Climate and Clothing

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Abstract
Clothing is a portable micro-environment of the human body. This paper confirms how effective clothing is a tool for the human body to adapt to various climates on the earth from cold to hot. First of all, from a spatial standpoint, the relationship between climate and the characteristics of folk costumes throughout the world, and from a perspective of time, the seasonal changes in Japanese clothing culture (koromogae) were briefly summarized. Then, the methods and the results through four different approaches which have conducted in our laboratory in order to develop the functional, climate adaptable and comfortable clothing were introduced. In the behavioral approach on climatic adaptability based on clothing, the dressing behavior of urban residents was examined with a fixed-point observation method using photography in order to survey the connection between clothing and climate in modern society. In the physical approach, the development of thermal/sweating thermal manikins in our laboratory and the evaluation of Cool-Biz products developed by fiber/apparel companies using a sweating thermal manikin “JUN” were introduced. In the physiological approach to develop climate adaptable clothing, physiological basic data on the human body in different climates, especially a distribution of skin temperature and sweating rate over the skin surface were described. In the psychological approach, local thermal sensation and humid sensation over the skin surface were examined and the research methods and the results obtained were briefly introduced.

Keywords: clothing, adaptation to climate, folk costume, “Cool Biz” campaign, sweating thermal manikin, local heat transfer coefficient, threshold of cold/warm sensation

1. Introduction
Given clothing’s nature as something that wraps individual people at all times and with which they never do without, Horn and Gural (1981) provide define it as follows: “Clothing is a second skin that replaces the fur human beings threw off during the process of their evolution.” Moreover, Watkins (1984) gives the following definition: “Clothing is a micro-environment that is closest to a person and is a tool for environmental regulation that can be moved from place to place and can be adjusted with ease by simply adding or removing layers.” Clothing is a portable micro-environment of the human body.

People wear clothing for a variety of reasons, among them adaptation to climate, ceremonial purposes, personal expression, occupational expression, protection, and facilitation of activity. The author has been engaged in continuous study on the functionality and comfort of clothing in a Human-Living Environment System from various angles, and in this paper she gives an overview of this topic with focus on the relationship between “clothing and climate.” With problems of the global environment becoming increasingly serious today, the climate adaptation function of clothing ought to be reaffirmed.

2. Clothing’s role in adaptation to climate
D. Morris (1967) called humankind “naked apes”. He insisted that apes lost their body hair through the revolution process because he had to discharge body heat when he continued to chase game. At a time he also obtained cooling device, sweat glands, all over the skin. Evaporation of sweat produced a great cooling effect on him. Human beings are originally animals acclimated to heat. After these, they ventured out of Africa, spread throughout Europe, and eventually settled in the various regions and climates of the world. This is not only because humans have become
biologically acclimatized to their environment, but also largely due to cultural adaptation, based on factors such as clothing and housing. Clothing, in particular, is indispensable as a means of environmental adaptation.

Today, various forms of folk costumes continue to be worn throughout the world. Folk costumes reflect how people adapt to climatic conditions and regional styles, as most of folk costumes were established at the end of nineteenth century when air-conditioning systems were not yet a part of people’s lives. As Figure 1 (Tamura 2013) shows, there are clear relationships between climate and the basic forms of folk costumes. Indeed, it was confirmed that the materials and shapes of the world’s folk costumes were intimately tied to the regional climates from which they came (Tamura and Yamamoto, 2001).

So what is the relationship between clothing and climate in a particular region? In Japan, a country with distinct seasons throughout the year, a culture of koromogae (changing one’s wardrobe to fit the new season, Figure 2) developed. Within this culture, people adapted to seasonal changes by changing the materials, colors, patterns, and layering of their clothing as required by the new season. In recent years, however, the advent of air-conditioning has produced temperature-controlled environments in offices and homes, while clothing styles have become more diversified. As a result, the culture of koromogae is being lost.

3. Methods for evaluating thermal comfort of clothing

In general, environmental heat, light, sound, etc., act on a human being as external stimuli, and when the stimulus information is received by the various sensory receptors and transmitted to and integrated in the brain, the human body gives rise to various physiological and psychological responses in accordance with the types and degrees of the stimuli. Among the psychological responses, the sensation of comfort/discomfort is an extremely important sensation that triggers human behaviors, and it is considered that the sensation of comfort/discomfort is basically brought about according to whether the integrated stimulus information is favorable or unfavorable for the survival of the living body, in other words, whether or not constancy (homeostasis) can be maintained somehow inside the living body.

