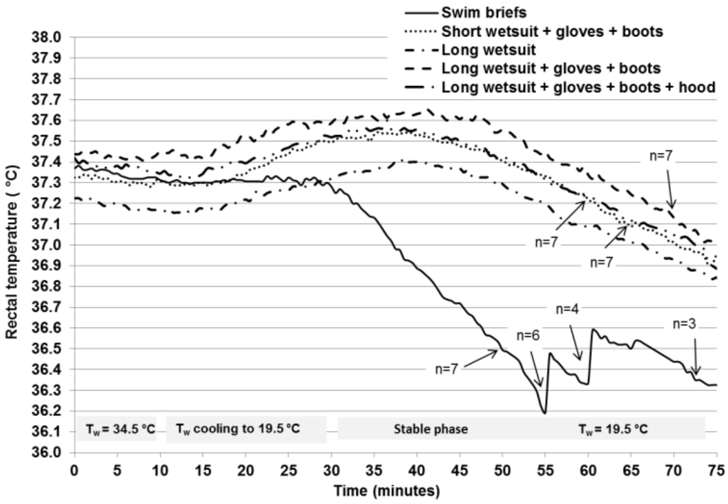


Fig. 9. Mean rectal temperature of volunteers exercising in water with different levels of protection (*n*=8 up to the 50th minute).

Region(s) responsible for the loss of overall thermal comfort, during exercise

Figure 10 shows that overall, the chest was reported as being responsible for the overall loss of TC most frequently. When all body parts were either exposed (*Swim briefs* condition), or protected (*Long wetsuit+gloves+boots+hood* condition), the lower back and the chest were reported more frequently than any other region. In all other conditions, the forehead was reported responsible for the loss of TC most frequently. Contrarily, hands, feet and calves were never reported.

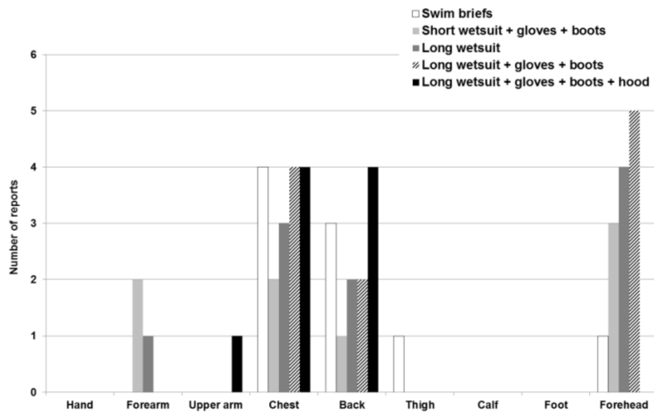


Fig. 10. Number of times when the different body regions were reported responsible for the loss of overall thermal comfort in water, in five clothing conditions (*n*=8).

During the cooling stage, the highest correlation coefficients were found between the overall TC votes and the TC votes for the lower back, and chest, in almost every clothing condition (Table 3). Conversely, the smallest correlation coefficients were found between the overall TC votes and the TC votes for the hands and feet.

Table 3. R^2 values of the best trend lines found between the overall and the local thermal comfort votes during immersion (*n*=8).

	Swim briefs	**Short wetsuit + gloves + boots**	**Long wetsuit**	**Long wetsuit + gloves + boots**	**Long wetsuit + gloves + boots + hood**	**Across conditions**
Chest	0.91	0.83	0.75	0.84	0.82	**0.83**
Back	0.80	0.71	0.78	0.89	0.83	**0.80**
Thigh	0.77	0.79	0.62	0.59	0.75	**0.70**
Upper arm	0.81	0.52	0.48	0.53	0.75	**0.62**
Forearm	0.54	0.62	0.61	0.44	0.73	**0.59**
Calf	0.51	0.63	0.58	0.44	0.69	**0.57**
Forehead	0.52	0.55	0.7	0.41	0.54	**0.54**
Hand	0.49	0.51	0.55	0.40	0.59	**0.51**
Foot	0.48	0.53	0.59	0.38	0.56	**0.51**

Thermal comfort during the stable cold stage (T_w=19.5 °C)

15 minutes into the stable cold stage (T_w=19.5 °C), mean (SD) overall TC in the *Long wetsuit+gloves+boots+hood* (4.75 [1.49]) was significantly greater than in the same condition without a hood (2.75 [1.49]), *P*=0.043, in the *Long wetsuit* condition (2.5 [0.92]), *P*=0.01, and in the *Short wetsuit+gloves+boots* condition (2 [0]), *P*=0.007 (*n*=8). No other significant difference was observed.

Phase Three - Skin temperature distribution in thermoneutral air environments

Volunteers remained thermally comfortable throughout the exposures. Tables 4 and 5 show the skin temperature distributions in thermoneutral air environments after one hour resting in air at 21 °C with light clothes on, and 26 °C with swim briefs only.

