Fashion and Textiles

RESEARCH

Open Access

Relationships between morphological factors and heat extraction from the upper arm using liquid cooling garment

Maria Stenkina[1], Ga-Young Lim[1], Yujean Ghim[1], Hyun-Soo Kim[2] and Joo-Young Lee[1,3,4*]

*Correspondence:
leex3140@snu.ac.kr

[1] Department of Fashion and Textiles, College of Human Ecology, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Korea
[2] Department of Physical Education, Seoul National University, Seoul, Korea
[3] Research Institute for Human Ecology, Seoul National University, Seoul, Korea
[4] Graphene Research Center for Convergence Technology, Advanced Institute of Convergence Technology, Suwon, Korea

Abstract

Astronauts wear liquid perfused garments inside their outer spacesuits for regulating body temperature. The present study explored relationships between local heat production from the upper arm and body morphology while wearing liquid perfused sleeve. Heat extraction from the upper arm of 19 subjects (8 males and 11 females) during three different exercise modes (running at 6–8 km·h^{-1}, cycling at 40–55 W, and arm ergometer at 10–20 W) and rest has been investigated. The total body fat (27.5 ± 7.2%), body mass index (24.4 ± 2.7 kg·m^{-2}), arm surface area (589 ± 90 cm^2), and arm volume (1300 ± 300 mL) were considered as covariates. Subjects wore a liquid perfused sleeve over the upper arm (left) with the water inlet temperature of 24.0 ± 0.3 °C and the heat extraction was calculated using the water flow rate and temperature differences. Heat extraction from the upper arm showed no significant differences among the three exercises. During cycling, there was a negative relationship between heat extraction and total body fat (r = − 0.527, $P < 0.05$). Heat extraction was more related to the arm volume ($P < 0.05$) than the surface area of the upper arm, which was significant only for the male group in the cycling mode. For the female group, heat extraction was related to upper arm temperature in the cycling and arm exercise modes (for both exercises $P < 0.05$). These results can be applied to improve liquid cooling garments for astronauts, considering their body morphology and sex.

Keywords: Liquid cooling garment, Space suit, Heat extraction, Arm volume, Surface area, Total body fat

Introduction

Among the various factors that determine body temperature, air temperature, air humidity, air flow, radiation, clothing insulation, and activity are considered as six main factors (Parsons, 2014). The effects of these six factors are modified by individual morphological characteristics, such as body size, body shape, or body composition. Heat extraction from the body differs across body regions, due to the specific characteristics of each body region. Body regions with greater muscle and adipose tissue were characterized by greater individual differences in heat flow, while similarity of heat flow in body zones with a greater proportion of bones was found (Koscheyev et al., 2007). Individuals who possess higher levels of adipose tissue necessitate less metabolic heat production to uphold core temperatures (Anderson, 1999). As a significant amount of heat produced by the contracting muscles is liberated from the skin of the exercising limbs during exercise to its environment (González-Alonso, 2012; Longman et al., 2021), morphologies of the limbs could be a significant factor for body temperature regulation.

Variation in human stature and limb proportions is widely accepted to reflect thermal adaptation. According to Bergmann's and Allen's rules (Longman et al., 2019), the large body size is associated with a large heat-producing mass relative to the heat-losing surface area, what was confirmed by a number of studies (Foster & Collard, 2013; Holliday, 1997a, 1997b; Tilkens et al., 2007); (Trinkaus, 1981). Longman et al. (2019) examined Bergmann's and Allen's rules through the multi-day ultra-marathons in hot and cold environments and found that finishers of hot-condition events had significantly longer limbs than finishers of cold-condition events. Furthermore, hot-condition finishers had significantly longer limbs than those failing to complete hot-condition events (Longman et al., 2019).

While previous studies have highlighted the association between body size and thermal regulation in varying environmental conditions, the unique challenges posed by space environments prompt a consideration of how these adaptations might influence astronauts during extravehicular activity (EVA). During EVA, ambient temperature extremes are ranging from over 120 °C on the side of the suit facing the sun to approximately − 157 °C on the shaded side (Goodman & Radnofsky, 1965). Weightlessness disrupted heat exchange processes in the human body, leading to imbalance in thermal sensation of astronauts. Astronauts can feel thermal discomfort at a temperature of 21.5 ℃, which considered as a comfortable temperature (Novak et al., 1980; Tsaplin et al., 2018). Astronauts during planetary exploring activity alternate between periods of high physical exertion and periods of low intensity movement (Koscheyev & Leon, 2014). Worth noting that EVA is mainly related to repairing working tasks using the hands in zero gravity, where arm muscles are most involved. That is, one third of the motions during EVA are related to the upper limb (England et al., 2010). Astronauts reported that during EVA the extremities (the arms and hands) are prone to be thermally discomfort and both in EVA and training activities a high number of injuries occurred in the upper arm and shoulders (Portree & Trevino, 1997; Strauss et al., 2005).

Heating or warming the most efficient body region in heat transfer may not only prevent thermal stress but also reduce the bulkiness of the spacesuit, while providing the same thermal comfort (Ferl et al., 2008; Koscheyev et al., 2006). For this purpose, liquid cooling and warming garment (LCWG) is mainly used for space exploration, which is a liquid perfused garment with an inserted tube system for water circulation provide (Chappell et al., 2017; Hexamer & Werner, 1996). LCWGs for astronauts have been independently developed in the US and Russia. A notable discrepancy in design among the two LCWGs lies in the placement of tubing, as noted by Warpeha (2010). Specifically, the Russian LCWG omits tubing on the forearms and calves, whereas the US LCWG incorporates tubing across the entire body, including the forearms and calves. The Russian LCWG emphasizes strategic tubing placement on major skeletal muscle groups, particularly on the upper arms (Warpeha, 2010). This design strategy reflects an intention to achieve comparable cooling or warming effects with reduced tubing, which is advantageous for missions to Mars where the weight of spacesuits is a critical consideration, distinct from lunar exploration or EVA.

