# An Analysis of Anthropometric Geometric Variability of the Lower Leg for the Fit & Function of Advanced Functional Garments

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## ABSTRACT
As advanced functional apparel (e.g. wearable technology) continues to develop and permeate the consumer market, sizing and fit for the human body have become obstacles to consumer accessibility and garment functionality. This study develops sizing and design strategies for an advanced functional compression garment for the lower leg through an investigation of anthropometric geometric variability of the North American civilian population (using the CAESAR database). We extracted six lower leg measurements - ankle, calf, and knee circumferences as well as knee-to ankle, knee-to-calf, and ankle-to-calf lengths - from a sample of CAESAR three-dimensional body scans ($n = 160$) and ran descriptive statistics to quantify lower leg variability.

We then arranged the sample population separately using six different grouping variables - body mass index (BMI), height, weight, knee-to-ankle length, ankle circumference, calf circumference, and knee circumference - and conducted an analysis of variance (ANOVA) using each sorting algorithm to determine which variable(s) produced the most distinct groups (quartiles) for the anthropometric dimensions of interest (e.g., lower leg circumferences/lengths).

The results conclude that sorting by BMI does not produce statistically discrete sizes; however, sorting by ankle circumference does ($p < 0.05$). Furthermore, length was found to be independent from circumference and vary consistently between ankle-based size groups. We conclude with sizing and design strategies for future development of advanced functional garments to aid in the transition from research to industry.

### Author Keywords
Advanced functional garments; wearable technology; sizing systems; body variability; compression garments


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

## INTRODUCTION
Functional garments are clothing designed to meet a specific set of user needs, typically extending beyond aesthetic needs [1]. Examples of functional garments include clothing that affords the user enhanced environmental protection, medical or therapeutic benefits, sports performance, or vanity satisfaction (e.g. body shapewear). Many garments provide multi-functionality (e.g. spacesuits), and special needs services (e.g. wheelchair gloves) [2]. Advanced functional garments are functional garments that achieve their function through integrated sensing and/or actuating components (e.g. electrocardiography (ECG) shirt (sensing garment), robotic exosuit (actuating garment) [3], [4].

The success of advanced functional garments is often dependent on proper placement of sensing and/or actuating components on the body as determined through garment sizing/fitting methodologies in the absence of customization [3], [5]. While clothing fit is defined as the relationship between the garment and the body, sizing is the method of adjusting all garment dimensions to maintain the desired fit across a designated population [1]. Poor fit and subsequent poor placement of actuators/sensors on the body can result in under-performance (e.g. sensing garments might pick up a weak signal; actuating garments might deliver a weak force to the body) and counter-performance (e.g. misplacement of sensing components could cause noise that obstructs the sensed signal or sends the wrong signal; misplacement of actuating components could deliver force to the wrong area of the body and hinder movement) [3], [5].

Due to the sensitivity and criticality of sensor-body and actuator-body interfacing, common ready-to-wear (RTW) apparel sizing methodologies do not meet the fit requirements of advanced functional garments for a consumer market. This research seeks to develop novel sizing and design strategies for advanced functional garments to maintain proper fit/placement across a large population. For the purpose of this paper, we will evaluate anthropometric variability and develop advanced functional garment sizing methodologies around a novel, active compression garment design for the lower leg.

## BACKGROUND

### Shape Memory Alloy Compression Garments (SMA-CG)

Here we evaluate geometric variability of the lower leg and seek to develop a sizing and fitting methodology for a novel, shape memory alloy (SMA) activated compression garment (SMA-CG). This advanced functional garment for the calf (depicted in Figure 1) delivers therapeutic pressures to the body by integrating contracting SMA springs, as outlined by Holschuh et al [6]. Compression therapy for the lower body is prescribed by physicians to treat a range of disorders, including orthostatic hypotension, postural orthostatic tachycardia (POTS), lymphedema, and deep vein thrombosis (DVT). Knit stockings are commonly used compression therapy because they are low-profile and do not inhibit mobility; however, they are difficult to don/doff and they are neither controllable nor dynamic. Pneumatic compression garments are easy to don/doff and are both controllable and dynamic; however, they are bulky, inhibit mobility, and are usually tethered to an inflation source. Active, SMA coils enable the design of novel SMA-CGs that are simultaneously mobile, dynamic, and untethered, as detailed in [7].

**Figure 1. Shape Memory Alloy Compression Garment**

The pressure generated by SMA-CG has been shown to be dependent on precise fit, specifically the ratio between the garment's circumferences and the limb's circumferences [7]. Consequently, to maintain fit across a population, garment circumference must vary in response to (1) individual dimensional changes (e.g. ankle circumference vs calf circumference) and (2) variability in population anthropometrics. Consequently, to design an SMA-CG for a North American consumer population, we need to know the lower leg dimensional variability of our population, determine the critical dimensions for SMA-CG design, and develop methods for adjusting critical dimensions across our population to maintain fit.

