An Analysis of the Variability of Anatomical Body References within Ready-to-Wear Garment Sizes

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ABSTRACT

Establishing a range of sizes for apparel that can effectively fit the body shapes of a diverse population is a complex task, that for ready-to-wear (RTW) apparel is often reduced to a solution that is cost-feasible, if not optimal. While prototype garments are developed with specific fit objectives relative to an individual fit model, that shape is made larger and smaller according to a defined set of increments between sizes. For RTW, the objective in selecting size parameters is usually based on aesthetics. However, as garment-integrated technologies that require more precise placement of integrated technologies (such as sensors) on the body surface become more common in clothing, the implications of current RTW sizing techniques for precise on-body placement is not yet fully understood. Here, we present a comparison of the variability in anthropometrics of a target population and the variability assumed by a sizing standard, with respect to the impact of this disparity for placement of chest-mounted sensing devices like ECG electrodes. We analyze a large (n=3982) publically available anthropometric database and compare our findings with a smaller (n=140) sample of more specifically measured landmarks manually collected from 3D body scans. We find that RTW sizing results in problematic variability of landmark position for a large portion of the population, with potentially important implications for the placement of garment-integrated sensors. Results illustrate the need for consideration of non-traditional sizing strategies for garment-integrated sensing.

Author Keywords

Wearable technology; smart clothing; wearable sensing; sizing; fit; apparel design.

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J.3. Life and medical sciences (Health); H.1.2 User/machine systems (Human factors); I.2.9 Robotics (Sensors).

INTRODUCTION

The sizing and fit of clothing is a system that for many consumers is hopelessly opaque, and/or viewed as a product of a nefarious industry bent on manipulating the self-image of its customers [1]. At best, both the problem and the solution are poorly understood, even within aspects of the garment industry itself. In most countries, although sizing guidelines have been issued by various standards organizations such as the EN 13402 European Clothing Size Standard, the Japanese Industrial Standard (JIS), the American National Standards Institute (ANSI), and the International Safety Equipment Association (ISEA), the degree to which they are used outside of government-influenced sectors like military clothing varies widely. Indeed, studies of the variability of human anthropometrics often clearly show that to effectively fit the variability of a given population, manufacturers would need to produce and distribute a huge number of sizes: making it difficult both for the manufacturer to profit, and for the consumer to understand how to select the appropriate size [2].

The consumer market for smart garments and wearable technology continues to grow. However, as much of the development of these garments is initiated from the tech sector (rather than the apparel sector), issues related to the manufacture and use of clothing can go unnoticed until late in the development process. Here, we consider the interaction of the need for precise placement of sensors on the body surface and the sizing increments assumed by a RTW sizing system.

BACKGROUND

Garment Grading, Sizing, and Fit

Human anthropometry (the dimensions of the human body) is, in general, far more variable than might be assumed. There are very few strong correlations between any two body dimensions across a population. The **fit** of a garment is defined by the relationship between the dimensions of the body and the dimensions of the garment. Fit is a designed parameter of a garment – some garments can be designed to fit tightly, and some loosely.

Because much RTW clothing is designed to fit reasonably closely to the body, it is often not economically possible to produce enough shapes to effectively fit the entire population, and therefore necessary to define the small set of shapes (**sizes**) for a given garment that *can* be produced. Figure 1 illustrates this challenge: the correlation in this case between waist and hip is not perfectly linear. The solid boxes show the bodies that would be fitted by a garment that is designed to adequately fit bodies within 1" of its dimensions. However, the dashed boxes show the bodies that may attempt to fit into that size, resulting in a poor match between body and garment dimensions. The position and size of each "box" defines the sizing system used for a particular garment. Adding a parallel line of boxes above and below the solid boxes would provide more bodies with well-fitting garments, but doubling or tripling the number of sizes has huge implications for the entire supply chain of garment manufacturing and is often not feasible.

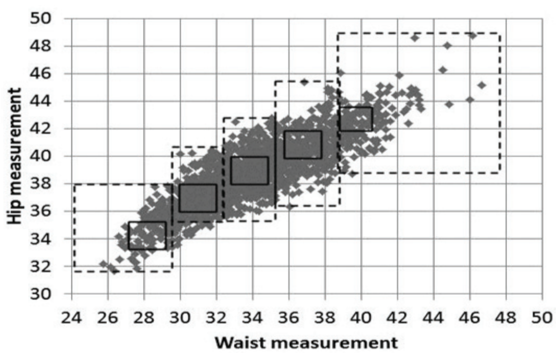


Figure 1. Body dimension spread assumed by a sizing system (solid boxes) and body dimensions within an actual population (dashed boxes). (Image from [2]).