However, the physiological role of the upper arm in thermoregulation has received relatively less attention compared to other anatomical regions, such as the head, chest, back, hands, or feet. The concept of the thermal core within the human body is defined as the inner tissues whose temperatures remain relatively constant in relation to each other despite circulatory adjustments and variations in heat dissipation to the environment (IUPS, 2001). While the thermal core traditionally encompasses the trunk and head, it could extend to include the upper arms in response to heat exposure. Cooling the upper arms resulted in a reduction of body heat storage by 30% (Shvartz et al., 1974), despite the fact that the surface area of the upper arms constitutes only 8.8% of the total body surface area (Lee & Choi, 2009). Kim and Hong (2014) explored the physiological responses by heating the waist, abdomen, shoulders, or feet, and found that the shoulders were the most effective region for increasing peripheral temperature (Kim & Hong, 2014). These results are coupled with the previous study of Hirata (2017) who found that upper extremities (the upper arms, forearms, and hands) are more efficient than the torso (the chest, abdomen, back, and waist) for heat dissipation from the body when exercising in a hot and humid environment. Recently, we assessed the thermoregulatory effects of down-filled jackets with baffle structure and found that subjects reported feeling colder when the upper arms were not insulated, when compared to the conditions of the chest, stomach, or waist-not insulated (Kwon et al., 2021).

Tkachenko (1998) noticed that the warmer sections of the upper limb will be the medial surface of the shoulder as it has large vascular bundles. The importance of the upper arm in temperature regulation is related to the efficiency in dissipating body heat based on the complex composition of blood vessels, muscle, adipose tissue, and bones, along with the body surface area to volume. For these reasons, a great attention should be given to the upper arm morphology when designing not only the space suit, but also other enclosed personal protective equipment (PPE).

In spite the fact that numerous research has been done on human morphology and thermoregulation, there are very few studies which investigated relationships between heat loss from the upper arm and human morphological characteristics during various types of exercise. Therefore, we explored relationships between local heat loss from the upper arm and body morphology during various types of exercise using a liquid cooling sleeve. We hypothesized that (1) the greater volume of the upper arm the greater heat flow from the skin, and (2) local heat extraction would be related to the whole body morphology (BMI or total body fat). These results can be applied to improved LCVGs for astronauts.

Methods

Subjects and four exercise conditions

We recruited subjects so as to ensure an even distribution of body mass index (BMI) and total body fat (%BF) across the spectrum from the underweight to the overweight. Eight males (24.8 ± 1.7 y in age, 174.8 ± 6.2 cm in height, 80.1 ± 13.6 kg in weight, and 1.99 ± 0.18 m^2 in body surface area) and 11 females (23.7 ± 2.2 y in age, 161.3 ± 6.2 cm in height, 60.3 ± 6.8 kg in weight, and 1.67 ± 0.11 m^2 in body surface area) (Table 1)

Table 1 Anthropometric characteristics of the subjects

Subject	Age (y)	Height (cm)	Weight (kg)	BMI* (kg/m^2)	Total body fat (%)	Total body water (L)	Skeletal muscle mass (kg)	Left arm mass (kg)	Upper arm		
									Girth (cm)	Surface area (cm^2)	Volume (L)
**F1	23	165.3	50.3	18.4	25.3	27.5	20.3	1.65	21.6	443.6	0.77
F2	27	160.0	53.2	20.8	31.9	26.4	19.0	1.44	27.0	512.1	0.79
F3	26	163.1	57.1	21.5	35.3	27.1	19.8	1.63	28.8	605.7	1.20
F4	22	156.5	52.2	21.6	31.3	26.5	19.4	1.56	27.0	456.7	1.06
F5	22	169.4	65.9	23.0	31.4	33.1	24.2	2.00	30.0	570.3	1.30
F6	21	164.1	62.1	23.1	24.9	34.1	25.8	2.29	31.8	585.3	1.10
F7	24	167.2	66.3	23.7	34.3	32.0	23.5	1.94	31.0	635.9	1.30
F8	24	165.3	68.8	25.2	31.0	34.8	26.1	2.26	30.2	560.4	1.39
F9	27	147.6	55.5	25.5	34.3	26.5	19.7	1.64	28.2	454.5	0.73
F10	21	160.0	67.7	26.4	31.9	33.7	25.6	2.34	33.5	598.4	1.21
F11	24	155.6	64.4	26.6	38.1	29.2	21.6	1.87	32.3	648.8	1.54
Mean	23.7	161.3	60.3	23.3	31.8	30.1	22.3	1.87	29.2	551.9	1.13
SD	2.2	6.2	6.8	2.6	3.9	3.5	2.8	0.32	3.3	74.1	0.27
***M12	22	170.2	64.7	22.3	18.1	39.0	29.8	2.80	30.6	574.5	1.35
M13	27	184.0	80.1	23.7	22.1	45.6	34.4	3.25	31.8	615.7	1.66
M14	26	170.8	78.5	24.3	26.9	43.6	33.6	3.03	34.6	676.0	1.41
M15	25	173.4	73.9	24.6	10.7	48.5	37.6	4.01	34.0	623.4	1.69
M16	23	169.1	71.6	25.0	25.4	39.0	29.8	2.56	31.0	644.4	1.42
M17	26	170.7	73.4	25.2	17.9	44.2	34.5	3.30	31.0	477.2	0.89
M18	24	175.6	89.6	29.1	20.0	52.4	40.8	4.13	37.0	757.1	1.49
M19	25	184.7	108.6	29.4	31.8	56.1	43.8	4.57	40.0	742.9	1.81
Mean	24.8	174.8	80.1	25.5	21.6	46.1	35.5	3.46	33.8	638.9	1.47
SD	1.7	6.2	13.6	2.5	6.5	6.1	5.0	0.71	3.4	90.5	0.28
[a] Mean	24.2	167.0	68.7	24.2	27.5	36.8	27.9	2.54	31.1	588.6	1.27
SD	2.0	9.2	14.0	2.7	7.2	9.3	7.7	0.9	90.4	4.0	0.30