### Anthropometric Resources

While there are many sources of anthropometric information, databases vary in the type of information they contain (e.g. dimensions vs. body scans) and the populations they sample. Outdated (e.g. ASTM), military (e.g. ANSUR), and overly specific or small populations (e.g. NASA Anthropometric Sourcebook) may not effectively represent a population of interest. The Civilian American & European Anthropometric Resource (CAESAR) is a database of three-dimensional body scans of a large civilian population. Measured dimensions allow direct quantitative assessment of a population, but are pre-defined by the survey and limited. 3-D scans allow for dimensional extraction straight from the surface scans; however, the extraction process is time consuming.

### Garment Patterning

While the limited measurements readily available within current anthropometric databases are enough to pattern ready-to-wear (RTW) clothing, they are not sufficient for garments requiring a skin-tight fit for a diverse population, especially when functionality is dependent on that fit, as shown in Figure 2. Apparel patterning is the process of developing 2D shapes used to create a 3D form [8]. At least one length and one width are needed to create a garment pattern; however, the more dimensions that are incorporated into the pattern, the more complex the 3D form geometry can become. Figure 3 shows a series of patterns that could be developed for the calf garment depending on the number of dimensions available.

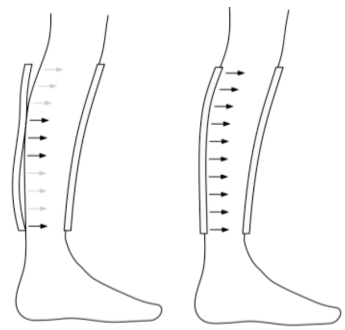

**Figure 2. Poor fit results in uneven pressures (left), proper fit results in even pressures (right).**

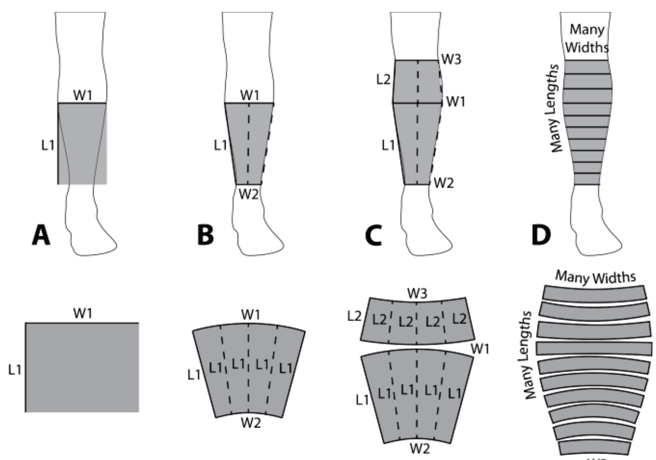


**Figure 3. Garment patterning with a) 2 dimensions, b) 3 dimensions, c) 5 dimensions, and d) many dimensions**

### Ready-to-Wear (RTW) Sizing & Fit

While fit and sizing challenges are magnified in advanced functional apparel design, they are pervasive within all apparel markets. Apparel sizing systems are developed to provide a limited number of sizes, or garments with a specific set of dimensions, to the population [9]. In the RTW garment industry, sizing systems are typically based off a specific set of dimensions as determined by a mannequin or a fit model (i.e. a person representative of the base size), then systematically graded (i.e. increased or decreased in dimension) to form larger and smaller sizes [9]. The grade rules are implemented by determining the amount that key points on the garment pattern should be systematically moved in the x or y direction [1]. While standards exist, grade rules used in the industry are most commonly determined by the designer or company; therefore, clothing fit varies between brands [10].

The number of sizes needed are determined by the ease that is acceptable within each size and the fabric stretch properties [10]. Ease is defined as dimensional difference between the garment and the body [11]. Ease is added for aesthetic (to alter the garment's silhouette), functional (to improve user mobility), and practical reasons (to fit a larger subset of the population). Fitting a population with less ease requires more sizes, because there is less room for variation within each size. High-stretch fabrics are often used in RTW clothing when a close-fit is required because extensible garments accommodate greater dimensional variation.

Almost all sizing systems are limited in their ability to fit a broad population, both because of limitations in the span of the size range (individuals above and below the range are not fit), but perhaps more significantly because most systems assume some correlation between body dimensions when very little exists in most populations. The latter results in individuals who may fit a given size for a given dimension, but not in other dimensions. The complexity of human body geometry means a system that effectively fits a population would require a prohibitively complex number of sizes [9].

Garment mass-customization is an alternative to RTW sizing and has potential to improve the fit of advanced functional garment. However, current computer-aided methods for developing mass-customized patterns are not capable of producing perfect fit for the consumer market [12]. Additionally, manufacturing one-off custom garments can be expensive and time consuming.