Table 4. Individual local and T_{msk} distribution after one hour resting in air at 21 °C with light clothes on. Temperatures recorded immediately following removal of clothing. The skin temperatures were recorded with a thermal imaging camera immediately following removal of clothing.

	Volunteers							
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**Mean**	**SD**
Fingers	25.4	23.7	24.9	24.0	24.4	25.2	**24.6**	**0.7**
Forearm	33.3	30.9	30.6	31.6	32.5	32.2	**31.9**	**1.0**
Upper arm	32.0	29.7	30.1	28.6	30.4	30.6	**30.2**	**1.1**
Chest	35.2	34.7	34.0	34.1	34.0	33.8	**34.3**	**0.5**
Back	35.1	34.8	33.7	34.0	34.2	34.3	**34.4**	**0.5**
Thigh	30.6	31.6	29.4	31.5	31.1	29.7	**30.7**	**0.9**
Calf	27.9	29.2	29.3	30.4	30.6	29.9	**29.6**	**1.0**
Toes	22.4	24.1	22.2	23.1	26.9	23.5	**23.7**	**1.7**
Forehead	34.6	34.9	33.8	33.9	33.6	33.9	**34.1**	**0.5**
Mean skin temperature	**31.6**	**31.5**	**30.7**	**31.3**	**31.7**	**31.1**	**31.3**	**0.4**

Table 5. Individual local and T_{msk} distribution after one hour resting in air at 26 °C with minimal clothing (swim briefs).

	Volunteers							
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**Mean**	**SD**
Fingers	30.6	26.4	32.7	30.0	31.8	28.6	**30.0**	**2.3**
Forearm	34.5	33.5	34.2	33.7	34.0	33.0	**33.8**	**0.5**
Upper arm	32.4	31.9	33.0	32.1	33.0	31.7	**32.4**	**0.6**
Chest	35.1	35.0	35.0	34.9	34.8	34.5	**34.9**	**0.2**
Back	34.1	35.0	34.7	34.6	34.4	34.5	**34.6**	**0.3**
Thigh	33.2	33.4	33.7	33.3	33.2	32.1	**33.2**	**0.5**
Calf	31.0	32.1	33.0	32.9	32.6	31.4	**32.2**	**0.8**
Toe	26.9	24.6	30.3	25.6	30.8	25.0	**27.2**	**2.7**
Forehead	36.2	36.0	35.6	36.1	35.5	35.2	**35.8**	**0.4**
Mean skin temperature	**33.1**	**32.9**	**33.8**	**33.2**	**33.6**	**32.4**	**33.2**	**0.5**

Table 6 shows the average between T_{sk} recorded after one hour resting in air at 21 °C with light clothes on, and those recorded in 26 °C with swim briefs only.

Table 6. Individual local and T_{msk} distribution after one hour resting in thermoneutral air environments. The figures are the average between T_{sk} recorded in air at 21 °C with light clothes on, and those recorded in 26 °C with swim briefs only. The skin temperatures were recorded with a thermal imaging camera immediately following removal of clothing.

	Volunteers							
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**Mean**	**SD**
Fingers	28.0	25.1	28.8	27.0	28.1	26.9	**27.3**	**1.3**
Forearm	33.9	32.2	32.4	32.7	33.3	32.6	**32.8**	**0.6**
Upper arm	32.2	30.8	31.6	30.4	31.7	31.2	**31.3**	**0.7**
Chest	35.2	34.9	34.5	34.5	34.4	34.2	**34.6**	**0.4**
Back	34.6	34.9	34.2	34.3	34.3	34.4	**34.5**	**0.3**
Thigh	31.9	32.5	31.6	32.4	32.2	30.9	**31.9**	**0.6**
Calf	29.5	30.7	31.2	31.7	31.6	30.7	**30.9**	**0.8**
Toes	24.7	24.4	26.3	24.4	28.9	24.3	**25.5**	**1.8**
Forehead	35.4	35.5	34.7	35.0	34.6	34.6	**34.9**	**0.4**
Mean skin temperature	**32.4**	**32.2**	**32.3**	**32.3**	**32.7**	**31.8**	**32.2**	**0.3**

Figure 11 shows the mean (SD) difference, between the T_{sk} measured when the loss of overall TC was reported in cooling water (in *Phase Two* of the study) and that measured in both 21 °C and 26 °C air (*Phase Three*).