**BMI* body mass index; ***F* female; ****M* male; [a]Total average of the 19 subjects participated in the four experimental conditions: (1) rest (sitting on a chair), (2) running on a treadmill at 6–8 km·h^{-1}, (3) cycling at 40–55 W with 50 RPM, and (4) arm exercise using an arm ergometer at 10–20 W with 50 RPM. The selection of the exercise modes was based on Functional Mobility Testing conducted by the Anthropometry and Biomechanics Facility at the Lyndon Johnson Space Center of NASA. The exercise modes were varied based on heart rate (moderate exercise intensity was chosen, which corresponds to 57 ~ 63% of their maximum heart rate) in pilot tests for both male and female group. No subject had a history of cardiovascular or heat-related illnesses. All subjects were informed about the experiment and provided signed informed consent prior to their participation. The Institutional Review Board of Seoul National University approved the present study (IRB#2204/002-009). The male group exhibited significantly greater height, body weight, total body water, skeletal muscle mass, upper arm surface area, and the upper arm volume compared to the female group ($P < 0.05$), whereas there were no sex differences in age and BMI. Total body fat was greater for the female group than for the male group ($P < 0.05$, Table 1).

Experimental clothing

Subjects wore a liquid cooling sleeve, which was developed for this study, over their left-upper arm with a water inlet temperature of 24.0 ± 0.3 ℃, resulting in a thermal sensation of being slightly cool for the upper arm. To prevent excessive cold-induced vasoconstriction, which could reduce heat extraction from the skin, we selected a mild cooling temperature. To ensure proper fit, we measured the upper arm size of all the 19 subjects and tailored the cooling sleeves accordingly. Based on the individual anthropometric data, we produced the liquid cooling sleeves in four sizes (sizes: 88, 77, 66, and 55), with the size 88 being the largest (suitable for tall males) and size 55 being the smallest (suitable for small females). Each liquid cooling sleeve comprised two layers with different materials: an outer layer (polyester 92% and polyurethane 8%) and an inner layer (nylon-spandex mesh: nylon 85% and polyurethane 15%). PVC tubes (inner diameter 4 mm and outer diameter 6 mm) were inserted into the inner layer using a basic stitch pattern. For easy donning and doffing, the sleeve featured a zipper (Fig. 1A). The sleeve covered the half of the armpit area. The total length of PVC tubing within a sleeve was 657 ± 82 cm (size 55 to 88), and the water flow rate through the cooling sleeve was 3,870 ± 1,860 mL·min^{-1}.

Measurements

The following anthropometric measurements were obtained using a bioelectrical impedance analysis (InBody 970, InBody, Korea): total body fat (%BF), total body water (L), skeletal muscle mass (kg), and the left arm mass (kg). Body weight was measured three times using a human scale (F105S, Satorius, Germany, resolution 1 g) and height was determined using a stadiometer. The girth of the upper arm (left) was measured using a measurement tape by an identical experimenter. The surface area of the upper arm (left) was measured according to the alginate method which was developed by Lee et al. (Lee et al., 2008). The volume of the upper arm was determined using an arm volumeter (Arm set, AliMed, USA). Upper arm skin temperature (T_{sk}) was recorded every 1 min using a data logger and a thermistor sensor (LT-8A, Gram Corporation, Japan; resolution of

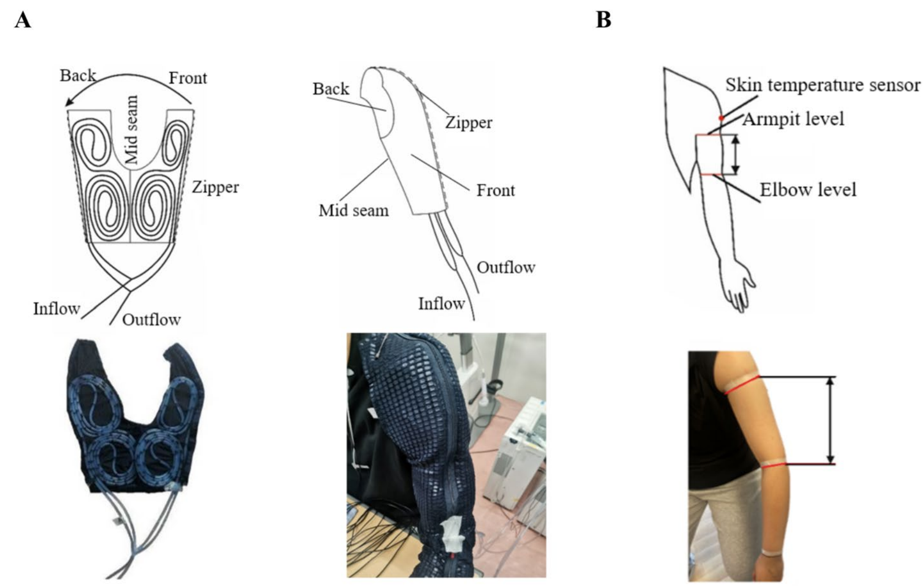

Fig.1 A liquid cooling sleeve (**A**) and marking lines on the left arm (**B**)

0.01℃). Water inlet temperature (T_{wi}) and water outlet temperature (T_{wo}) were recorded every 5 s using the same data logger and sensors. The water inlet temperature was maintained at 24.0 ± 0.3 °C using a circulating water bath (SIBATA Cool Man Pal C-332, Japan). Heat flow (HF) through the liquid sleeve was calculated using Eq. 1(Ko et al., 2020).

$$HF = W \cdot C_w \cdot (T_{wi} \cdot T_{wo}) \tag{1}$$

where,

HF: heat flow ($kcal \cdot h^{-1}$);
W: water flow rate of the sleeve ($L \cdot h^{-1}$);
C_w: specific heat of water, 1 $kcal \cdot kg^{-1} \cdot °C^{-1}$;
T_{wi}: water inlet temperature (°C);
T_{wo}: water outlet temperature (°C).
Heat flow was converted to watts (1 kcal h^{-1} = 1.163 W).