As shown in Figure 3, upon being transmitted to the brain, the external information received by the sensory receptors gives rise to physiological responses and psychological responses in accordance with the stimuli and cause behaviors (performance) in accordance with the comfort sensation. Therefore, in evaluating whether or not certain clothing is comfortable for a wearer, methods for observing, measuring and evaluating the psychological response, physiological response and behavioral (performance) response of the wearer are used (Tamura 2015). Here, in order to quantitatively ascertain the relationship between the stimuli and the responses, the stimulation amounts (physical quantities of the clothing) must also be quantified, and in clothing comfort research, not only the responses of the human body but evaluation of the physical characteristics of the clothing assuming the state of being put on the human body is also essential.

Then, the methods and the results through four different approaches having conducted in our laboratory in order to develop the functional, climate adaptable
and comfortable clothing are described here.

4. Behavioral approach on climatic adaptability based on clothing

4-1. A fixed point observation method using photography

Tamura and Maruta (2004) and Maruta and Tamura (2004) observed the dressing behavior of urban residents with a fixed-point observation method by photography, that was introduced by Yasuda and Yamashina, in 1967, in order to survey the connection between clothing and climate in modern society.

A street observation method was utilized over the course of one year. Observations were made at an intersection near a major Tokyo railway terminal that is used by in excess of 3 million people each day. At 10-day intervals, approximately 300 pedestrians were photographed (Figure 4) for a roughly 30-minute period beginning at 2:00 P.M., a time of day when people could be observed passing through the intersection for the broadest range of purposes and destinations. Analyses focused on a total of 10,831 subjects (of which 7,132 were men and 3,699 were women). Wearing rates for individual types of clothing were obtained by using the total number of subjects for each observation day (by men and women) as the denominator, and then their relationship with climatic data for the date, time, at the location of observation was studied. Figure 5 provides time series variation in the wearing rates for each type of clothing. For upper garments, clear seasonal changes were observed. In July and August, the wearing rates for short-sleeve shirts and sleeveless shirts were high for both men and women. Entering September, long-sleeve shirts and long-sleeve jackets had higher rates. Rates for jumpers and coats soared in November and December, respectively. The wearing rate for coats suddenly fell in March, while the rates for long-sleeve shirts and long-sleeve jackets rose again. Short-sleeve shirts began appearing again in May. Similar seasonal changes were seen in wearing rates for individual lower garment types. Because only outer garments can be discerned using photographs, a method was studied whereby clo value for all clothing worn could be estimated by predicting based on a separate study the types of inner garments worn from outer garments. This method was used to determine the clo values of clothing worn by pedestrians. The result shown in Figure 6 was obtained by superimposing these values with clo values of clothing worn comfortably by people walking in the average temperature of the survey days and in an air current of 1 m/sec that were arrived at using SET* (Maruta and Tamura, 2009). With the exception of cases in which the temperature was at or above 25°C, both values matched well, demonstrating that the clo value of worn garments has a high correlation with temperature. While details have been published separately, it is apparent that, despite the fact that photography is an extremely simple and superficial means of study, it can ascertain the...
relationship between the dressing behavior of Japanese urban residents and climatic conditions with some accuracy when observations are made over the course of a year. The results indicate that, even in the modern age, people adjust the amount of clothing they wear to subtly fine-tune their body temperatures in accordance with seasonal changes.

4-2. The “Cool Biz” campaign
In general, men’s business dress tends to be extremely conservative in accordance with social restraints, and thus it is thought resistant to be change. The previously mentioned street observations revealed that the amount of clothing worn by men when the temperature is 25 °C or higher was far above the amount of comfortable clothing of SET*. It goes without saying that this was the effect of social norms—i.e., the wearing of suits by businessmen. Around 2001 the air-conditioning temperature of offices was set low at 23 to 25 °C to accommodate male workers wearing suits. As a result, female workers wearing light clothes suffered from the strong air-conditioning. In response, the Ministry of the Environment began what was coined the “Cool Biz” campaign in 2005. Under Cool Biz, the ministry encouraged businesses to conserve air-conditioning energy by keeping their office temperature at 28 °C (the highest level set by the Ordinance on Health Standards in the Office). This would be achieved by having employees dress lightly, without jackets and ties. According to data released by the Ministry of the Environment in September 2010, 93.6 % of the public knew of the Cool Biz campaign, 61.8 % of companies were setting their air-conditioning temperature higher, and, as a result, CO₂ emissions had been reduced by approximately 1.72 million tons (roughly equivalent to the CO₂ emitted by 3.85 million households in one month).

