Body Measurements and Comfort Temperatures for Women and Men of Different Size

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Abstract

In this study, we analyze scan data from women and men collected in the sizing campaign “Size NorthAmerica”. Our goal is to find regularities between the sizes, proportions, and shapes of the human body, and we pursue the thesis that body size and weight systematically influence human physiology and biomechanics. In order to make the results usable for applications in occupational physiology, ergonomics, clothing industry, medicine, and sports physiology, we summarize the data in anthropometric scale models that describe the distribution of body measures for women and men of different lengths and weights. The results show that the volume and width-to-length ratio of various body segments systematically change with body length and weight, which must be considered when designing bandages and orthoses. In addition, we are conducting a numerical experiment to investigate the influence of body size on temperature regulation. This reveals that people of different sizes have different requirements in terms of ambient temperature, which must be considered in areas such as air conditioning or clothing design.

Keywords: Digital anthropometry, anthropometric studies, ergonomics, body measurement, sizing campaigns, applications in sports, health and fitness, medical diagnostics and therapy

1. Introduction

Detailed knowledge of body measures and their distribution is of major economic importance, not only in the clothing industry, where body measures are used to calculate clothing sizes, but also in the development of ergonomic equipment, tools, human-machine interfaces, or vehicles, and thus in the optimization of work processes, working conditions, spaces for movements, fields for vision, reachability, and handling forces with the aim of productive, healthy, and sustainable work [1, 2, 3]. In addition, anthropometric methods are becoming increasingly important in the field of medical diagnosis and therapy, as exemplified by the NAKO Health Study, which for the first time investigates correlations between girth of waist and hip and cardiovascular disease (CVD), metabolic disease (MetD), cardiometabolic disease (CMD), or cancer [4].

The girth of waist and hip also correlate with abdominal and gluteofemoral fat mass, and for this reason, anthropometric methods are increasingly being used in body fat analysis, for example in addition to magnetic resonance imaging (MRI) [5], ultrasound, or bioelectrical impedance analysis [6]. Research in this field is of great social relevance, as in 2016, 59% of the adult population in Europe was overweight or obese [7], meaning that the prevalence of overweight and obesity has reached epidemic proportions. By definition, people with a body mass index greater than approximately 25 kg m^{-2} are considered overweight and those with a BMI greater than approximately 30 kg m^{-2} are considered obese. However, BMI does not differentiate between muscle tissue, subcutaneous adipose tissue (SAT), and visceral adipose tissue (VAT) [8, 9]. There is a great need for research in this area and a wide field of application for anthropometric methods. The same applies to research on the influence of age [10], ethnicity [11], fitness, gender [12, 13], and body length on metabolism, not only in connection with anorexia and obesity, but also with temperature regulation [14].

Anthropometric applications also exist in research into phlebological, lymphological, and orthopedic diseases, and in the treatment of these diseases through the design and manufacture of precisely fitting and functioning bandages and orthoses. Further anthropometric applications exist in the field of smart textiles and in the monitoring of vital functions [15, 16, 17, 18]. In some cases, it may not even be necessary to remeasure people, as scan data from approximately 45 thousand people in the US, Canada, Germany, Italy, and China is already available [19]. However, analyzing such scan data requires models that mathematically represent the regularities of weights, sizes, proportions, and shapes for healthy and sick people. Such models are being developed as part of this study.

2. Body measures

The data is based on the sizing campaign “Size North America”, conducted by Humanetics (formerly Avalution and Human Solutions) in the United States and Canada from 2016 to 2019. The Vitus Smart XXL body scanner and Anthroscan software were used. A representative selection was made of 72 adult women with a body weight (m_b) between 44.4 and 95.6 kilograms (average 72.5 kilograms) and 72 adult men with a body weight between 48.0 and 124.6 kilograms (average 80.0 kilograms). The women and men were between approximately 20 and 60 years of age. Six characteristic body mass indices (BMI) of 16, 19, 22, 25, 30, and 35 kg m^{-2} were considered, covering the wide range from severely underweight to obese. For each of the body mass indices mentioned, 12 women and 12 men are selected who differ in body weight (m_b) and body length (l_b). On average, the body mass index for the women examined is 25.1 kg m^{-2} and for the men examined 25.5 kg m^{-2}.