Experimental protocol

Subjects arrived at the experimental site at 7 am. We provided a light breakfast (tuna rice bowl; 204 g in total mass; 400 kcal) with a 330-ml water, and all subjects finished their breakfast within 15 min. Subjects then changed into the provided experimental clothing, which included a cotton T-shirt, long trousers (75% cotton/25% polyester), socks, and sneakers. Following this, we measured the following anthropometric parameters: height, arm girth, total body fat, upper arm volume, and upper arm surface area. Marking lines were drawn on the skin at the elbow and armpit levels of the left arm to facilitate the measurement processes including the arm volume, surface area, and arm circumferences (Fig. 1B). To measure the upper arm volume, the left arm was immersed into the volumeter until the elbow and armpit levels, and the difference between the water volume displaced by the arm volume was calculated. The surface area of the upper arm was measured from the elbow to the armpit level (Fig. 1B) using the alginate method (Lee et al., 2008).

After completing the anthropometric measurements, thermistor sensors for measuring skin temperature were attached to the designated sites on the left arm (Fig. 1B). Subjects then entered a climate chamber maintained at an air temperature of 25 °C with a relative humidity of 50% and an air velocity of below 0.15 m · s^{-1}. Immediately upon entering the climate chamber, subjects sat on a chair for 60 min (rest)(Fig. 2). The subjects started the three exercises of running on a treadmill (ECS science treadmill S-505, South Korea), cycling (Corival CPET, The Netherlands), and arm exercise using an arm ergometer (Monark 881E, Sweden) at 9 am, 2 pm, and 4 pm, respectively. Between the three modes of the exercises, the subjects had a sufficient break time of 1 to 4 h. Each exercise comprised four bouts of 10-min exercise with 5-min break, resulting in a total exercise duration of 60 min. The duration of the 10-min exercise and 5-min break was determined through pilot tests involving male and female subjects. The subjects wore the liquid cooling sleeve starting from the 8 am to 5 pm, and heat extraction from the upper arm was continuously measured.

Data analysis

All data were presented as mean and standard deviation between the subjects (mean ± SD). Repeated measures ANOVA was conducted to test differences in the heat flow among the four exercise modes. *Pearson*'s correlation coefficients between heat extraction and major morphological factors (upper arm volume, upper arm surface area, upper arm volume/upper arm surface area, etc.) were analyzed during rest, running, cycling, and arm exercise. All statistical analyses were conducted using SPSS 26.0. A significance level was set at $P < 0.05$.

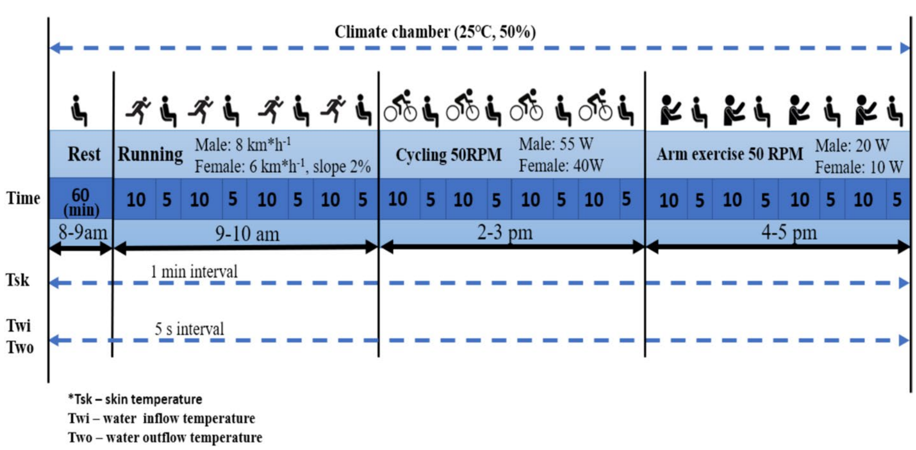

Fig. 2 Experimental protocol and measurement intervals of the present study: rest (sitting on a chair), running on a treadmill at 6–8 km·h-1, cycling at 40–55 W with 50 RPM, and arm exercise using an arm ergometer at 10–20 W with 50 RPM

Results

Relationships between morphological characteristics

Significant correlations were found between BMI and other major anthropometric parameters, such as upper arm volume and surface area except for total body fat (all *Ps* < 0.05, Fig. 3)**.** The surface area and volume of the upper arm showed positive relationships with all anthropometric parameters including height, but excluding total body fat (Table 2). In particular, a very strong relationship was observed between the upper arm surface area and volume of the upper arm (r = 0.832, $P < 0.001$). For both male and female groups, significant relationships between the surface area or volume of the upper arm and other parameters were found (all *P*s < 0.05).

Heat extraction from the upper arm during rest and exercise

There were no significant differences in heat extraction between the four experimental phases, showing that the values were 36.9 ± 22.5, 42.1 ± 24.3, 37.9 ± 20.5, and 35.8 ± 21.7 W during rest, running, cycling, and arm exercise, respectively. Correlation coefficients were calculated between heat extraction in the four phases (rest, running, cycling, and arm exercise) and the following morphological parameters: height, body weight, BMI, total body fat, total body water, skeletal muscle mass, left arm mass, and arm girth. Among all the calculations, only the relationship between heat extraction and total body fat during cycling was statistically significant (r = -0.527, $P = 0.02$). That is, heat extraction from the upper arm during cycling was greater for subjects who have smaller total body fat (Fig. 4A, Table 3). The total skeletal muscle mass was positively related to the heat extraction from the upper arm, but the relationship was not significant (r = 0.215 and $P = 0.376$ at rest; r = 0.218 and $P = 0.369$ during running; r = 0.379 and $P = 0.11$ during cycling; r = 0.33 and during exercise $P = 0.186$).