The Cool Biz campaign received high praise abroad as well. Today, a time of global warming, Cool Biz is seeing growing acceptance throughout the world as an attempt to rethink the European dress code that dominates the world and discover a new fashion culture that fits with global climates. It should be noted that fixed-point observations taken in the summer (July and August) of 2001, 2006, and 2011 showed that Cool Biz was penetrating into all parts of Japanese society. As a result, female workers wearing light clothes suffered from the strong air-conditioning. In response, the Ministry of the Environment began what was coined the “Cool Biz” campaign in 2005. Under Cool Biz, the ministry encouraged businesses to conserve air-conditioning energy by keeping their office temperature at 28 °C (the highest level set by the Ordinance on Health Standards in the Office). This would be achieved by having employees dress lightly, without jackets and ties. According to data released by the Ministry of the Environment in September 2010, 93.6 % of the public knew of the Cool Biz campaign, 61.8 % of companies were setting their air-conditioning temperature higher, and, as a result, CO₂ emissions had been reduced by approximately 1.72 million tons (roughly equivalent to the CO₂ emitted by 3.85 million households in one month).

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The first manikin, “LUMPY,” was followed by a more accurate manikin called “Chauncy.” In Japan, research on the heat resistance of various clothing forms has been advanced using manikins developed by Toda (1958), Mihira et al., (1977), and Tamura and Iwasaki (1981) among others. Including commercial production, thermal manikins are being manufactured in all parts of the world. They are constructed of such materials as copper, aluminum, aluminum alloy, and reinforced plastic, and utilize various segmented/heat supply systems; some even have moveable joints. They are effective devices for physically evaluating full-body and localized sensible heat transfer from the body’s surface to the external environment; the effects that materials, structures, and layering have on such transfer; regional characteristics; and the effects of posture, movement, air current, and room temperature distribution.

Measurements of the heat resistance of individual garments and clothing combinations are made in clo units. Conditions for measuring clo units, methods for estimating clo value when thermal manikins are not used, and other matters are stipulated in ISO 9920 (2007), and thus description of them is omitted here.

On the other hand, sweating thermal manikins are used to evaluate the evaporative heat resistance of clothing, which is an important characteristic of clothing in hot environments. Fonseca (1970) simulated the body’s perspiration by covering a standing copper thermal manikin with moistened knit T-shirt fabric, and then evaluated the heat transfer characteristics of 10 combinations of inner and outer garments. Since then, sweating thermal manikins having various water-supply and control systems have been developed throughout the world. In 1995, Tamura et al. made a prototype of a perspiring/urinating manikin that can eject the kind of liquid that would be expected during heavy perspiration. They wrapped manganin wire at a 3-mm pitch around a FRP body surface representing an infant’s waist, in between which they packed highly heat conductive RTV rubber. They then covered the manikin with RTV rubber sheet, and then on top of this placed imitation skin for water dispersal. They applied this same method to produce moveable sweating thermal manikins.
manikins for infants for use in evaluating diapers, etc., as well as for elementary school-age children and adult Japanese women. The manikins were used to measure the heat resistance and evaporative heat resistance of clothing for infants, schoolchildren, and adult women. Moreover, in 2006, they developed a 2-layer moveable perspiring thermal manikin “JUN” having the standard measurements of a Japanese adult man and capable of independent adjustment of the core and shell temperatures (Tamura, 2006). The perspiration adjustment method involves a computer-controlled water pump that can emit perspiration from 180 perspiration pores arranged over the entire body at a rate of one pore for every 100 cm². The manikin families at Bunka-Gakuen University are shown in Figure 7.