### Functional Garment Fit & Sizing

To design a successful sizing strategy for advanced functional garments (e.g. SMA-CG), traditional RTW fit and sizing methodologies require modification. Griffin et al. evaluated the effectiveness of the ASTM sizing standard when applied to the placement of ECG electrodes integrated into a shirt. They concluded that RTW is not an effective way to size sensing garments and a "more advanced, adjustable or mass-customized sizing system" is required for garments with precise sensor placement [3]. Because advanced functional garments require precise placement of actuators/sensors on the body, they usually need to be designed using inextensible fabrics to prevent garment drift and anchor to the body. Other wearables that are affected by sensor or actuator placement include human exosuits [5], sensing garments [13], and heating/cooling garments [14].

This research seeks to develop methods for quantifying and evaluating anthropometric variability in the North American consumer population within groups specified by different anthropometric dimensions, to inform the development of sizing systems and design strategies that satisfy the needs of advanced functional apparel intended for the consumer market.

## METHODS

### Civilian American & European Anthropometric Surface Anthropometry (CAESAR)

The CAESAR survey provided the foundational data for this study: the survey contains 2391 3-dimensional body scans ($N_{female}$ = 1264; $N_{male}$ = 1127) of North American civilians taken from the year 1998 to 2000. CEASAR offers a representative sample of our target population (North American civilian consumers). The database of body scans is accompanied by 40 additional pre-measured dimensions for each body/participant gathered by traditional means, such as measuring tapes and calipers. Dimensions that were not pre-measured could be obtained by manual extraction from each individual body surface scan.

### Sizing System Approach

Traditionally, apparel sizing systems are developed by determining key, correlating body dimensions from a large dataset through statistical analyses, such as principal component analysis (PCA) or random decision forest [1]. Only 2 of the 40 CAESAR pre-measured dimensions were relevant to the lower leg; therefore, analyses that require a large dataset were impractical for our data source. Through our knowledge of patternmaking (see Figure 3) we hypothesized 6 dimensions, shown in Figure 4, that could provide the foundational dimensions for a SMA-CG sizing system, once statistically evaluated for covariance. It was impractical to manually extract these dimensions for all 2391 CAESAR scans; therefore, we chose to sample 80 scans.

### Population Sampling

To provide a representative sample (n = 80) of the full distribution of lower leg dimensions, we sought to determine a predictive variable that would place the CAESAR population in a framework of incrementally increasing, lower body proportion (i.e. smallest leg dimensions to largest leg dimensions). From this framework, we could randomly sample from sub-groups and ensure our sample contained the full breadth of possible dimensions. Determining how to create this framework without having access to specific dimensions was a challenge. With only major body measurements available in the list of 40 pre-measured dimensions (e.g. height, weight), we hypothesized that overall body height would be the greatest influencer of leg lengths, while overall weight would be the greatest influencer of leg circumferences. The calculation for body mass index (BMI) factors in both height and weight, meaning BMI provides implicit predictive power for both measurements. Consequently, BMI was determined to be a suitable organizing dimension for sample collection.

Due to anthropometric dissimilarities, male and female participants were placed in separate groups and arranged by

BMI. Descriptive statistics were run for both groups to determine quartiles by BMI, a simple method to place the population into sub-groups. Ten participants of each sex were randomly sampled from each quartile to provide a representative sample of the CAESAR population.

### Data Collection

Figure 4 depicts the measurements extracted from CAESAR for each sample body/participant (n = 80). The anatomical markers are the hypothesized key dimensions and were determined by the locations required to pattern a garment that would interface closely with the human leg (see Figure 3); those being 1. calf, 2. knee, 3. ankle, and the vertical spacing between the three circumferences (4. knee-to-ankle, 5. knee-to-calf, 6. ankle-to-calf). For this study, calf circumference is located at the apex of the gastrocnemius muscle, knee circumference is located at the bottom-most part of the patella, and ankle circumference is defined as the narrowest point of the leg just above the medial malleolus.

While the ankle circumference was included in the CAESAR pre-measured dimensions, the traditional measurement was gathered low on the foot on top of the medial malleolus. Because this location was not the smallest circumference along the leg, a new ankle measurement was defined and extracted from the surface scan for analysis. Additionally, the leg dimensions gathered varied noticeably between right and left legs of the same participant due to right/left biases and developmental differences; Consequently, we used the dimensions from each leg as its own dataset and the new sample group shifted from $n_{participant} = 80$ to $n_{legs} = 160$. Additionally, contours of the sample legs were gathered using cross-sections in both the length and the width directions to evaluate the nature/topography of the dimensions.