The heat extraction was greater for the male group when compared to the female group. For the male group, heat extraction was 45.1 ± 17.5 W (rest), 51.3 ± 23.6 W (running), 51.2 ± 14.8 W (cycling), and 48.8 ± 20.0 W (arm exercise), while the female group showed 32.2 ± 24.9 W (rest), 35.5 ± 23.7 W (running), 28.4 ± 19.0 W (cycling), and 26.4 ± 18.3 (arm exercise) (between male and female group: $P = 0.137$ at rest, $P = 0.019$ during running, $P = 0.021$ during cycling, and $P = 0.032$ during arm exercise).

The male group did not show any correlations between heat extraction and upper arm skin temperature, whereas there was a negative relationship between heat extraction

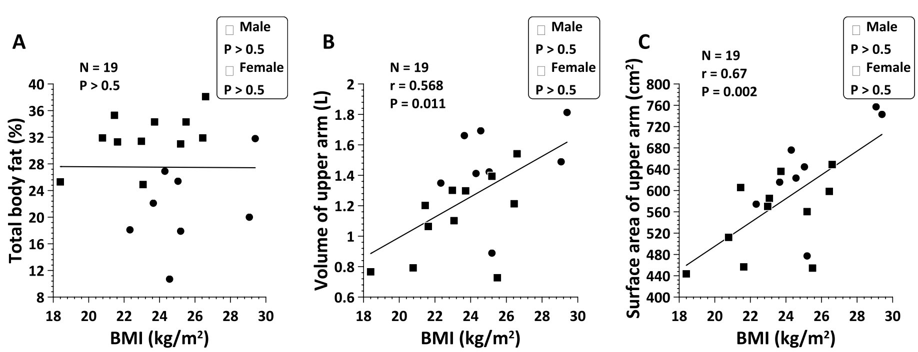

Fig. 3 Relationships between body mass index (BMI) and total body fat (**A**), upper arm volume (**B**), or upper arm surface area (**C**)

Table 2 Correlation coefficients between the surface area or volume of the upper arm and other morphological parameters

	Height (cm)	Body weight (kg)	BMI	BF (%)	BW (L)	SMM (kg)	AM (kg)	Upper arm		
								Girth (cm)	Volume (L)	Surface area (cm^2)
Surface area of UA (cm^2)	0.592**	0.785***	0.670**	− 0.07	0.677**	0.668**	0.652**	0.856**	0.832***	
Volume of UA (L)	0.676**	0.752***	0.568*	− 0.20	0.697**	0.681**	0.681**	0.766***		0.832***

UA_Upper arm; BMI_Body mass index; BF_Total body fat; BW_Total body water; SMM_Skeletal muscle mass; AM_Left arm mass; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$

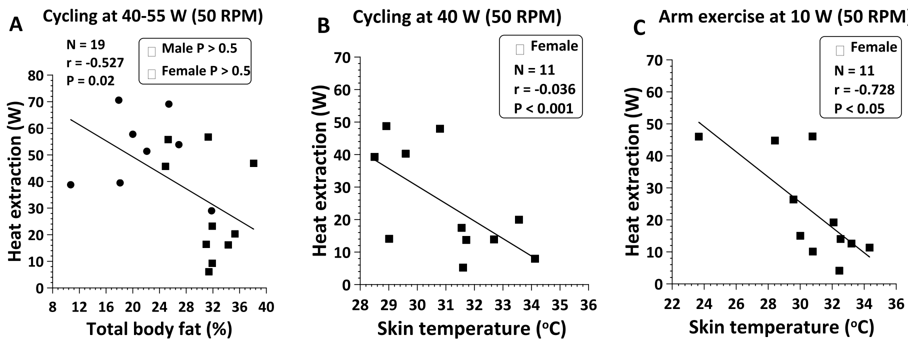

Fig. 4 Relationships between heat extraction and total body fat during cycling (**A**), female upper arm temperature during cycling (**B**), female upper arm temperature during arm exercise (**C**)

Table 3 Correlation coefficients between heat extraction from the upper arm and the surface area or volume of the upper arm during rest, running, cycling, and arm exercise

	Exercise mode	Surface area of upper arm (cm^2)	Volume of upper arm (L)
Heat extraction for all subjects (W) (N = 19)	Rest	− 0.049	0.091
	Running	0.023	0.041
	Cycling	0.064	0.098
	Arm exercise	0.110	− 0.010
Heat extraction for males (W) (n = 8)	Rest	− 0.145	− 0.402
	Running	0.015	− 0.416
	Cycling	− 0.377	− **0.719***
	Arm exercise	− 0.353	− 0.689
Heat extraction for females (W) (n = 11)	Rest	− 0.289	0.083
	Running	− 0.321	0.007
	Cycling	− 0.252	− 0.065
	Arm exercise	− 0.306	− 0.181

*$P < 0.05$

and the upper arm skin temperature for the female group, especially during cycling ($P = 0.036$, Fig. 4B) and arm exercise ($P = 0.011$, Fig. 4C). That is, the lower skin temperature represented the greater heat extraction from the upper arm.

Correlation coefficients were obtained between heat extraction in the four activity phases (rest, running, cycling, and arm exercise) and the following two morphological parameters: surface area and volume of the upper arm (Table 3). The heat extraction from the upper arm was related to the volume of the upper arm rather than the surface area during cycling for males ($r = -0.719$, $P < 0.05$). That is, the greater heat extraction was found from the male subjects who had smaller volume of the upper arm during cycling.