However, if various thermal manikins and sweating thermal manikins are used throughout the world (Figure 8), then the issue of data compatibility among manikins becomes a problem. Here, McCullough (2001) conducted a project in 2001 that involved rotating five ensembles ranging from everyday clothing to protective clothing among six laboratories of the world that evaluate clothing using sweating thermal manikins (the author was a participant in this project) and then gathering and comparing measurement data acquired by these laboratories. As a result, it was found that, with some exceptions, data on thermal resistance showed good proximity and compatibility. However, for evaporative heat resistance, it was concluded that, although relative evaluation of clothing in a single laboratory is possible, significant differences in sizes, control methods, and other conditions among laboratories make comparison of absolute values that reach beyond the laboratory level problematic. In 2015, Wan et al. conducted the second round robin test project (the author was a participant again) focusing the evaluation of the evaporative heat resistance, especially the effects of mass loss method and heat loss method on the results. Wicking of water to the clothes as shown in Figure 9 was discussed as a factor to produce disagreement between them. Looking forward, it will at the very least be necessary to standardize environmental conditions, manikin skin temperature distribution, perspiring regions, skin moisture rates, sustainability of moisture conditions, skin surface characteristics (e.g., use of breathable waterproof fabrics, etc.), and computation methods.

Figure 7. The manikin families at Bunka-Gakuen University (Tamura, 2013)

(a) Spray type
(b) Vapor transport / diffusion Type
(c, d) Pump-regulated water squirting type
(e) Breathable-waterproof balloon type
(f) Filter paper type

Figure 8. Representative sweating thermal manikins In a world (Tamura, 2013)

Figure 9. Wicking water to the clothes affects on the results of evaporative heat resistance measured by heat loss method and mass loss method (Tamura at al., 2016)
5. Evaluation of Cool-Biz products developed by fiber/apparel companies using a sweating thermal manikin “JUN”

After 2005, especially after the Great East Japan Earthquake of March 2011, people had a great interest to Cool Biz products for energy-saving. Fiber and apparel companies have been engaged in fierce competition to develop comfortable and newly functional materials and propose new designs that are suited to Cool Biz fashion. It is expected of each company to provide evidence regarding the effects of the clothing they develop. Thus, a sweating thermal manikin as an evaluation tool has become even more important.

The thermal and evaporative heat resistance of representative Cool Biz garments and ensembles sold on the Japanese market by utilizing the sweating thermal manikin JUN as well as a skin model. The comfort zone for each ensemble calculated by the equation of Mecheel and Umbach verified the effect of cool biz style was equivalent to 2.5 °C and more of room temperature (Figure 10).

Apparel companies are developing more progressive cool biz fashion now, with new fibers and textiles such as super fine, aero capsule, moisture absorptive/heat generating, smart/intelligent and so forth being developed using nanotechnology. With the aim of producing intelligent fashion which acts as a partial cooling system for individual wearers, the physiological and psychological effects of clothing on human beings as well as evaluation methods for determining the physical effects of fiber, textile and the construction of clothing on the human body are areas that require further research.

6. Physiological approaches on climatic adaptability based on clothing

When evaluating clothing with thermal manikins, the only viable approach is to measure the physical properties of heat and moisture transfer that occurs on the body’s exterior. However, in the case of the human body, different body regions react to the same stimuli in different ways. Moreover, physiological response can vary from region to region. For example, when making physical measurements, the heat resistance of clothing is roughly proportional to covered area (i.e., the ratio of the body’s surface area that is covered by clothing). Furthermore, when the area of coverage is the same, heat-retention effect becomes greater when the limbs (which have greater curvature) are covered rather than when the trunk (which has smaller curvature). However, when viewed in terms of personal experience and physiology, most people would agree that they would feel warmer in a cold environment if just their trunk were covered rather than if just their limbs were covered. Thus, studying climate adaptability (comfort) from clothing requires an approach that is based on human physiology, a field that cannot be evaluated using thermal manikins.