The scan data is used to generate individual and statistical avatars using Anthroscan software. In a first analysis step, 21 body measure are derived from the individual avatars, which are shown in Figure 1 sorted by size. Shoulder width (w_{Sh}), girth of wrist (g_{Wr}), and waist-hip distance (l_{WaHi}) average less than 20 centimeters. The distance between the bust points (w_{BP}) and the distance between the neck and chest points (l_{NeBP}) average 20 to 30 centimeters. The girth of the upper arm (g_{uAr}), neck (g_{mNe}), calf (g_{Ca}), and knee (g_{Kn}) average 30 to 40 centimeters. The back width (w_{Ba}) and neck-waist length (l_{cNeWa}) average around 40 centimeters. The thigh girth (g_{Th}) is around 60 centimeters and is the only body measure in this comparison for which women have higher average values than men. The arm length (l_{Ar}) averages about 60 centimeters and the inseam (l_{Cr}) about 80 centimeters. The girth of waist (g_{Wa}) and underbust (g_{uCh}) average less than 90 centimeters only for women. In contrast, the girth of hip (g_{Hi}) averages over 100 centimeters for both women and men. The waist length (l_{WaS}) averages 107 centimeters for women and 111 centimeters for men. The body length (l_b) averages 170 centimeters for women and 177 centimeters for men.

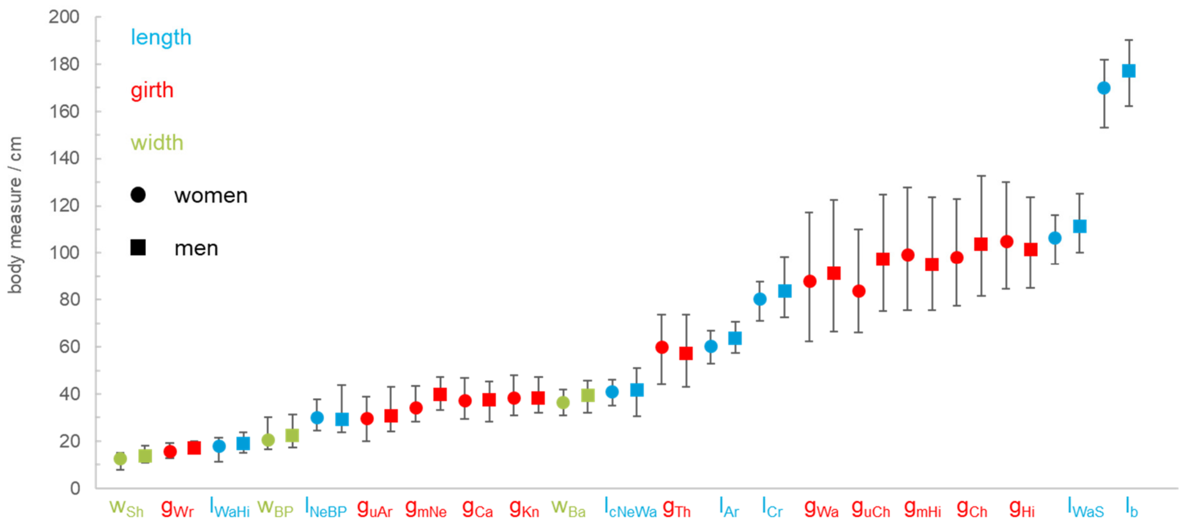

Fig. 1. Various body measures (mean and range) of 72 women and 72 men.