The center of each solid box in Figure 1 is the "body size" for each garment size – the middle of the spread of dimensions deemed to be adequately fitted by that size. That set of articulated body size definitions makes up a **sizing system.** Sizing systems for apparel emerged in the US with the first ready-to-wear clothing, around the time of the Revolutionary War. Early sizing systems were mostly based on guesswork, but became formalized with the first somewhat large-scale anthropometric survey in 1940 and the resulting government sizing standard in 1970, which was based on data collected in 1940. The ASTM D-5585 and D-6240 US garment standards are based on data collected in 1993 [3]. However, it is unclear how many retail manufacturers use regulated sizing standards in their day-to-day practice (anecdotally it would seem very few do, relying instead on tradition, rules derived from a competitor brand, or – much more rarely – experiential investigation of the dimensions of their consumer population). In reality, at minimum the center size of the range and at best each size in the range is represented by an individual actual body (human or mannequin). Therefore, while the sizing standard may articulate only a small sub-set of the possible dimensions of the body, in practice the remaining 3D dimensions are defined by the individual body that will be used for garment development. Each body size in the range is made smaller or larger by specific increments (in the case of mannequins, a 3D body shape can be precisely scaled into different shapes but much more commonly these are rough approximations that grow by specific increments in the key measurement dimensions, but that may have other variability in 3D topography). In many cases, only some of the sizes in the range will be fit-checked on bodies, and the remainder are assumed to be correct.

From the increments between body sizes, growth between garment sizes in the horizontal and vertical dimensions is specified in the form of **grade rules**, rules for the distribution of the increment across a pattern piece. For example, as the circumference of the body grows, the grade rule distributes that growth around the circumference un-equally – bodies don't typically get larger like nesting dolls, they grow more in some areas than others.

Most manufacturers establish their own sizing system and grade rules. In some sizing systems (more commonly in the EU, or for menswear in the US), sizes are labelled based on a given body measurement, like the waist circumference or leg length. In other systems, size labels do not correspond to any specific body dimensions, such as the Small/Medium/Large labelling system or the womenswear numeric sizes (2-4-6-8, etc.). In those cases, it is entirely at the discretion of the manufacturer to determine the body dimensions that correspond to each garment size.

As previously mentioned, the amount of anthropometric variability in the human population would make it difficult for a manufacturer to be profitable if they needed to produce enough sizes to fit the entire population. A centralized standard might make the relationship between a size label and garment measures more consistent, but would effectively exclude large parts of the population from finding well-fitting RTW clothing. Current practice, where each manufacturer plots their individual size grade, is likely to ultimately end up fitting more body shapes (albeit with the burden of locating the correct manufacturer and size placed on the consumer).

A typical garment development workflow proceeds like this:

1) Initial garment design is established;
2) One or (usually) more prototypes is developed and refined to fit the fit model for the middle size of the range;
3) When the garment pattern (which determines the shape and fit of the garment) is finalized, its shape is made bigger and smaller in 2D by moving the points that define the pattern shape (cardinal points) according to increments specified in the grade rule;
4) Sample garments are (sometimes) made in the full size range and (sometimes) fit on mannequins or fit models for each size;

5) (Sometimes), the grade rules are tweaked to improve fit in different sizes;
6) When the graded pattern is finalized, the garment is put into production.

Importantly, a grading process does **not** specify the garment fit, only the way that fit changes as the pattern is made bigger or smaller. The garment pattern is independent of the grade rule – the same grade rule can be applied to a loose-fitting garment pattern or a tight-fitting garment pattern. Similarly, grade rules are used to produce garments in different sizes, but they do not specify the dimensions of a garment that is assigned that size (for example, a loose flowy top can be correctly marked the same size as a tightly fitted top). Because the fit is perfected on a specific body, it is implicitly assumed that all other bodies that fit this size will be the same shape. Of course that is not true in practice, but in RTW the implications of imprecise fit are mild and acceptable given the economic tradeoff. Because of this, most garments are designed to include some amount of wearing ease. Ease is defined as the difference in dimension (usually circumference) between the garment and the body. Ease is usually a positive number, but in the case of closely-fitted stretch garments or compression garments, it may also be negative. Wearing ease allows for the expansion of certain body areas during movement (such as across the shoulders during protraction), but also allows a garment to fit a wider range of body dimensions (equivalent of making the solid boxes in Figure 1 larger.)