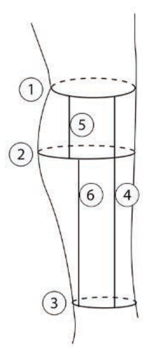


**Figure 4. Measurements extracted from sample group.**

### Statistical Analysis

A correlational analysis was conducted to determine covariance between the 6 extracted lower body dimensions, specifically length and circumference measurements, to form the framework for a sizing system. Covariance of the lower body was found to be weak; the largest correlation was between measurements 2 and 6 (r = 0.46) and the weakest between measurements 1 and 5 (r = -0.16). Refer to Figure 4. Consequently, we redirected our approach and sought to determine a singular dimension that would organize the population into the best possible, or most discrete, size categories. A depiction of perfectly discrete size categories is shown in Figure 8. We returned to our hypothesized predictive dimension used for sampling purposes, BMI, and began a statistical analysis to determine if organizing the population by BMI organized the population in discrete size categories in all, or most lower leg dimensions. An analysis of variance (ANOVA) was run for each of the 6 dimensions gathered to determine if the differences between the mean of each quartile (sub-group) were statistically different. A post hoc analysis was run to determine which specific quartiles were statistically different. A pairwise comparison using t-tests with pooled standard deviations with p-values adjusted with the Bonferroni method was used to identify which quartiles were statistically significant (or, which quartiles maintained discrete sub-groups) and which quartiles did not (no evidence of statistically significant differences). While the mean of each quartile would not directly validate a size category, an ANOVA provided strong evidence that the sub-groups were statistically different and had potential to become independent size categories upon further analysis.

In response to the results presented below for BMI and to test the relative effectiveness of different predictive variables, the same sample data (n = 80) were reshuffled by other potential predictive dimensions, specifically height, weight, ankle-to-knee length, ankle circumference, calf circumference, and knee circumference. Because height and weight data were available for the full population, statistical quartiles were determined for the full population and the reshuffling resulted in uneven numbers from our original sample in each re-shuffled quartile. The remaining dimensions were only available for the sample (n = 80); therefore, these groups maintained a sample group of 10 of each sex in each quartile. The dimension that had the greatest quantity of statistically significant sub-groups was evaluated through descriptive statistics to determine sub-group variability and overlap.

## RESULTS

### Anthropometric Variability: Circumference by BMI

The results of the variability analysis for ankle, calf, ankle, and knee circumferences for men and women when grouped by BMI quartiles are shown in Table 1A (mean ± SD). We can be confident that men's lower limb circumferences are, on average, larger than women's (ankle circumference: $\bar{x}_m$ = 8.77 in, $\bar{x}_w$ = 8.25 in; calf circumference: $\bar{x}_m$ = 15.21 in, $\bar{x}_w$ = 14.65 in; knee circumference: $\bar{x}_m$ = 13.92 in, $\bar{x}_w$ = 13.67 in). The sample range of women's circumferences are generally larger than the sample range of men's circumferences; however, we discovered that an outlier in the female group skews the ranges (ankle circumference: $range_m$ = 2.98 in, $range_w$ = 2.74 in (with outlier, 4.14 in); calf circumference: $range_m$ = 6.02 in, $range_w$ = 5.5 in (with outlier, 8.67 in), knee circumference: $range_m$ = 4.48 in, $range_w$ = 4.84 (with outlier, 10.44 in)). We decided to keep the outlier data as a good example of possible anthropometric variability; however, if we examine the ranges without the outlier, we see that the range of ankle and calf circumference is larger in men and the range of knee circumference in larger in women.

### Anthropometric Variability: Length by BMI

The results of the variability analysis for knee-to-ankle, knee-to-calf, and ankle-to-calf lengths for men and women

A)

**ANOVA results | BMI**

| | Ankle Circumference: Women (mean ± sd) | Ankle Circumference: Men (mean ± sd) | Calf Circumference: Women (mean ± sd) | Calf Circumference: Men (mean ± sd) | Knee Circumference: Women (mean ± sd) | Knee Circumference: Men (mean ± sd) |
|---|---|---|---|---|---|---|
| Q1 = | 7.77 ± 0.57 | 8.21 ± 0.54 | 13.57 ± 0.72 | 13.98 ± 1.17 | 12.38 ± 0.56 | 12.83 ± 0.64 |
| Q2 = | 8.16 ± 0.47 | 8.72 ± 0.38 | 14.29 ± 0.80 | 14.98 ± 0.44 | 13.41 ± 0.60 | 13.90 ± 0.65 |
| Q3 = | 8.17 ± 0.43 | 8.82 ± 0.36 | 14.58 ± 0.61 | 15.53 ± 0.69 | 13.57 ± 0.71 | 14.32 ± 0.63 |
| Q4 = | 8.91 ± 0.43 | 9.31 ± 0.66 | 16.19 ± 1.61 | 16.34 ± 0.95 | 15.31 ± 2.25 | 14.62 ± 0.70 |
| ALL = | 8.25 ± 0.75 | 8.77 ± 0.63 | 14.65 ± 1.39 | 15.21 ± 1.20 | 13.67 ± 1.62 | 13.92 ± 0.94 |
| ANOVA = p-value | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 | < 0.001 |