Figure 1 becomes very informative when analyzing the ranges. For body length (l_b), the range for women is between 153.1 and 181.8 centimeters and for men between 162.3 and 190.1 centimeters. In both cases, the range is therefore approximately 28 centimeters. In contrast, the range for the girth of waist (g_{Wa}), mid-hip (g_{mHi}), and chest (g_{Ch}) is over 50 centimeters, and the range for the girth of underbust (g_{uCh}), hip (g_{Hi}), and thigh (g_{Th}) is also significantly greater than the range for body length (l_b). In addition, the girth measures of thigh and trunk correlate linearly with the body mass index. The girth of thigh (g_{Th}) increases comparatively the least, by an average of about 1.1 centimeters per body mass index value, and the girth of waist (g_{Wa}) increases the most, by 2.4 centimeters per body mass index value. For the other body measurements shown in Figure 1, the range is, in some cases, considerably smaller than for body length (l_b). Overall, the analysis shows that individual body measures change very differently with body length and weight, and that the length-to-width ratio of the torso and thighs changes systematically with body mass index (BMI), which is of great importance for the design of precisely fitting and functioning clothing, compression garments, bandages, and orthoses.

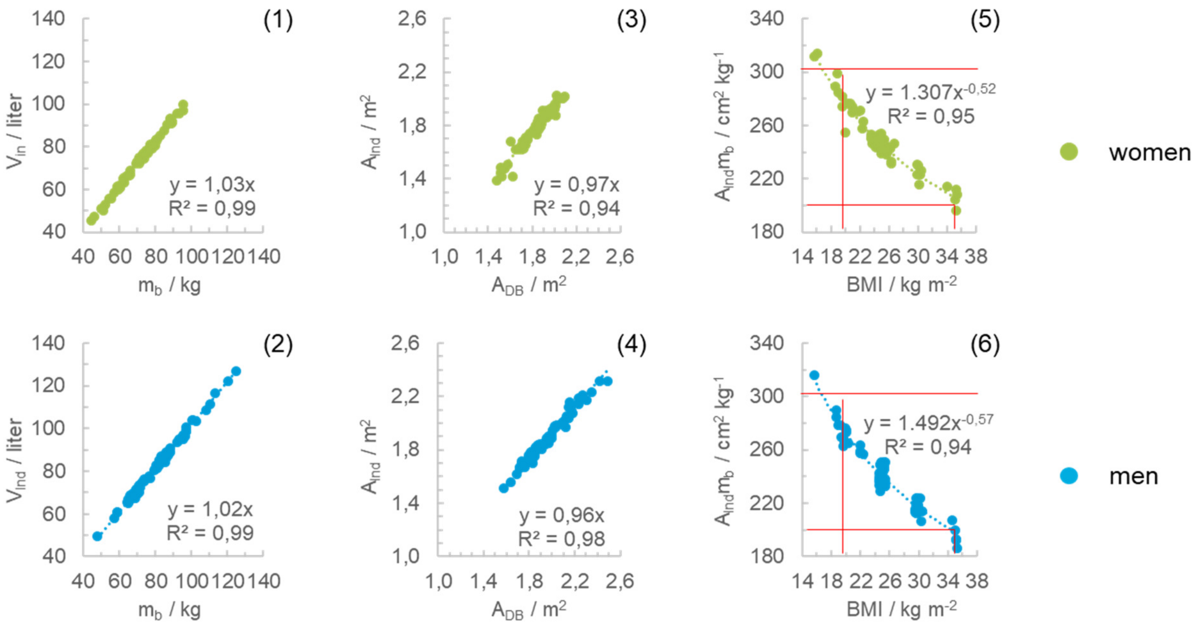

Fig. 2. Correlations between different body measures.

In a further analysis procedure, the volumes and surfaces of the individual avatars are determined. The avatar volume (V_{Ind}) varies between 45.5 and 99.6 liters (average 74.6 liters) for women and between 49.4 and 126.9 liters (average 81.3 liters) for men. The avatar volume (V_{Ind}) correlates linearly with body weight (m_b), with the average avatar volume (V_{Ind}) being 3 percent (Figure 2.1) larger than body weight (m_b) in women and 2 percent (Figure 2.2) larger in men, with the consequence that the body density (ρ_b) of women and men is on average less than 1.00 g cm^{-3}. Only 2 out of 72 women and 13 out of 72 men have a body density (ρ_b) equal to or greater than 1.00 g cm^{-3}. There is no correlation between body density (ρ_b) and body mass index for the data set considered.