Finally, the increments between sizes also vary. In some cases, this variability is driven by cost: in most instances it is more expensive to produce more sizes than fewer sizes. In other cases, it is driven by the style of the garment: loosely-fitted garments can use a larger increment between sizes and still "fit" the same population. However, the increment between sizes is also affected by the fabrication of the garment. Typical increments between sizes for woven (non-stretch) garments are usually in the 1"-2" range for adults, where typical increments between sizes for knit (stretch) garments can be 4" and larger.

Several studies in the apparel field have examined the difficulty of creating sizing systems to fit the variability found in a large population [4], [5]. Solutions to the problem have ranged from creating an optimized size system based on anthropometric data [4] to modifying the body sizing table and ease amounts at the bust and hip [5]. While the research offers methods to improve RTW sizing, consumer dissatisfaction with size and fit [3] would indicate that current sizing systems have not adequately improved. Innovative but technologically complex approaches like automated custom fit have been proposed but have not yet been successful in mass-market RTW trials [6], [7].

Wearable Technology and Fit

As the limitations of wristband-type wearable technology become increasingly apparent, it is likely that commercial products will need to transition into garment forms to achieve body access. However, a key obstacle to garment-integrated technology (especially for sensing) is the challenge of achieving accuracy. For garment-integrated body sensing, the influence of garment movement [8]–[11] and the fit of a specific garment [12], [13] have been explored, if not fully resolved. However, these studies focus on single garments or specific fits, and do not address the kind of fit variability that would happen in a commercial development process that uses typical approaches to garment sizing. Wearable sensing is an area where precision and accuracy needs are perhaps most dramatically affected by the position and placement of the embedded sensor relative to the body beneath, but the placement of a technology on the body is also important in other domains like actuation and display. Many sensing domains are affected by sensor positioning, including biomechanical signals like joint movement [14], thermal signals [15], optical signals like pulse [16], and vital signs like heart activity [17], and breathing [18], [19], [20]. Within sensing, the acquisition of electro-dermal signals is perhaps the area most sensitive to sensor (in this case, electrode) placement.

Electro-dermal sensing, which senses electrical potentials of the body through conductive electrodes in contact with the skin, includes electromyography (EMG, sensing of the electrical activity of the muscles), electrocardiography (ECG, sensing of the electrical activity of the heart), electroencephalography (EEG, sensing of the electrical activity of the brain), and galvanic skin response (GSR, sensing of the conductivity of the skin). Here, we will focus on ECG signal acquisition, which is achieved through electrodes placed on the torso surface, with many layers of muscle and bone between the electrode and the active muscle (the heart). Typical ECG sensor placement paradigms rely on positioning of electrodes relative to anthropometric landmarks like the ribs and sternum [21]. Previous studies have shown that as little as a 2cm longitudinal shift in chest lead positions by clinical technicians can result in a 25% change or more of R wave amplitudes causing major diagnostic errors [22]. Moreover, placement inaccuracy of chest leads has been shown to alter computer-based diagnostic statements in up to 6% of recordings [23], [24].

METHOD

In this study, we sought to contextualize common grading increments in terms of their effect on the placement of a hypothetical set of ECG electrodes embedded in a knit garment. In our approach, we imagine an ECG-sensing shirt that has been developed and optimized for a given fit model, with effective electrode placement for that individual. If that shirt is then put into common RTW production processes, how far from the optimal location will the electrodes fall on the full range of bodies within a population? To narrow our analysis, we selected one point on the torso to represent an electrode position.

The actual dimensions or fit of the hypothetical garment in question are not specified, nor are they necessary: for any given garment shape, we assume the development process results in correct fit for one body, and compare the variability of other bodies within a specified grade rule increment.

To conduct this investigation, it is necessary to select both a grading system and a human population. There is an immense amount of variability in both of those categories, and a comprehensive dataset is not available for either. Because no ideal anthropometric database exists that has collected the body dimensions specified by a standardized sizing system, we conduct a two-phase analysis. In the first phase, we analyze the variability in a large anthropometric database, from which the measures we are able to use are not perfectly matched to the specifications of the sizing standard (we perform a transformation to better match the data to the sizing specification), and in which the available measures are general torso lengths and widths (rather than the location of a specific point on the torso). Subsequently, we analyze a smaller sample of manually measured 2D dimensions for a specific point on the torso, using 3D human body scans.

Sizing System

In this study, we evaluate the ASTM D6240-98 system for menswear, the ASTM D5585-11 system for womenswear, and a Unisex sizing scenario created using a reduced version of the menswear size range, a common base for Unisex clothing. A unisex scenario was included to fit both populations with one sizing system, a common approach for garment categories like functional apparel in medical and protective industries. Although it is unclear how widespread the use of the ASTM standard is in RTW, it is likely that it does not accurately represent the precise body sizes used by RTW manufacturers. RTW sizing is often considered proprietary or confidential information and not readily available from manufacturers. However, for this investigation the important aspect of a sizing system is not the base body sizes, but the **increment** between sizes. Our intent is to evaluate the amount of anthropometric variability in a human population within each size, which for a consistent increment should not change substantially based on what the "target" body within that span is.