Skin temperature on the upper arm

The skin temperature of the upper arm was approximately 0.7 ~ 1.4 °C (on average) higher for the male group (32.9 ± 1.5 °C, 33.9 ± 1.2 °C, 32.7 ± 1.5 °C, and 32.7 ± 2.5 °C for the rest, running, cycling, and arm exercise phases, respectively) when compared to the female group for all the four exercise phases (32.2 ± 1.7 °C, 32.6 ± 1.8 °C, 31.3 ± 1.8 °C, and 31.4 ± 1.8 °C). However, the group differences were not significant due to the great standard deviations, although the significance level was 0.091 for the cycling condition (Fig. 5). Among the three exercise modes, the upper arm temperature for the male group remained mostly stable during cycling, and showed the highest value for the running condition. A noticeable circadian rhythm in the upper arm temperature was not observed (Fig. 5). The upper arm skin temperature did not exhibit any relationship to BMI, total body fat (%BF), surface area of the upper arm, volume of the upper arm, or the surface area to the volume of the upper arm for all the four conditions.

Discussion

In order to explore the relevancy of morphological factors to heat extraction, we recruited a total of 19 subjects so that the BMI and total body fat (%) were evenly distributed from the underweight to overweight (BMI 18 ~ 29 kg/m^2; Body fat 11 ~ 38%BF). The original findings of the present study were that the heat extraction from the upper arm during exercise was related to morphological parameters, especially total body fat (%BF) and volume of the upper arm, rather than the arm surface area. Hypotheses 1 was not supported. That is, the heat extraction from the upper arm was smaller for subjects who have greater total body fat (overweight or obese individuals) and greater volume of the upper arm, which supports hypothesis 2. However, the relationships were mostly significant for males during cycling, while heat extraction for the female group had a significant relationship with the upper arm temperature. Our finding from the upper arm is consistent to Mekjavic et al. (1987) reporting that the level of mean heat flow from the body decreases with increasing the subcutaneous fat.

The greater total body fat, the smaller heat extraction from the upper arm

The present findings indicated that local heat loss from the upper arm can be estimated to some extent from the overall body characteristics. The greater the total fat mass, the greater the amount of subcutaneous fat in the upper arm region, and the lower thermal conductivity of the subcutaneous fat layer compared to muscle would reduce the

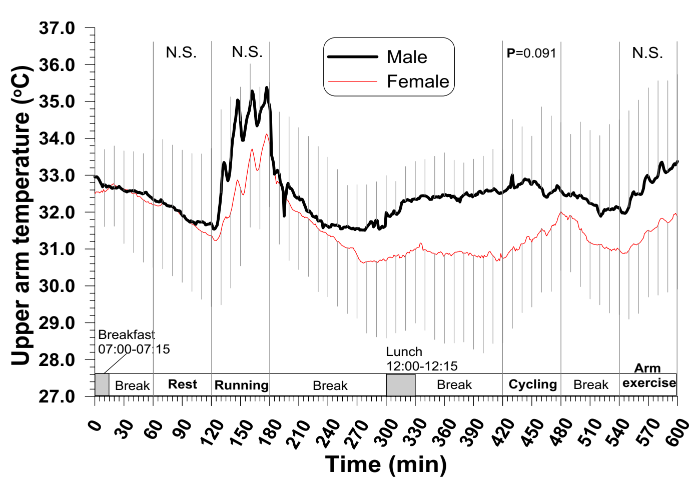

Fig. 5 Time courses of upper arm skin temperature for the male and female groups during rest, running, cycling, and arm exercise (8 males and 11 females)

efficiency of heat transfer by convection and conduction during skin blood circulation (Koscheyev et al., 2007; Melnikov, 2006). This can explain the decrease in the amount of heat extraction in the upper arm of the overweight or obese individuals. It can be predicted that the lower the total fat mass, the larger the muscle mass in the upper arm, and more heat must be generated from the muscle during exercise, which can explain the greater amount of heat lost in the upper arm.

However, the present results showed that this depends on sex and the exercise type. Arms act as important avenues for vascular heat loss from the central circulation during leg exercise (Hirata et al., 1989). The significant correlation observed exclusively during cycling exercise may be attributed to the nature of this activity. Unlike running on the treadmill or performing arm exercises, cycling involves isometric exercise where individuals hold the handle with both hands without continuous movement. It is thought that heat from the upper arm skin during cycling is more stably absorbed by the cold water flowing through the tubing inside the liquid circulation sleeve because there was less forced convection generated by arm or trunk movements. Furthermore, one can presume that the correlation being identified solely in males, and not in females, may be attributed to the larger range of upper arm volume and skeletal muscle mass in males (0.89 ~ 1.81 L and 29.8 ~ 43.8 kg) than for females (0.73 ~ 1.54 L and 19.0 ~ 26.1 kg). This assertion finds support in other research findings, which indicate that the efficiency of heat dissipation from muscles is greater in males compared to females (Fernández-Peña et al., 2023; Wang et al., 2023).

Physiological and practical significance of the upper arm in cooling/warming garments

Anatomically, the upper arm is the part that connects the torso and the arm, and has well-developed muscles compared to the forearm. The heat exchange efficiency will be high as the part that contributes to the amount of heat dissipation of astronauts who mainly work with both arms during EVA. We propose that, when wearing a full-body liquid cooling suit inside the spacesuit, tubing on the upper arm is preferred over tubing on the forearm in terms not only regional heat transfer efficiency, but also mobility. According to previous studies, upper arm warming when exposed to cold can alleviate the peripheral temperature decline. Cho (2023) investigated optimal combination of heating regions of upper body (the chest and back vs. back and upper arm) using liquid-perfused shirt for workers in a cold environment. The combination of heating the upper back and upper arm was not only effective in maintaining mean skin temperature, forearm and hand skin temperature, but also leads reducing the sense of shivering. Taguchi et al. (2004) estimated heat transfer, regional heat distribution, and core rewarming of a circulating-water garment (Roh et al., 2023). According to the results, the regional body heating including the upper arm can increased whole body heat content as well as the peripheral tissue heat content (Taguchi et al., 2004). Moreover, a substantial peripheral-to-core tissue temperature gradient indicated that peripheral tissues insulated the core, which makes heat transfer slow.