The avatar surface (A_{Ind}) varies between 1.39 and 2.03 square meters (average 1.78 square meters) for women and between 1.52 and 2.32 square meters (average 1.89 square meters) for men. The avatar surface (A_{Ind}) correlates linearly with the body surface (A_{DB}), which is calculated using DuBois' formula [20] based on body length (l_b) and body weight (m_b). On average, the avatar surface (A_{Ind}) is 3 percent smaller for women (Figure 2.3) and 4 percent smaller for men (Figure 2.4) than the body surface area according to DuBois (A_{DB}). On average, the DuBois formula overestimates the avatar surface area (A_{Ind}) by a maximum of 2017 square centimeters for men and 1677 square centimeters for women. Only three women and one man have an avatar surface area (A_{Ind}) that is larger than the body surface area according to DuBois (A_{DB}).

In Figure 2.5 and Figure 2.6, the relative body surface area ($A_{Ind}m_b$) is calculated by dividing the avatar surface (A_{Ind}) by the body weight (m_b). Related to one kilogram of body weight (m_b), this results in a body surface area (A_{Ind}) between 197 and 314 square centimeters (average 248 cm^2 kg^{-1}) for women and between 186 and 316 square centimeters (average 241 cm^2 kg^{-1}) for men. The relative body surface area ($A_{Ind}m_b$) correlates nonlinearly and inversely with the body mass index (BMI). Based on one kilogram of body weight (m_b), women (Figure 2.5) and men (Figure 2.6) with a body mass index (BMI) of less than 20 have a relative body surface area ($A_{Ind}m_b$) of partly more than 300 square centimeters per kilogram body weight (m_b). In contrast, women and men with a body mass index (BMI) greater than 35 have a relative body surface area ($A_{Ind}m_b$) of less than 200 square centimeters per kilogram of body weight (m_b) in some cases.

3. Proportions

In a further analysis process, the individual avatars are segmented and body volume (V_{Ind}) and body surface (A_{Ind}) are determined for each body segment separately. Figure 3 shows the volume of different body segments sorted by size. The volume of the right and left body segments on the arms and legs is combined, i.e., added together. Figure 3 (left) shows the absolute volume in liters. It amounts to 0.2 to 1.0 liters for both hands (V_{Ha}) 1.1 to 3.2 liters for both feet (V_{Fo}), 1.0 to 3.5 liters for both forearms (V_{fAr}), 1.8 to 5.9 liters for both upper arms (V_{uAr}), 3.4 to 5.9 liters for the head (VHea), 3.8 to 9.5 liters for both calves (V_{Ca}), 9.0 to 23.4 liters for both thighs (V_{Th}), and 24 to 80 liters for the torso (V_{To}). Figure 3 (right) shows the relative volume of the body segments as a percentage of the total body volume (V_{Ind}). Both hands (V_{Ha}), feet (V_{Fo}) and forearms (V_{fAr}) usually account for less than 5 percent, both upper arms (V_{uAr}), head (V_{Hea}), and both calves (V_{Ca}) account for between 5 and 10 percent, both thighs (V_{Th}) account for between 15 and 25 percent, and the torso (V_{To}) accounts for between 50 and 65 percent.