The **body** sizes specified by the ASTM D6240-98 and ASTM D5585-11 specifications are described in Tables 1 and 2. In order to determine the effect of garment size on placement of electrodes across the ANSUR population, it was necessary to extract torso measurements in two dimensions: length (vertically) and width (horizontally). Specifically, we focus on two dimensions identified in the standard and used to articulate body sizes, the horizontal dimension of Upper Chest and the vertical dimension of Center Front Natural Waist Length.

From the ANSUR database, we extracted two dimensions corresponding to the ASTM chest and waist length measures: "Chest Breadth" and "Center Front Natural Waist Length" from the ANSUR database.

However, there is not a perfect match between the methods used to collect the measures specified in the ASTM standard and the body measures recorded in the ANSUR study. Specifically, the ASTM upper chest measure is taken with a tape measure placed on the surface of the chest, from underarm to underarm, representing a measure of the surface contour of the chest, while the ANSUR chest breadth measure is taken with a caliper from underarm to underarm, representing a linear measure of the chest. Similarly, ASTM gives no anthropometric direction about the landmarks used to determine the Center Front Natural Waist Length measurement. Therefore, mean measurements of the ANSUR population rarely aligned with the middle of the ASTM sizing system. Figure 2 illustrates how the ASTM sizing system dimensions were skewed compared to the ANSUR database measurements. In order to compensate for this, and operating under the assumption that the ASTM standard would aim to center the middle size around the median of the population, we adjusted the middle size of each ASTM sizing system (a standard starting point for grading) to align with the mean of the ANSUR database in the horizontal and vertical dimensions. After the center size dimension was created, we used the established ASTM grade rules (without changing the inter-size increment) to create the remaining sizes (as seen in Tables 1 and 2).

ASTM D5585-11 Size	ASTM Upper Chest (mm)	ASTM CF Waist Length (mm)	Re-Centered Chest Breadth (mm)	Re-centered CF Waist Length (mm)
34	346.1	393.7	292.4	408.8
35	352.4	393.7	298.7	408.8
36	355.6	393.7	301.9	408.8
37	362	393.7	308.3	408.8
38	365.1	393.7	311.4	408.8
39	371.5	393.7	317.8	408.8
40	374.7	396.9	321	412
41	381	396.9	327.3	412
42	387.4	396.9	333.7	412
43	393.7	396.9	340	412
44	400.1	400.1	346.4	415.2
45	406.4	400.1	352.7	415.2
46	415.9	400.1		

Table 1. Men's Size System, ASTM D6240-98.

ASTM D6240-98 Size	ASTM Upper Chest (mm)	ASTM CF Waist Length (mm)	Re-Centered Chest Breadth (mm)	Re-centered CF Waist Length (mm)
00	314.3	352.4	248	341
0	320.7	355.6	255	344.2
2	327.0	358.8	265	347.4
4	333.4	362.0	274	350.5
6	339.7	365.1	283	353.7
8	346.1	368.3	293	356.9
10	352.4	368.3	302	360.1
12	355.6	371.5	313	363.3
14	362.0	374.7	319	366.4

Table 2. Women's Size System, ASTM D5585-11.

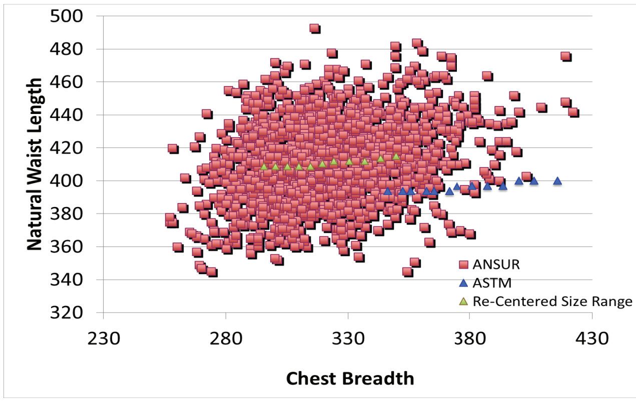


Figure 2. Men's Front measurement comparison: ANSUR data with original and re-centered ASTM size ranges.