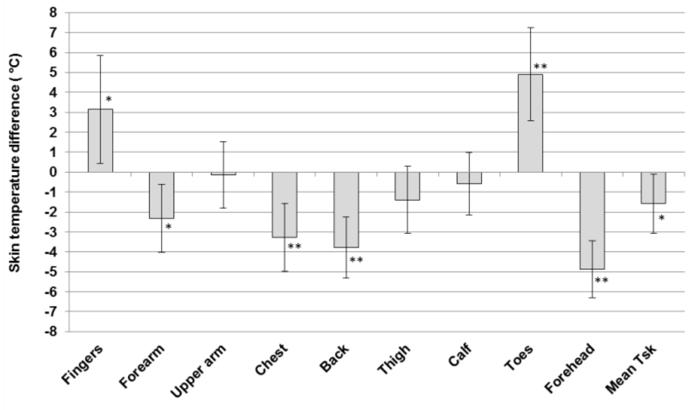


Fig. 11. Mean (SD) difference in local and mean skin temperature between the point of loss of overall TC in cooling water and after one hour at rest in thermoneutral air environments (21 °C and 26 °C air). Note: * represent significant differences within each body site, across the two situations. * $P<0.05$; ** $P<0.01$ ($n=6$).

Skin temperature on the fingers was significantly higher when overall TC was lost in water than in thermoneutral air conditions (mean (SD) difference was 3.1 [2.7] °C, $P=0.037$). T_{sk} on the toes was significantly higher when TC was lost in cooling water than in thermoneutral air (mean (SD) difference was 4.9 [2.3] °C, $P=0.004$).

In thermoneutral air environments, T_{sk} was significantly higher than at the point of loss of comfort during immersion for: the forearms (mean (SD) difference was 2.3 [1.7] °C, $P=0.021$); the chest (mean (SD) difference was 3.3 [1.7] °C, $P=0.005$); the back (mean (SD) difference was 3.8 [1.5] °C, $P=0.002$); and the forehead (mean (SD) difference was 4.9 [1.4] °C, $P<0.001$).

Similar conclusions can be drawn when comparing local T_{sk} at the point of loss of comfort during immersion to those collected in either 21 °C or 26 °C air.

DISCUSSION

The determinants of the loss of overall thermal comfort in cool water

During the cooling stage, the loss of overall TC can be attributed to the changes in T_{sk} as T_{re} had remained stable. Surprisingly, the chest and the lower back were responsible for the onset of thermal discomfort rather than the hands and feet. Supportive of this finding, correlation analyses revealed that during the cooling stage, the highest correlation coefficients were found between the overall TC votes and the TC votes for the lower back, and chest, in almost every clothing condition. Conversely, the smallest correlation coefficients were found between the overall TC votes and the TC votes for the hands and feet. As a consequence we reject our main hypothesis; that thermal discomfort during immersion in cooling water occurs due to cooling of the hands and feet.

Cooling the chest in a cold air environment has been shown to influence overall TC (Nakamura et al. 2008). Recently, it was noticed that cooling the lower back during whole-body mild cold air exposure significantly increased discomfort, whereas the hands had relatively little effect on overall TC (Nakamura et al. 2013). The reasons behind this apparent larger influence of the chest (and lower back) on TC are unclear, but in our study the greater surface area might have enhanced the impact on overall TC. In effect, it has been shown that a reduction in the cold threshold could be observed when the stimulation area is increased, and this was proposed to be due to the activation of a larger number of thermosensitive units (Defrin et al. 2009). A few studies (Zhang, 2003; Arens et al. 2006) have reported the importance of a single or a couple of body sites for general TC, and overall, these findings are in good agreement with our observations. However, the mechanisms behind these findings have remained unexplored. The third phase of the present study provided, for the first time, a possible explanation for the impact of some body regions on overall TC.