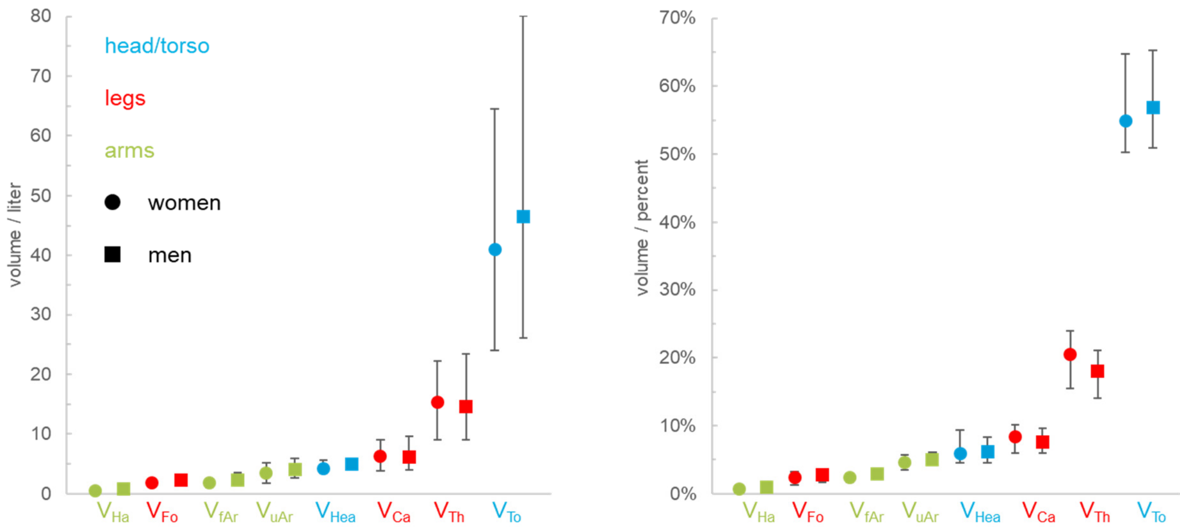

Fig. 3. Absolute (left) and relative (right) volume of different body segments (mean value and range).

We calculate the surface area of the body segments in Figure 4 by multiplying the body surface (A_{Ind}) by the relative proportion of the body volume in Figure 3 (right). The surface area of the body segments amounts to 46 to 179 square centimeters for both hands (A_{Ha}), 0,02 to 0,07 square meters for both feet (A_{Fo}), 0,03 to 0,07 square meters for both forearms (A_{fAr}), 0,05 to 0,12 square meters for both upper arms (A_{uAr}), 0,08 to 0,14 square meters for the head (A_{Hea}), 0,10 to 0,20 square meters for both calves (A_{Ca}), 0,26 to 0,46 square meters for both thighs (A_{Th}), and 0,73 to 1,46 square meters for the torso (A_{To}). The direct derivation of the body segment surface area from the individual avatars is currently in progress. The comparison will show whether and to what extent similar or different body segment proportions result for volume and surface area.

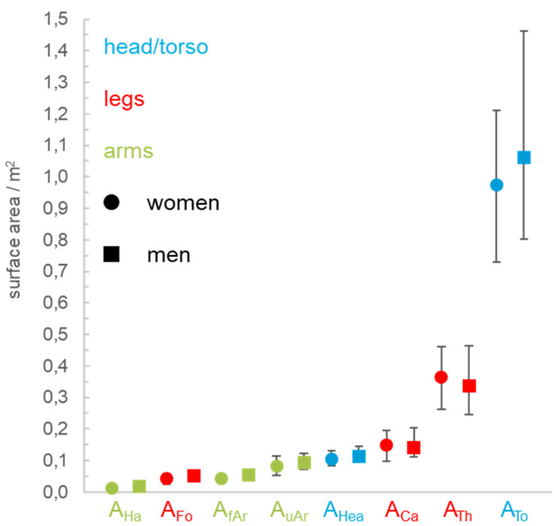

Fig. 4. Surface area of various body segments (mean value and range).

4. Temperature regulation

Calorimetry, and thus the experimental determination of metabolism and heat, dates back to the 18th century and to the scientists Fahrenheit [21], Celsius [22], and Lavoisier [23], with calorimetric methods continuing to evolve in terms of type and accuracy to this day [24]. In the 19th century, calorimetric measurements were performed on animals [25, 26, 27] and in the first half of the 20th century on resting [28, 29, 30, 31] and working [32, 33, 34, 35, 36] people. With the development of the respirometer in 1940 [37], the number of studies multiplied, so that by 1960 at the latest, detailed knowledge of human performance (P_b) was available [38], which is now available in standards [39].