Human Population: CAESAR

Because of the previously discussed limitations with the available ANSUR measurements, we collected a smaller sample (n=140, 60 women) of measurements from 3D human body scans extracted from the Civilian American and European Surface Anthropometry Resource Project (CAESAR). This database contains the most current measurements for bodies today and was developed from a comprehensive research project. It contains anthropometric measures of civilian men and women between the ages of 18 and 65 and was conducted from 1990-2000. A random sample of five scans was selected within each ASTM size, as determined by chest circumferences. Because the CAESAR population is civilian, the range of bodies is much larger than in the ANSUR military population (particularly at the large end of the spectrum). Therefore, for women we extended the ASTM size range up to size 20, and for men we extended the ASTM size range up to size 52.

The CAESAR library of measures includes a surface measure of chest breadth (rather than a distance measure of chest breadth, used by ANSUR), which is measured in the same manner as the ASTM standard specifies. Further, because these are 3D surfaces of actual bodies, we were able to manually measure on each body the position of one of the landmarks placed by the study: in our case, the 10th Rib landmark (shown in Figure 3). NB: the 10th rib is not necessarily an ideal electrode placement for ECG. However, it is a specific ribcage-based landmark, which we would expect to show similar anthropometric variability as actual electrode placements, which are also based on ribcage references. Position of the 10th rib landmark was measured in the X (horizontal) and Y (vertical) dimensions, relative to the position of the shoulder-neck intersection, or High Point Shoulder (HPS) which in apparel is the main reference point from which other garment measures are oriented.

Data Analysis

ANSUR analysis

Once the ASTM and ANSUR data were aligned, each ANSUR subject was assigned to the best-fitting ASTM size, according to their chest breadth. For a given size, the range of body dimensions in the ANSUR population fitted by that size was calculated for the two key dimensions: chest breadth and natural waist length. Because participants were fitted directly by the re-centered chest breadth, the mid-range chest breadth distribution always matched the increment between sizes. However, for the smallest and largest size, all body sizes below and above these sizes would also be included.

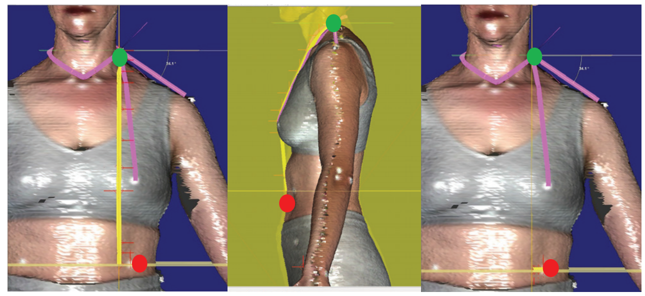


Figure 3: Measurement of 10th Rib landmark position (red dot) in X (right) and Y (left) directions (yellow lines), from the HPS reference point (green dot), and side view showing surface measurement method (center).

Variability (range of horizontal and vertical torso measurements) was calculated for three conditions: female ANSUR subjects fitted by the ASTM women's standard (even numerical sizes), male ANSUR subjects fitted by the ASTM men's standard (even numerical chest circumferences), and both male and female ANSUR subjects fitted by a unisex increment. The original men's sizes used for the unisex sizing system were as follows: XS=34-35, S=36-37, M=38-40, L=41-43, XL=43-45. For the unisex condition, we collapsed the men's size range to XS-XL and re-centered the size range based on the full population of the ANSUR database.

CAESAR analysis

For the CAESAR scan data, each CAESAR subject was assigned to the best-fitting ASTM size according to their the chest circumference (the most common body measure to determine the appropriate size of a fitted shirt, as it is usually the largest circumference on the garment and the body). For each segment of the population fitted by each size, the variability in X and Y position of the 10th Rib landmark relative to the HPS was calculated.

RESULTS

ANSUR data

ANSUR body dimension spreads within each ASTM size for our three sizing conditions are shown in Figures 4, 5, and 6.

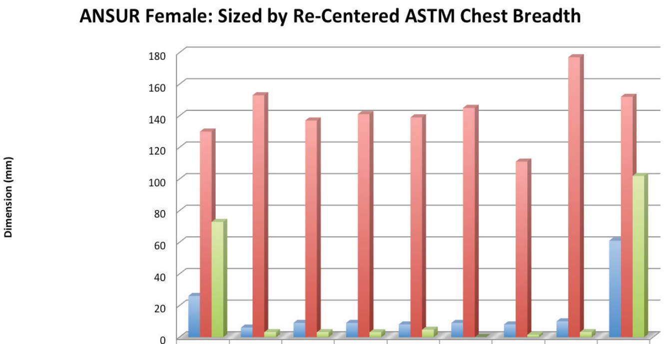
CAESAR data

CAESAR landmark position spreads within each ASTM size for our three sizing conditions are shown in Figures 7-9.