Possible mechanisms determining the loss of thermal comfort in cool water

During immersion, when TC was lost wearing swim briefs, local T_{sk} on the chest and lower back were close to that on hands and feet. Therefore, the perceived responsibility of the chest for the loss of TC cannot be directly explained by absolute temperature. From our findings in *Phase One* and *Two*, we proposed that when the T_w reached levels at which the hands and feet had been shown to be the main source of discomfort in cool/cold air (Zhang, 2003), T_{sk} on the chest and lower back were already well below comfort thresholds (Figure 8). An assessment of the “reference” T_{sk} distribution in thermoneutral air indicated that the extremities were warmer when the loss of overall TC was reported during immersion than when volunteers were in thermoneutral and comfortable air. We therefore accept our second hypothesis: the regions where body temperature remains above the “reference” thermoneutral temperature in air will not be the ones reported as the cause of loss of comfort in cooling water. This finding is in apparent contradiction with Zhang (2003). However, in the cold air conditions of their study, the extremities would have demonstrated more intense vasoconstriction than other body regions and, as a consequence, they were the coldest body parts, and were below adapting temperatures in thermoneutral air. Indeed, during their experiments, 23.1 °C and 21.4 °C were recorded for hands and feet, respectively. In *Phase Two* of our study, when overall thermal comfort was lost during immersion in cooling water, the skin temperature on the extremities was above 30 °C, which was, on average, 3 °C and 5 °C (for hands, and feet) higher than in comfortable air conditions. In Zhang’s study, colder skin temperatures in these regions when compared to thermoneutral air environments would have increased the frequency of discharge of the cold sensitive fibres to higher levels than those observed at adapting temperatures. This could explain why the extremities were an important source of discomfort in air, whereas they were not responsible for the loss of overall thermal comfort in cool water during our study. Thus, our findings are specific to immersion, when skin temperatures are clamped and made much more uniform. In contrast with the extremities, the chest, and back strongly influenced overall thermal comfort. This differs from the reports from Zhang (2003) where in cold air neither the back, nor the chest was the source of discomfort. This would have been due to an insufficient stimulation of these regions in comparison to that of others, as the skin temperature on the lower back, for example, was around 32.4 °C in the air environments of Zhang's study. Consequently, their relative influence on overall thermal comfort was limited. However, when cold air was alternatively supplied to separate body regions in the studies of Zhang, the back had the greatest influence on overall thermal comfort, which supports our observations. Similarly, it was shown (Stevens, 1979) that cooling the skin of the lower back only (when other regions were maintained at thermoneutral temperature) from 34.4 °C to 30 °C, yielded a greater cold sensation than when the same stimulus was applied to any other body part. More recent reports also support our findings (Ouzzahra et al. 2012; Nakamura et al. 2013), although the cold stimuli (20 °C to 22 °C stimulators) were greater than in our study, when TC was lost. In cooling water the strong local stimulus on the chest and the lower back would have triggered a higher cold receptor discharge frequency, ultimately leading to cold sensation and discomfort. We therefore suggest that the regions where T_{sk} remains above the "reference" thermoneutral temperature in air, will not determine the onset of thermal discomfort in cooling water, mainly because the stimulation of these regions will not cause a sufficient increase in the frequency of discharge of the cold cutaneous thermoreceptors. Another possible explanation could lie in the processing of the thermal input, and may thus occur in more central regions as it is the case for cold habituation (Tipton et al. 1998).

The influence of the extremities became important during the later period of the resting immersions in cold water (below 20 °C); their temperatures were then below adapting temperatures in thermoneutral air. Although at that point volunteers were already uncomfortable, exposing hands and feet significantly influenced the subjective responses and added more thermal discomfort to the overall state. During the cold phase of our study, local skin temperatures of around 21 °C on these regions may have constituted a more "specific" stimulus than that in the warmer temperature of the cooling phase. It seems reasonable to suggest that in the present work, the cold sensitivity of the extremities was greater at this lower range of temperature (below 20 °C), compared to that in the cooling phase, because unprotected hands and feet will have been colder than what they are "naturally" in air. It is also possible that cooling may have affected deeper tissues in the hands and feet than it did in the more massive regions. In addition, it has been observed that minimal blood flow and maximum pain may occur at the same time (Wolf and Hardy, 1941), and that "deep" cold pain could be observed at temperatures approximating 20 °C (Fruhstorfer and Lindblom, 1983). In our study, intense vasoconstriction in the extremities may have caused ischaemic pain, participating to the overall discomfort. The influence of the extremities on overall TC in cold water was not observed during the exercising immersions; we therefore suspect that non-thermal factors could have been involved during exercise. These may include hormonal mechanisms or distraction effects related to the exercise. In addition, it was shown that the transmission of cutaneous information to the central nervous system could be reduced by voluntary movements, probably due to inhibitory mechanisms on the synaptic system (Ghez and Lenzi, 1971). It is therefore possible that the activation of mechanoreceptors during exercise partially suppressed the input of cold receptors to the somatosensory cortex. Finally, in the exercising immersions the head was also partially exposed, which may have reduced the influence of the hands on overall TC. Nonetheless, it should be remembered that the conditions experienced during water-sports can often be much colder (water temperature below 15 °C) than those of the present work. In such situations, the extremities may account for most of the discomfort, especially when the temperature reaches painful levels (Geng et al. 2006).

PERSPECTIVES

The present work investigated the determinants of thermal discomfort during immersion in cool water in humans. It is concluded that in cooling water, or when the skin is more uniform in temperature and cools slowly from a warm stating point, the chest and the lower back rather than the extremities are responsible for the loss of overall thermal comfort. During such cooling, the absolute skin temperatures causing the loss of thermal comfort are best interpreted in the context of the distribution of skin temperature in thermoneutral air. In these situations, hands and feet are already adapted to colder air temperatures whilst the chest and lower back cool by more than normal. This manuscript reports for the first time some of the physiological mechanisms that drive the onset of thermal discomfort. This should have an impact on future research, as it may help understand variations in thermal comfort responses to stimuli across the body. Also, our findings should influence the design of clothing for water sports: the chest and the lower back may need additional insulation to maintain thermal comfort, whereas hands and feet could only require protection in colder conditions.

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