Conclusions

The present study explored the importance of morphological factors in temperature regulation and heat exchange, focusing on the upper arm using liquid cooling garments. We concluded that heat extraction from the upper arm was more related to the arm volume or skin temperature rather than the surface area of the upper arm, with the significance varying by exercise mode and sex. However, because all the three types of exercises were conducted on the same day, the results might be affected by the circadian rhythm in body temperature. In addition, local body fat mass was not measured, but total body fat (%) was estimated. We applied moderate intensity of exercise in neutral ambient conditions, but more clear relationships may be obtained during heavy exercise in hot environments. Even though those limitations in experimental setting, it is significant that the volume of the upper arm and total body fat (%) was related to the heat extraction from the upper arm during exercise. The results can be verified through further studies with more extensive exercise in different environmental conditions, including weightlessness environments.

Abbreviations

AM	Left arm mass
BMI	Body mass index
BW	Total body water
EVA	Extravehicular activity
LCG	Liquid cooling garment
LCVG	Liquid cooling and ventilating garment
MACS-Delphi	Minnesota advanced cooling suit
NASA	National aeronautics and space administration
PPE	Personal protective equipment
RPM	Revolutions per minute
SMM	Skeletal muscle mass
BF	Total body fat
PVC	Polyvinyl chloride
HE	Heat extraction
UA	Upper arm (left)

Acknowledgements
We would like to express our thanks to Yoon-Jeong Hur and Hoyeon Jeong for their technical assistance, and to Andrew Gorski for proofreading the English.

Author contributions
Maria Stenkina and Joo-Young Lee developed the study concept and were involved in the design of the study. Maria Stenkina, Ga-Young Lim, Yujean Kim, and Hyun-Soo Kim conducted experiments and data analyses along with the subject recruitment. Maria Stenkina and Joo-Young Lee prepared the 1st draft, and all authors went through the draft and approved the final manuscript.

Funding
This research was supported by the Basic Research Program through the National Research Foundation of Korea (NRF) funded by the MIST (2022R1A4A503404611).

Availability of data and materials
The data is available for requesting from reviewers.

Declarations

Ethics approval and consent to particiapte
This research was conducted under the approval and supervision of Seoul National University Institutional Review Board (IRB Approval No: #2204/002-009) regarding ethical issues including consent to participate.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Received: 23 December 2023 Accepted: 22 July 2024
Published online: 26 September 2024

References

Anderson, G. S. (1999). Human morphology and temperature regulation. *International Journal of Biometeorology, 43*, 99–109. https://doi.org/10.1007/s004840050123

Chappell, S. P., Norcross, J. R., Abercromby, A. F., Bekdash, O. S., Benson, E. A., Jarvis, S. L., Conkin, J., Gernhardt, M. L., House, N., & Jadwick, J. (2017). Evidence Report: Risk of injury and compromised performance due to EVA operations (Report No. 20220004017). Johnson Space Center.

Cho, Y.S. (2023). Performance evaluation of an active heating garment in a cold environment. [Master's thesis, Seoul National University]. 82SNU_SSPACE2. https://apastyle.apa.org/style-grammar-guidelines/references/examples/published-dissertation-references.

England, S. A., Benson, E. A., & Rajulu, S. L. (2010). Functional mobility testing: Quantification of functionally utilized mobility among Unsuited and Suited Subjects (Report No. 2010-216122). National Aeronautics and Space Administration.

Ferl, J., Hewes, L., Aitchison, L., Koscheyev, V., Leon, G., Hodgson, E., & Sneeringer, F. (2008). Trade study of an exploration cooling garment. SAE Technical Paper. #2008-01-1994. https://doi.org/10.4271/2008-01-1994

Fernández-Peña, C., Reimúndez, A., Viana, F., Arce, V. M., & Señarís, R. (2023). Sex differences in thermoregulation in mammals: Implications for energy homeostasis. *Frontiers in Endocrinology, 14*, 1093376. https://doi.org/10.3389/fendo.2023.1093376

Foster, F., & Collard, M. (2013). A reassessment of Bergmann's rule in modern humans. *PLoS ONE, 8*(8), e72269. https://doi.org/10.1371/journal.pone.0072269

González-Alonso, J. (2012). Human thermoregulation and the cardiovascular system. *Experimental Physiology, 97*(3), 340–346. https://doi.org/10.1113/expphysiol.2011.058701

Goodman, J. R., & Radnofsky, M. I. (1965). Lunar surface and free space hazards relating to space suit design (Report No. 19650044278). National Aeronautics and Space Administration.

Hexamer, M., & Werner, J. (1996). Control of liquid cooling garments: Technical control of body heat storage. *Applied Human Science, 15*(4), 177–185. https://doi.org/10.2114/jpa.15.177

Hirata, K. (2017). Heat loss from the upper extremities and clothing thermal comfort. *Journal of Textile Engineering & Fashion Technology, 3*(2), 00094. https://doi.org/10.15406/jteft.2017.03.00094543

Hirata, K., Nagasaka, T., & Noda, Y. (1989). Venous return from distal regions affects heat loss from the arms and legs during exercise-induced thermal loads. *European Journal of Applied Physiology and Occupational Physiology, 58*(8), 865–872. https://doi.org/10.1007/bf02332220

Holliday, T. W. (1997a). Body proportions in Late Pleistocene Europe and modern human origins. *Journal of Human Evolution, 32*(5), 423–448. https://doi.org/10.1006/jhev.1996.0111

Holliday, T. W. (1997b). Postcranial evidence of cold adaptation in European Neandertals. *American Journal of Physical Anthropology, 104*(2), 245–258. https://doi.org/10.1002/(SICI)1096-8644(199710)104:23.0.CO;2-%23