DISCUSSION

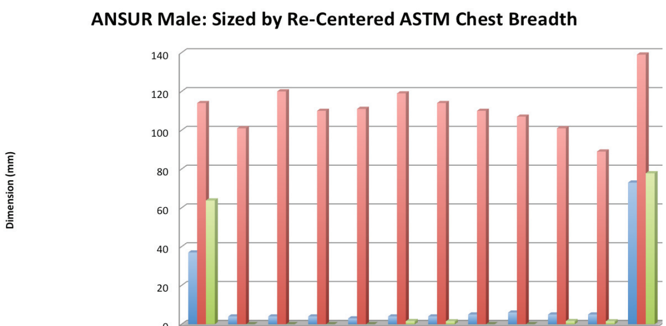
ANSUR data

As seen in figures 4-6, the vertical spread within the population fit by each size for gender-specific sizes ranges from a minimum of around 89mm in the male size 44 to 177mm in the women's size 12. For the unisex condition, that variability jumps to 193mm in the size L. Overall the spread is smaller within sizes for the men's population, as that sizing system has a larger number of sizes (and therefore a smaller increment between sizes.)



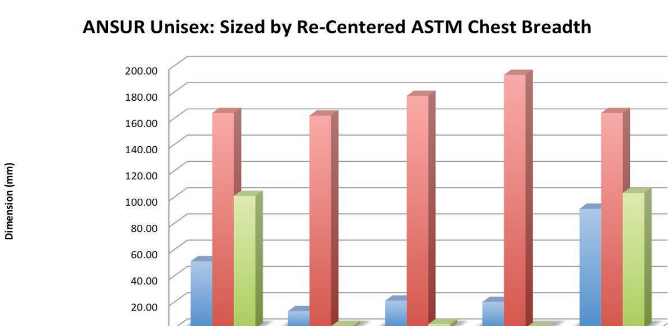
	00	0	2	4	6	8	10	12	14
Horizontal spread: ANSUR BODY	26	6	9	9	8	9	8	10	61
Vertical spread: ANSUR BODY	130.00	153.00	137.00	141.00	139.00	145.00	111.00	177.00	152.00
Vertical spread: ASTM GRADE	72.86	3.12	3.11	3.06	4.66	0.00	1.45	3.15	101.95

Figure 4. ANSUR Women's front horizontal and vertical body spread compared to ASTM spread grade.



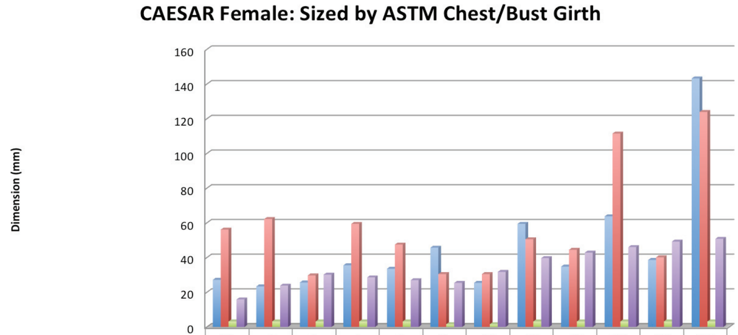
	34	35	36	37	38	39	40	41	42	43	44	45
Horizontal spread: ANSUR BODY	37	4	4	4	3	4	4	5	6	5	5	73
Vertical spread: ANSUR BODY	114.00	101.00	120.00	110.00	111.00	119.00	114.00	110.00	107.00	101.00	89.00	139.00
Vertical spread: ASTM GRADE	63.80	0.00	0.00	0.00	0.00	1.60	1.50	0.00	0.00	1.60	1.50	77.80

Figure 5. ANSUR Men's front horizontal and vertical body spread compared to ASTM spread grade.



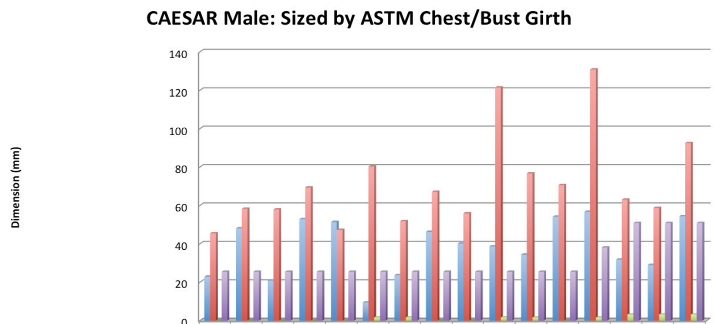
	XS	S	M	L	XL
Horizontal spread: BODY	51.00	13	21	20	91
Vertical spread: BODY	164.00	162.00	177.00	193.00	164.00
Vertical spread: ASTM GRADE	100.80	1.60	3.10	0.30	103.00

Figure 6. ANSUR Unisex front horizontal and vertical body spread compared to ASTM spread grade.