According to this, the power (P_b) of resting people averages about 1 watt per kilogram of body weight (m_b), with the consequence that body temperature (T_b) rises by about 1 Kelvin per hour regardless of body weight (m_b). At the same time, resting people emit about 10 watts of infrared radiation per square meter and Kelvin through their skin [40, 41]. Thus, heat emission (E_{MIR}) depends on the specific body surface ($A_b m_b$), which varies between approximately 200 and 300 square centimeters per kilogram body weight (m_b) in women (Figure 2.5) and men (Figure 2.6).

Resting people with a small specific body surface ($A_b m_b$) of 200 square centimeters per kilogram body weight (m_b) are therefore in thermal balance at an ambient temperature (T_a) that is 5 Kelvin lower than the skin temperature (T_s). In contrast, resting people with a large specific body surface ($A_b m_b$) of 300 square centimeters per kilogram body weight (m_b) are in thermal balance at an ambient temperature (T_a) that is 3.3 Kelvin lower than the skin temperature (T_s). Thermal balance means thermal comfort, which is why ambient temperatures (T_a) of thermal balance are referred to as comfort temperatures (T_{ac}) [42]. For rest and an average skin temperature (Ts) of 34 degrees Celsius, the comfort temperature (T_{ac}) is 29.0 degrees Celsius for people with a small specific body surface ($A_b m_b$) and 30.7 degrees Celsius for people with a large specific body surface ($A_b m_b$) (Figure 5).

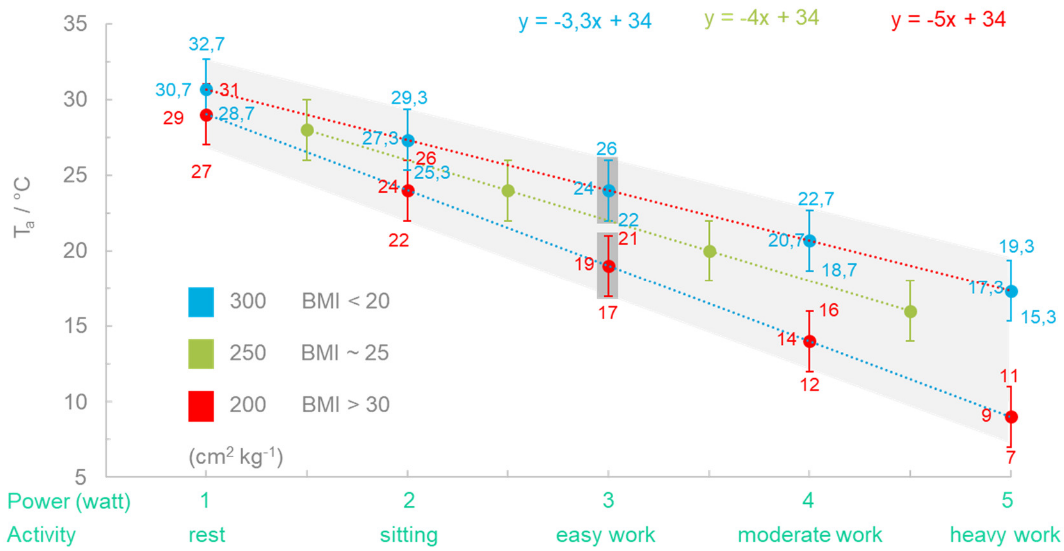

Fig. 5. Model of comfort temperatures (T_{ac}) for unclothed people depending on body surface area ($A_b m_b$), body mass index (BMI), activity (P_b), and ambient temperature (T_a).

Therefore, the comfort temperatures (T_{ac}) for people of different sizes differ by only 1.7 Kelvin at rest or the corresponding specific power (P_b) of 1 watt per kilogram body weight (m_b), but when the power (P_b) increases during activity to 2 watts when sitting and standing, to 3 watts during light work, to 4 watts during moderate work, or to 5 watts during heavy work, heat production increases proportionally, while comfort temperatures (T_{ac}) decrease inversely proportionally (Figure 5). For people with a small specific body surface ($A_b m_b$), the comfort temperatures (T_{ac}) decrease more sharply by 5.0 Kelvin per watt power (P_b) than for people with a large specific body surface ($A_b m_b$), where the decrease is only 3.3 Kelvin per watt of power (P_b). Therefore, the comfort temperatures for people of different sizes diverge proportionally to the increase of activity (P_b). For heavy work and an average skin temperature (T_s) of 34 degrees Celsius, the comfort temperature (T_{ac}) is 9.0 degrees Celsius for people with a small specific body surface ($A_b m_b$) and 17.3 degrees Celsius for people with a large specific body surface ($A_b m_b$).