| | Knee-to-Ankle Length: Women | Knee-to-Ankle Length: Men | Knee-to-Calf Length: Women | Knee-to-Calf Length: Men | Ankle-to-Calf Length: Women | Ankle-to-Calf Length: Men |
|---|---|---|---|---|---|---|
| Q1 = | 11.65 ± 0.57 | 12.78 ± 0.40 | 3.16 ± 0.29 | 3.68 ± 0.39 | 8.49 ± 0.46 | 9.10 ± 0.55 |
| Q2 = | 11.43 ± 1.02 | 12.46 ± 0.60 | 3.23 ± 0.28 | 3.42 ± 0.43 | 8.21 ± 1.75 | 9.03 ± 0.51 |
| Q3 = | 11.02 ± 0.53 | 13.03 ± 0.73 | 2.59 ± 0.41 | 3.41 ± 0.58 | 8.43 ± 0.63 | 9.63 ± 0.62 |
| Q4 = | 11.46 ± 0.95 | 12.54 ± 0.89 | 2.68 ± 0.45 | 3.43 ± 0.59 | 8.78 ± 0.69 | 9.11 ± 0.89 |
| ALL = | 11.39 ± 0.80 | 12.70 ± 0.69 | 2.92 ± 0.45 | 3.49 ± 0.50 | 8.48 ± 0.75 | 9.22 ± 0.68 |
| ANOVA p-value = | 0.367 | 0.244 | < 0.001 | 0.577 | 0.408 | 0.175 |

**Bonferroni correction**

| | | Women p-value Q1 | Women Q2 | Women Q3 | Men p-value Q1 | Men Q2 | Men Q3 |
|---|---|---|---|---|---|---|---|
| Ankle | Q2 | 0.371 | | | 0.013 | | |
| | Q3 | 0.343 | 1.000 | | 0.002 | 1.000 | |
| | Q4 | <0.001 | 0.003 | 0.003 | <0.001 | 0.002 | 0.017 |
| Calf | Q2 | 0.169 | | | 0.003 | | |
| | Q3 | 0.014 | 1.000 | | <0.001 | 0.295 | |
| | Q4 | <0.001 | 0.001 | <0.001 | <0.001 | <0.001 | 0.023 |
| Knee | Q2 | 0.068 | | | <0.001 | | |
| | Q3 | 0.022 | 1.000 | | <0.001 | 0.269 | |
| | Q4 | <0.001 | <0.001 | <0.001 | <0.001 | 0.006 | 0.992 |

| | | Women p-value Q1 | Women Q2 | Women Q3 | Men p-value Q1 | Men Q2 | Men Q3 |
|---|---|---|---|---|---|---|---|
| Knee to Ankle | | NO STATISTICAL DIFFERENCE | | | NO STATISTICAL DIFFERENCE | | |
| Knee to Calf | Q2 | 1.00 | | | NO STATISTICAL DIFFERENCE | | |
| | Q3 | 0.007 | 0.002 | | | | |
| | Q4 | 0.034 | 0.012 | 1.000 | | | |
| Ankle to Calf | | NO STATISTICAL DIFFERENCE | | | NO STATISTICAL DIFFERENCE | | |

B)

**Bonferroni correction | Ankle**

| | | Women p-value Q1 | Women Q2 | Women Q3 | Men p-value Q1 | Men Q2 | Men Q3 |
|---|---|---|---|---|---|---|---|
| Ankle | Q2 | 0.049 | | | <0.001 | | |
| | Q3 | 0.006 | 1.000 | | <0.001 | 0.001 | |
| | Q4 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Calf | Q2 | 0.052 | | | <0.001 | | |
| | Q3 | <0.001 | 0.076 | | <0.001 | 1.000 | |
| | Q4 | <0.001 | <0.001 | <0.001 | <0.001 | 0.007 | 0.024 |
| Knee | Q2 | 0.054 | | | 0.011 | | |
| | Q3 | 0.001 | 1.000 | | <0.001 | 1.000 | |
| | Q4 | <0.001 | <0.001 | <0.001 | <0.001 | 0.004 | 0.137 |

C)

**Bonferroni correction | Knee-to-Ankle**

| | | Women p-value Q1 | Women Q2 | Women Q3 | Men p-value Q1 | Men Q2 | Men Q3 |
|---|---|---|---|---|---|---|---|
| Knee to Ankle | Q2 | 0.001 | | | <0.001 | | |
| | Q3 | <0.001 | 0.003 | | <0.001 | 0.009 | |
| | Q4 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| Knee to Calf | | NO STATISTICAL DIFFERENCE | | | NO STATISTICAL DIFFERENCE | | |
| Ankle to Calf | Q2 | 0.045 | | | 0.222 | | |
| | Q3 | 0.007 | 1.000 | | 0.003 | 0.607 | |
| | Q4 | <0.001 | 0.001 | 0.004 | <0.001 | 0.021 | 0.944 |