	00	0	2	4	6	8	10	12	14	16	18	20
Horizontal spread: CAESAR BODY	27.18	23.37	25.66	35.56	33.53	45.72	25.4	59.43	34.8	63.76	38.61	143.25
Vertical spread: CAESAR BODY	56.13	62.23	29.72	59.44	47.49	30.48	30.48	50.54	44.47	111.50	40.13	123.95
Vertical spread: ASTM GRADE	3.18	3.18	3.18	3.18	3.17	1.59	1.59	3.18	3.18	3.18	3.17	3.18
Horizontal spread: ASTM GRADE	15.875	23.8125	30.1625	28.575	26.9875	25.4	31.75	39.6875	42.8625	46.0375	49.2125	50.8

Figure 7. CAESAR Women's horizontal and vertical 10th rib position spread compared to ASTM spread grade.

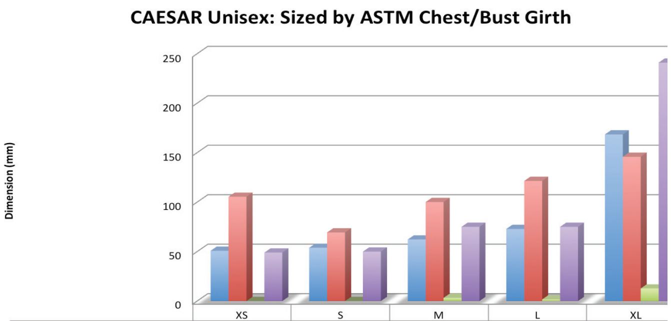


	34	35	36	37	38	39	40	41	42	43	44	45	46	48	50	52
Horizontal spread: CAESAR BODY	22.86	48.01	20.83	52.83	51.31	9.4	23.62	46.22	40.13	38.61	34.29	54.1	56.64	31.75	28.96	54.36
Vertical spread: CAESAR BODY	45.47	58.17	57.91	69.34	47.24	80.26	51.81	67.05	55.88	121.41	76.71	70.61	130.81	62.99	58.67	92.45
Vertical spread: ASTM GRADE	0.00	0.00	0.00	0.00	0.00	1.59	1.59	0.00	0.00	1.59	1.59	0.00	1.59	3.17	3.17	3.18
Horizontal spread: ASTM GRADE	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	25.4	38.1	50.8	50.8	50.8

Figure 8. CAESAR Men's horizontal and vertical 10th rib position spread compared to ASTM spread grade.

The Unisex evaluation illustrates the greatest vertical spread within sizes, with an average of 133mm of difference between the shortest and tallest torso in each size. Figure 10 illustrates this variability graphically: it shows a shirt sized Unisex "Large", for which the median length of torso within the "Large" bodies fits with accurate electrode placement. However, the minimum and maximum length torsos result in a shift that is at least one rib away from the intended placement of the electrode. This represents a significant error in sensor placement, likely to have adverse effects on the accuracy of body sensing.

The vertical spread of the ASTM grade shown in Figures 4-6 reflects the difficulty of sizing in the vertical as well as horizontal dimension. The lack of increase in vertical spread as sizes increase indicates the limited range of vertical variability within any given size. The ASTM standard does not use a consistent vertical growth between sizes, which is atypical of RTW. However, the growth increment is very small in most sizing systems.



	XS	S	M	L	XL
Horizontal spread: CAESAR BODY	50.8	53.85	62.23	72.9	168.4
Vertical spread: CAESAR BODY	105.41	69.34	100.07	121.41	145.80
Vertical spread: ASTM GRADE	0.00	0.00	3.18	1.59	12.70
Horizontal spread: ASTM GRADE	49	50	75	75	241

Figure 9. CAESAR Unisex horizontal and vertical 10th rib position spread compared to ASTM spread grade.

Width measures show more consistency, as we are fitting based on circumference in this example. However, the smallest and largest sizes must accommodate the tails of the distribution, and exhibit a larger amount of horizontal variability. For the smallest sizes, women show 26mm of potential mis-fit in circumference. The smallest woman experiences error of 51mm. That means a garment that is not likely to be in good contact with the skin (never mind placing the electrode accurately).