6-1. Skin temperature distribution and changing skin temperature in response to localized cooling and heating

Figure 11 shows the average skin temperature distribution of a nearly naked young woman at 22 °C, 28 °C and 34 °C of air temperature (Tamura, 1983). Because the amount of heat radiated from the body is proportional to the difference between skin temperature and external temperature, regions having higher skin temperature tend to radiate heat more easily. This is effective in retaining temperature where it is needed in the trunk. Figure 12 shows the results of a study on the ripple effects on the skin temperature of specific body regions (Maruyama and Tamura, 1989). In the study, a subject was dressed in full-body suite resembling a toy stuffed animal and placed in a cold environment. The
vapor pressure of the air. Here, the evaporative heat transfer coefficient and convective heat transfer coefficient are parallel and air flow and curvature of the skin’s surface are related. Accordingly, in order to promote perspiration, it is important to lower vapor pressure within clothing by giving absorbency and moisture permeability to fabrics and allowing air to enter clothing by providing openings and fabric breathability. Even though arms and legs generally produce comparatively little sweat, their large curvature facilitates evaporation when they do sweat. However the body’s trunk (such as the back, chest, and lower back), which produces great amounts of sweat (Figure 13), has little curvature. In fact, some regions have negative curvature. Consequently, sweat in these regions occasionally fails to evaporate and drips off. Dripping sweat is called ineffective sweat, and increased production of ineffective sweat can stress the body. Accordingly, the skin wettedness (i.e., the ratio of the amount of actual sweat transpiration against the maximum amount of sweat that can evaporate from the skin’s surface) demonstrates extremely high correlation with discomfort during exposure to heat and is used as an indicator of heat-caused discomfort (Figure 14). Intelligent fabrics with superior moisture absorption, ventilation, vapor transmission, and drying qualities are effective as materials for such as sportswear and working wear.

**6-2. Distribution of sweating and evaporation in the skin surface**

The evaporation of sweat has the priority for clothing worn under hot environments. Thus, measuring the distribution of sweat from the body is essential when considering adaptation to climate with summer clothing (Yamada and Tamura, 2012). The speed at which sweat evaporates is proportional to the difference between vapor pressure on the surface of the skin and...
However, the absorption of water during times of heavy sweating can impede breathability due to the blockage of pores and thus lead to the sticking of clothes and increased friction resistance. Therefore, fabrics with non-smooth surfaces and superior drying qualities are effective in preventing clothing from becoming stuck to the skin due to the absorption of water.

7. Psychological approaches on climatic adaptability based on clothing

7-1. Sensitivity to temperature of the skin’s surface

Heat information of the skin’s surface is sent from sensory receptors on the skin to the central nervous system, where it is integrated. This activates autonomic temperature regulation and simultaneously causes sensation of heat or coolness and comfort.

Research on temperature sensitivity began in the late 19th century with searches for hot spots and cold spots (Dallenbach, 1927). Murata and Iriki (1974) reported that the cold spot density of eight regions declined significantly in elderly people. Lee and Tamura (1995) and Tamura and Lee (1995) demonstrated the correlation between density and temperature sensitivity, the former by measuring the cold spot density and the latter by measuring the warm spot density of 25 regions throughout the bodies of 10 young women using a water circulation-type stimulator that allowed slight adjustments to stimulus temperature.

However, these “classic” methods take time and place considerable burden on subjects. Given this, Tamura et. al., (2001) developed a cold/warm sensation threshold measuring device that simplifies measurements, shortens the time required for measurements, alleviates burden on subjects, and has excellent precision and reproducibility (Figure 15). This device evaluates cold/warm sensation thresholds and heat flow thresholds. A probe is brought into contact with the targeted skin area of a subject, and the temperature of the contact point is adjusted to make it equal to the local skin temperature. Then the probe temperature is raised or lowered at an appropriate speed (usually 0.1°C/second), and the subject is asked to press a button when he or she feels warmth or coldness. Using this device, Uchida and Tamura (2007) carefully studied the cold/warm sensation thresholds of age groups between 20 and 89 with focus on 26 regions, 14 on the front of the body and 12 on the back. The results demonstrated that cold sensitivity thresholds differ among body regions. They also revealed that, for both young women and elderly women, thresholds for the face (forehead, cheek, and chin) tend to be low; thresholds for the legs (lower legs, instep, and bottoms of the feet) are large; and, while thresholds for the trunk and upper arms are between those of the face and legs, the cold sensation thresholds of the shoulders are an exception as they are comparatively large. It is thought that the small cold thresholds of the face arise from the face’s role as an “antenna” that detects the temperature environment of the outside world. It is further thought that, when considering adaptation to climate with clothing, the trunk is more sensitive than the legs and thus should receive higher priority in terms of heat retention. Elderly subjects had higher thresholds for both warm and cold sensation (Figure 16), and it is therefore theorized that elderly people have more difficulty taking appropriate