Skin temperatures (T_s) are regulated by vasomotoric via the central nervous system in order to compensate the thermal fluctuations in ambient temperature (T_a) and power (P_b). For this reason, skin temperatures (T_s) do not remain constant at 34 degrees Celsius, but vary between approximately 32 and 36 degrees Celsius. In Figure 5, the range of vasomotor regulation is indicated by scatter bars. At low specific power (P_b) of 1 or 2 watts per kilogram body weight (m_b), the scatter bars overlap, which means that the comfort temperatures resulting for people of different sizes can be compensated by vasomotoric. This is not the case at higher power (P_b) of 3, 4, or 5 watts.

5. Discussion

People with a small specific body surface (A_bm_b) systematically require lower comfort temperatures (T_{ac}) than people with a large specific body surface (A_bm_b). The differences are relatively small at rest, but increase proportionally to performance (P_b), and this results in different climatic requirements for people of different sizes, which must be considered when air conditioning or designing equipment. This applies in particular to clothing that cannot be put on or taken off at will, such as protective clothing, bandages, or orthoses.

The specific body surface (A_bm_b) correlates inversely with the body mass index (BMI). Therefore, people with a high body mass index (BMI) systematically require lower ambient temperatures (T_{ac}) than people with a low body mass index (BMI). This applies equally to men and women, and thus the body mass index (BMI) appears to have a greater influence on temperature regulation than gender. However, physiological studies have not yet been conducted primarily from an anthropometric perspective. There is a need for research in this area.

When considering temperature regulation, the left and right segments of arms and legs must be considered together, but when designing bandages or orthoses, they must be considered individually. The volume of those body segments varies by a factor of approximately 3 depending on body weight (m_b) and body length (l_b). Thus, individual hands have a volume of approximately 0.2 to 0.5 liters, individual feet approximately 0.5 to 1.6 liters, individual forearms approximately 0.5 to 1.7 liters, individual upper arms approximately 0.9 to 3.0 liters, individual calves approximately 1.9 to 4.7 liters, and individual thighs approximately 4.5 to 11.7 liters. In addition, the width-to-length ratio of the thighs and torso changes with body weight (m_b) and body length (l_b). Nevertheless, body size is often not considered when designing bandages and orthoses. There is a need for research in this area and a wide field of application for the knitting industry. It would be conceivable to develop mathematic models that correlate compression classes with the body volume to be compressed [43].

DuBois' relatively simple formula overestimates the body surface area of the women and men examined by up to 0,20 square meters, whereby deviations between the body surface (A_{DB}) according to DuBois and the body surface of individual avatars (A_{Ind}) need to be described more precisely in further analyses. In addition, models need to be developed to calculate the surface area of individual body segments on the basis of body weight (m_b) and body length (l_h).

Muscle tissue has a higher density than fatty tissue. Nevertheless, the data set examined shows no correlation between density and body mass index (BMI). The reasons for this are probably that body mass index (BMI) does not distinguish between skeletal tissue, muscle tissue, subcutaneous adipose tissue (SAT), and visceral adipose tissue (VAT). Therefore, people with a low body mass index (BMI) have a high density due to their high skeletal proportion. In contrast, muscular people have a high body mass index (BMI) and, at the same time, a high density due to their high muscle mass. For future studies, consideration should be given to dividing the torso body segment (V_{To}) into two body segments, shoulder (V_{Sh}) and pelvis (V_{Pe}), in order to better distinguish between abdominal and gluteofemoral fat mass in analyses.

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