CAESAR data

The CAESAR analysis results shown in Figures 7-9 reflect the position of the 10^{th} rib landmark relative to the HPS landmark. Similar to the results from the ANSUR data comparison, CAESAR data comparison shows a large amount of variability within the vertical spread on the body. However, overall there appears to be a much larger vertical spread among ANSUR subjects, versus CAESAR bodies, which is partly explained by the ANSUR measure being a longer distance (neck to waist) than the CAESAR measure (shoulder to 10^{th} rib). Nonetheless, there is a great deal of variability in vertical 10^{th} rib position, ranging from 30 to 131mm in the gender-specific sizes and 69-146mm in the unisex condition.

While the ANSUR analysis did not permit the evaluation of the variability in horizontal position of a landmark on the torso, CAESAR data shows 9-143mm of spread in the gender-specific sizes, 51-168mm in the unisex condition. This is an immense amount of variability in the worst cases: important to note that for outlier bodies in the smallest and largest sizes, the garment may not fit at all (especially for largest bodies, who may not be able to put the garment on).

Figure 11 shows the "best-case" and "worst-case" scenarios for sensor placement on a chest garment. CAESAR measurements for 10^{th} rib positions within each size for all 3 conditions were used to create scatterplots. The scatterplots with the least and most amount of variability are shown here, superimposed on a front shirt pattern block for their respective size to show the landmark position in context. Variability is evident even in the best-case scenario, but is extreme for the worst-case female size 20. The strongest outlier has a 10^{th} Rib position outside of the garment (as the largest size in the range this garment would be expected to fit all larger bodies).

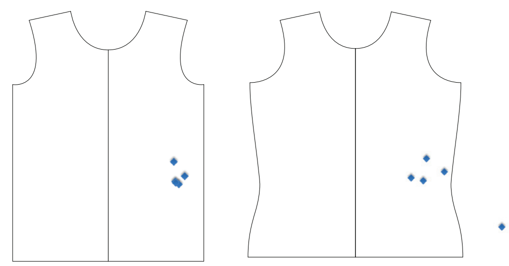


Figure 11. Best-case scenario (Left, Male size 39) and worst-case scenario (Right, Female size 20) for sensor placement.

CONCLUSION

From the analysis presented here, it is clear that RTW sizing presents an obstacle for accurate sensor placement within off-the-shelf garments. For wearable sensing applications that require accuracy in sensor placement, it is likely that an advanced, adjustable, or mass-customized sizing system may be necessary. The results of this study can be used to characterize that need, and to inform the design of a sizing system or paradigm suited to a specific sensing application.

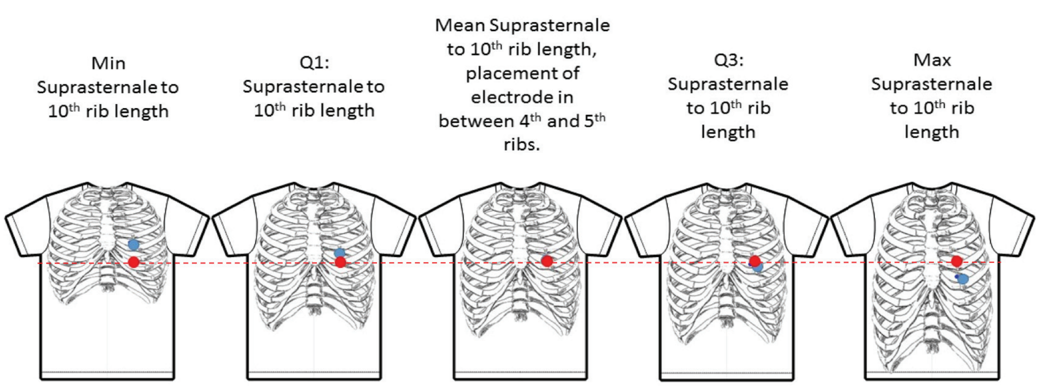


Figure 10. Visualization of the effect of anthropometric variability in length of the ANSUR population on placement of an ECG electrode in the "Large" size unisex garment across population quartiles (red = actual location, blue = expected location on body).

When developing design requirements for a garment with integrated sensors, it is crucial that the sizing system be considered from the beginning of the development process. Targeted sizing and design solutions can then be pursued much earlier, reducing unexpected and significant adverse affects when garments are sold. Application developers should critically evaluate their design requirements in conjunction with anthropometrics of the targeted population of wearers before the prototype phase begins. This will allow a design and sizing solution specific to the needs of the garment to be addressed in a more holistic manner.

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