Kim, S. Y., & Hong, K. H. (2014). Effects of local body heating and cooling on thermogram analysis of the extremity with hot pack. *Korean Journal of Human Ecology., 23*(6), 1205–1215. https://doi.org/10.5934/kjhe.2014.23.6.1205

Ko, Y., Seol, S.-H., Kang, J., & Lee, J.-Y. (2020). Adaptive changes in physiological and perceptual responses during 10-day heat acclimation training using a water-perfused suit. *Journal of Physiological Anthropology, 39*(1), 10. https://doi.org/10.1186/s40101-020-00217-x

Koscheyev, V., & Leon, G. (2014). Spacesuits: development and design for thermal comfort. In Protective Clothing (pp. 171–191). Elsevier. https://doi.org/10.1533/9781782420408.1.171

Koscheyev, V. S., Coca, A., & Leon, G. R. (2007). Overview of physiological principles to support thermal balance and comfort of astronauts in open space and on planetary surfaces. *Acta Astronautica, 60*(4–7), 479–487. https://doi.org/10.1016/j.actaastro.2006.09.028

Koscheyev, V. S., Leon, G. R., Coca, A., & Treviño, R. C. (2006). Physiological design of a space suit cooling/warming garment and thermal control as keys to improve astronaut comfort, performance, and safety. *Habitation, 11*(1), 15–25. https://doi.org/10.3727/154296606779507097

Kwon, J.-Y., Kim, S., Baek, Y.-J., & Lee, J.-Y. (2021). Comparison and evaluation of clothing insulation of newly-developed air-filled baffle jackets and down padded jackets. *Fashion & Textile Research Journal, 23*(2), 261–272. https://doi.org/10.5805/SFTI.2021.23.2.261

Lee, J.-Y., & Choi, J.-W. (2009). Estimation of regional body surface area covered by clothing. *Journal of the Human-Environment System, 12*(1), 35–45. https://doi.org/10.1618/jhes.12.35

Lee, J.-Y., Choi, J.-W., & Kim, H. (2008). Determination of body surface area and formulas to estimate body surface area using the alginate method. *Journal of Physiological Anthropology, 27*(2), 71–82. https://doi.org/10.2114/jpa2.27.71

Longman, D. P., Murray, A. M., Roberts, R., Oakley, S., Wells, J. C., & Stock, J. T. (2019). Ultra-endurance athletic performance suggests that energetics drive human morphological thermal adaptation. *Evolutionary Human Sciences, 1*, e16. https://doi.org/10.1017/ehs.2019.13

Longman, D. P., Murray, A., Roberts, R., Oakley, S., Wells, J. C., & Stock, J. T. (2021). Energetics as a driver of human morphological thermal adaptation; evidence from female ultra-endurance athletes. *Evolutionary Human Sciences, 3*, e22. https://doi.org/10.1017/ehs.2021.17

Mekjavic, I. B., Mittleman, K. D., & Kakitsuba, N. (1987). The role of shivering thermogenesis and total body insulation in core cooling rate. *Annals of Physiological Anthropology, 6*(2), 61–68. https://doi.org/10.2114/ahs1983.6.61

Melnikov, D. S. (2006). *Physiological foundations of thermoregulation in muscular work*. St. Petersburg State University of Physical Education named after P.F.

Novak, L., Prokopova, L., Genin, A., & Golov, V. (1980). Results of the" heat exchange 1" experiment performed aboard biosatellite "Cosmos-936." *Kosmicheskaia Biologiia i Aviakosmicheskaia Meditsina, 14*(6), 73–76.

Portree, D., & Trevino, R. (1997). Walking to Olympus: An EVA chronology (monographs in aerospace history series 07). National Aeronautics and Space Administration, History Office, Office of Policy and Plans.
Roh, S.-H., Baek, Y. J., Lee, H.-L., Lee, D.-S., Kang, C. H., & Lee, J.-Y. (2023). Subjective perceptions of 8, 11 and 14 C chemotherapy liquid cooled gloves and socks. *Fashion and Textiles, 10*(1), 42. https://doi.org/10.1186/s40691-023-00358-4
Shvartz, E., Aldjem, M., Ben-Mordechai, J., & Shapiro, Y. (1974). Objective approach to a design of a whole-body, water-cooled suit. *Aerospace Medicine, 45*(7), 711–715.
Strauss, S., Krog, R. L., & Feiveson, A. H. (2005). Extravehicular mobility unit training and astronaut injuries. *Aviation, Space, and Environmental Medicine*, 76(5), 711–5, 469–474.
Taguchi, A., Ratnaraj, J., Kabon, B., Sharma, N., Lenhardt, R., Sessler, D. I., & Kurz, A. (2004). Effects of a circulating-water garment and forced-air warming on body heat content and core temperature. *The Journal of the American Society of Anesthesiologists, 100*(5), 1058–1064. https://doi.org/10.1097/00000542-200405000-00005
Tilkens, M. J., Wall-Scheffler, C., Weaver, T. D., & Steudel-Numbers, K. (2007). The effects of body proportions on thermoregulation: An experimental assessment of Allen's rule. *Journal of Human Evolution, 53*(3), 286–291. https://doi.org/10.1016/j.jhevol.2007.04.005
Tsaplin, S., Bolychev, S., & Romanov, A. (2018). *Heat transfer in space*. Samara National Research University named after Academician S.P.
Wang, L., Ren, X., Zhu, X., Li, W., Yang, J., Zhang, H., Yang, J., & Yin, H. (2023). Effects of body muscle and fat on differences in thermal preference. *Building and Environment, 243*, 110643. https://doi.org/10.1016/j.buildenv.2023.110643
Warpeha, J. M. (2010). Testing and evaluation of three liquid cooling garments for use during spaceflight. University of Minnesota [Doctoral dissertation, University of Minnesota]. University Digital Conservancy.

Publisher's Note