Figure 15. A device measuring the cold/warm threshold of the human skin and its application to the aging effect on the thermal sensitivity of male and female subjects. (Tamura et al., 2001)

Figure 16. Cold sensitivity threshold of women with focus on 26 regions. Elderly subjects had higher thresholds for both cold and warm sensation. (Uchida and Tamura, 2007)
behaviors in response to heat and cold. This makes it necessary to propose ways of offsetting this lost function when considering clothing for the elderly. Moreover, incidences of low-temperature burn in daily life—such as those caused by making bathwater too hot or using electric foot warmers, electric carpets, or disposable pocket body warmers—result from lost temperature sensitivity. Thus, measures that presume the loss of temperature sensitivity, particularly in the legs, are required to prevent erosion in quality of life among the elderly.

7-2. Sensitivity to moisture of the skin’s surface

Together with cold/warm sensation, sensation of dampness presents a problem under hot conditions. However, neither anatomical nor physiological research has discovered receptors that can sense moisture. Thus, in order to identify the mechanism by which moisture is sensed, Tamura and Koshiba (1995) studied the relationship between total-body warmth/cold sensation and total-body humidity sensation. This study involved having 24 adult women remain in an artificial climate chamber set at temperature degrees of 25, 31, and 37 °C and then adjusting relatively humidity between a range of 30 and 80 % at each (Figure 17). From this, it was learned that the relationship between total-body humidity sensation and temperature rises with rising room temperature. In a separate experiment, Koshiba and Tamura (1995) employed humidity fluctuation and paired comparison to conduct sensory tests to determine whether or not subjects could sense differences in humidity on their skin surfaces when air adjusted to have a relative humidity of between 10 and 90 % was passed to a 3 cm-diameter capsule and put in contact with the skin (Figure 18). The tests were conducted on three subjects and targeted six body regions. It was found that only the palms could sense slight differences in humidity. As for the other regions, none of the subjects could even sense the difference between 10 % and 80 % humidity. Furthermore, in order to find the dominant factors behind moisture sensation of the skin, measurements of changes in moisture sensation were taken when moistened filter paper of varying sizes and moistened knitted cotton fabric of various water temperatures, water amounts, and weights were exposed to or drawn across surfaces of the human body. The results clearly indicated that the largest factor behind moisture sensation is change in temperature and heat flow on the exposed skin, and that tactile sensation plays a role in determining the degree of moisture sensation. Summing up these results, it appears the surface of the skin cannot detect the existence of moisture per se. Rather, the moisture humidity sensation that we feel is a synthesized sensation comprised of differences in tactile sensation arising from the existence of moisture, degree of

moisture movement generated by differences in vapor pressure on the skin’s surface and the environment, the speed of temperature change on the skin arising from the evaporative latent heat of such movement, and other factors. Additionally, the ratio of amount of evaporative heat release required to achieve body heat balance between the body and environment (Ereq) and actual amount of evaporative heat release from the body (Es) plays a significant role in sensation of humidity by the entire body.

8. Conclusion

The start of the Cool Biz campaign in 2005, the exceptionally hot summer of 2010, and energy conservation measures from the summer of 2011 have generated high public interest in “climate and clothing.” Indeed, this subject frequently appears in newspapers, magazines, and television reports. People have many questions. How can clothing prevent heat stroke? What about babies and the elderly? Does moisture-absorbing exothermic fiber really keep you warm? Why isn’t my exposed face cold when my body wrapped in winter clothing is cold?

Due to space limitations this paper could not completely cover all areas of research concerning clothing
and climate. Many issues requiring attention still remain, among them amounts of clothing required for various body shapes and environments; differences among individuals; relationships with age differences that range from newborns to elderly; and relationships between various illnesses and clothing. If we consider the Earth’s finite resources and energy supplies and the unavoidable manifestation of global warming, then we recognize that clothing as a means of climate adaptation offers numerous advantages over air-conditioning equipment: Clothing is inexpensive, energy efficient, adaptable to individuals, capable of handling body heating from exercise or work, and portable. Someday soon, scientific and technical advancements will lead to the development of individually controllable garments that are smaller, more lightweight, and use minimal amounts of energy. An important question here is how we will use the clothing that wraps our bodies and provides them with their most familiar environment.

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