**Table 1. A) ANOVA and descriptive results for leg circumferences and lengths grouped by BMI with post-hoc Bonferroni correction; B) best dimension to organize leg circumferences into discrete groups (ankle circumference); C) best dimension to organize leg lengths into discrete groups (knee-to-ankle length).**

grouped by BMI quartiles are shown in Table 1A (mean ± SD). We can be confident that men's lower limb lengths are, on average, longer than women's (knee-to-ankle: $\bar{x}_m = 12.7$ in, $\bar{x}_w = 11.39$ in, knee-to-calf: $\bar{x}_m = 3.49$ in, $\bar{x}_w = 2.92$ in; ankle-to-calf: $\bar{x}_m = 9.22$ in, $\bar{x}_{w=} 8.48$ in) and the sample range of women's lengths are generally the same as the sample range of men's circumferences (knee-to-ankle: $range_m = 3.06$ in, $range_w = 3.1$ in; knee-to-calf: $range_m = 1.92$ in, $range_w = 1.92$ in). The exception is the ankle-to-calf length where women have a larger range than men (ankle-to-calf: $range_m = 3.01$ in, $range_w = 3.34$ in).

### Alternate Predictors: Circumference

The best predictive dimension for a single-predictor sizing system would result in the ability to divide the population effectively into groups that overlap as little as possible for the fewest dimensions (see Figure 8). To evaluate the effectiveness of BMI as a predictor, an ANOVA was conducted to determine if organizing the CAESAR sample into groups based on BMI would produce statistically independent circumferences (i.e. ankle, calf, knee) between quartile groups. The ANOVA results (see Table 1A) show that grouping by BMI does produce at least one independent size between quartiles for both men and women within all three circumferences (ANOVA p-values < 0.001). A pairwise comparison using t-tests adjusted with the Bonferroni method was conducted to specify which quartiles were different from each other. The post-hoc analysis (see Table 1A) shows that some groups are significantly different and other are not when organized by BMI; therefore, the same data was reshuffled by other potential predictive dimensions (i.e. (1) height, (2) weight, (3) ankle-to-knee length, (4) ankle circumference, (5) calf circumference, and (6) knee circumference) to determine if organizing by another dimension might produce an organization framework with more discrete quartiles/sizes.

The subsequent ANOVA results show that grouping by (1) height and (3) ankle-to-knee length did *not* produce any discrete circumferential sizes between quartiles for either men and women. Conversely, grouping by (2) weight, (4) ankle circumference, (5) calf circumference, and (6) knee circumference all produced at least one discrete size between quartiles for both men and women within all three circumferences. Of the dimensions that *do* organize the sample group into discrete circumferential sizes/groups, (4) ankle circumference produced the largest number and most consistent groups of discrete sizes. See Table 1B for results.

### Alternate Predictors: Length

An ANOVA was conducted to determine if organizing the CAESAR sample into groups based on BMI would produce sizes with discrete lengths (i.e. knee-to-ankle, knee-to-calf, ankle-to-calf). The ANOVA results (see Table 1A) show that grouping by BMI does not form discrete quartiles for the length dimension, with the exception being the knee-to-calf length in females. Consequently, the same data was reshuffled by other potential predictive dimensions (i.e. (1) height, (2) weight, (3) ankle-to-knee length, (4) ankle circumference and the ANOVA was repeated.

The subsequent ANOVA results show that arranging by (1) height and (3) ankle-to-knee length *do* produce at least one discrete size between quartiles for both men and women within all three circumferences, while dimensions 2, 4, 5, and 6 do not. Of the dimensions that *do* organize the sample group into discrete circumferential sizes/groups, (3) ankle-to-knee length produced the largest number of and most consistent groups of discrete sizes. See Table 1C.

## DISCUSSION

### Anthropometric Variability: Circumference

The data suggest that men have larger average lower leg circumferences than women and would require generally larger lower leg garments. Additionally, the results imply that male and female groups have different amounts of variability at different points along the leg, suggesting slightly different shapes in addition to scales. At the knee, for example, the range was larger for women than men with and without the outlier data, however, men had greater ranges of ankle and calf circumferences than women when the outlier was removed. The greatest amount of variability for both men and women was observed at the calf, while the ankle fluctuated the least in male and female populations, suggesting the ankle is less susceptible to fluctuations in response to weight gain or muscle development. Consequently, less circumferential variability may be required at the ankle and more variability may be required at the calf when developing a garment sizing system.

Figure 5 depicts the overlaid cross sections of the knee, calf, and ankle for an average man and woman from each quartile. The cross sections are not circular but irregular in topography. From a qualitative visual analysis we see that the ankle is the most irregular of all the cross sections, probably due to prominent bones and tendons at the joint.

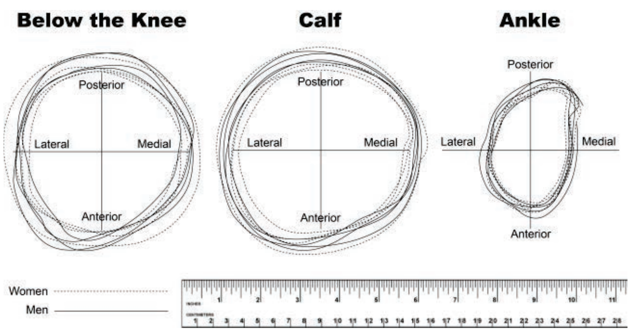


**Figure 5. Cross sections collected from under the knee, calf and ankle for men and women from each quartile.**

### Anthropometric Variability: Length

The range in length from below the knee to the ankle for men and women is similar, however, men have a larger average length. While knee-to-ankle length is only dependent on bone length, the positioning of the calf apex is dependent on gastrocnemius muscle development/placement along the leg. The results suggest that the range of possible calf apex locations is similar for males and females; consequently, we suspect similar trends in gastrocnemius muscle location. Figure 6 depicts the profiles for all men and women in the sample and shows that calf apex location as well as the shape of the calf varies throughout the population. This suggests that garment shape and dimension are critical for proper fit (see Figure 2). A more thorough analysis of variance in lower leg contour shape is needed to understand this problem.

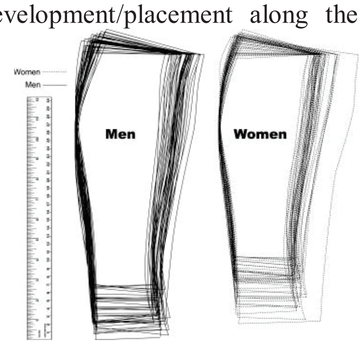


**Figure 6. Calf profile collected from all participants.**

### Alternative Predictors: Circumference

The results of the ANOVA and the pairwise comparison using t-tests adjusted with the Bonferroni method suggest that the circumference of the ankle is a key dimension for organizing the population in order of increasing lower leg circumferences (i.e. calf, knee). More research is required to understand anatomically why the ankle is better at organizing the population than other limb circumferences; however, here we are hypothesizing that for every ankle circumference (a bony leg cross section) there is a relatively narrow range of potential growth of the gastrocnemius muscle, which affects the circumferences of both the calf and knee (because the knee circumference is taken below the patella).

To test the statistical results and determine if organizing by ankle circumference could produce discrete sizes, we plotted actual ankle, calf, and knee circumferences (in) and highlighted the range (in) of dimensional variation for each quartile (Figure 7). Additionally, we calculated the percent difference between the smallest and largest circumferences in each size/sub-group. Because no statistical difference was detected between Q2 and Q3 (see Figure 3), we combined Q2 and Q3 and depicted the three new quartiles: Q1 (size small), Q2-Q3 (size medium), and Q4 (size large). Because the sample group of women contained one outlier that skewed the data, we represented the two leg dimensions for that individual with asterisks. Figure 7 shows that organizing the sample group by groups/sizes that are statistically different still results in size overlap, suggesting that the dimensional variability in the population is highly complex.

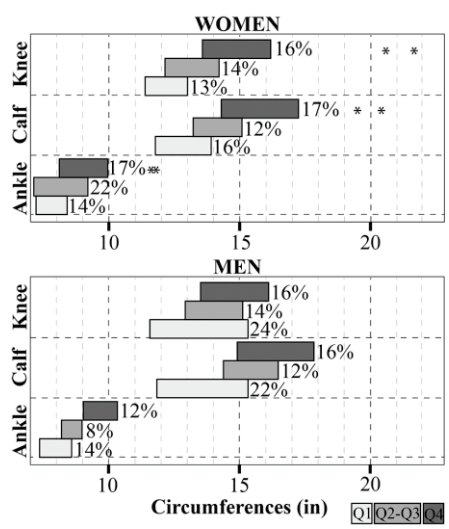


**Figure 7. Circumferential variability (in) and percent difference organized by ankle circumference; (top) women, (bottom) men.**

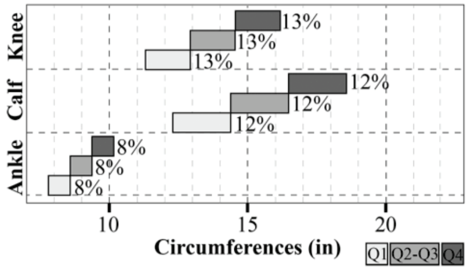


**Figure 8. Ideal single-predictor sizing system: circumferential variability (in) and percent difference.**

### Alternative Predictors: Length

The results of the ANOVA and the pairwise comparisons suggest that the length between the ankle and the knee is a key dimension for organizing the population in order of increasing leg lengths; however, the dimension only forms discrete groups for itself and for ankle-to-calf length (see Table 1C). Because we cannot group the population by two different dimensions at once, we determined that grouping by ankle circumference would produce a sizing system that best meets the functional requirements of our advanced functional garment: SMA-CG. Consequently, we plotted possible length variability *within* each size group determined in Figure 7, still organized by ankle circumference.

Figure 9 shows the range of possible length fluctuation for the calf apex and the ankle if the advanced functional garment (i.e. SMA-CG) were placed just below the knee on a human leg. Figure 9 suggests that there is a relatively small amount of dimensional fluctuation of both points, and the amount of fluctuation remains consistent across quartiles/sizes for both males and females; exceptions are: (1) the potential fluctuation of calf apexes for Q1 women is smaller than the other groups, and (2) the potential fluctuation of total leg length is smaller for Q1 men than in other groups. Generally, the potential fluctuation of total leg length is larger than the potential fluctuation of calf apex for both men and women in all size groups.

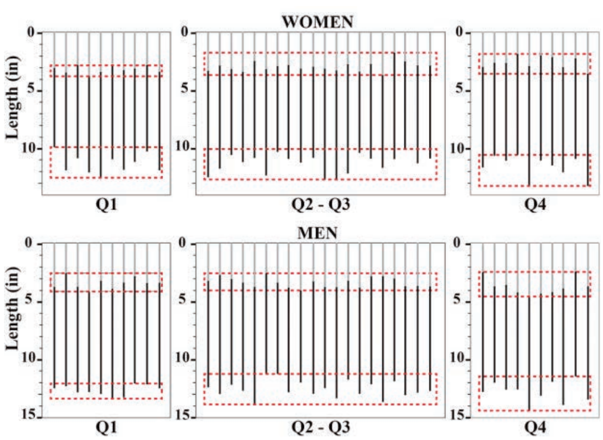


**Figure 9. Length variability (in).**

## CONCLUSIONS & FUTURE WORK

### Sizing Strategies for Advanced Functional Garments

To accommodate the anthropometric variability of the North American civilian population, all methods for garment sizing require areas of adjustability (or adjustable dimensions) to prevent the need for an unreasonable number of sizes. Here, we present several sizing strategies and their feasibility.

A one-size-fits-all garment could be manufactured with a wide range of build-in adjustability in the length and width direction; however, this garment would be challenging for the consumer to manipulate, particularly for non-stretch garments. Alternatively, several size options could be made for male and females (e.g. S, M, L men; S, M, L women) with limited, build-in length and circumferential adjustability; however, multi-directional adjustability is still challenging for the general public.

A third alternative is to develop a small size run of garments for men and women, each size with a different, fixed length and limited range of adjustable circumference. The inverse would be to develop a small size run, each size with a different fixed circumference and a limited range of adjustable length. Because circumference is the critical dimension for the functionality of SMA-CG, an adjustable circumference and several fixed lengths would be preferred. We recommend that future researchers take a graded sizing approach to non-critical dimensions and adjustability approach to dimensions critical for garment functionality. A researcher's knowledge of the garment's intended function determines the appropriate application of methods.

### Design Strategies for Advanced Functional Garments

*Methods for adjustability:*

To achieve the sizing systems outlined above, methods of adjustability should be considered. Traditional methods of adjustability for non-stretch garments rely heavily on fastening systems. While these methods are native to cut-and-sew manufacturing, familiar to the consumer, inexpensive, and easy to clean with traditional washing methods, discrete fasteners like hooks and eyes and snaps can only be adjusted in steps, are cumbersome to adjust in large amounts, and require strength and/or user dexterity.

Hook and loop tape is a common alternative in medical garments. It is quick to adjust, familiar to the consumer, inexpensive and easy to manufacture, provides continuous adjustability, and can be washed; however, excess material can create stiffness and large overlap, hook tape can scratch and snag surrounding objects, durability and noise can be a problem, and fine-tuned fit is difficult to achieve.

Lacing can also accommodate a wide range of adjustability. Lacing is familiar to consumers (e.g. athletic shoes), inexpensive, easy to manufacture, provides continuous adjustability, and is easy to clean with traditional washing methods. On the down side, excess lacing can be cumbersome to manage and tensioning can be imprecise.

Ratcheting systems provide an alternative to lacing that maintains the benefits without the excess material or time consuming process. Ratcheting systems (e.g. Boa) provide a quick and precise method for tensioning garments; however, ratcheting systems can be bulky, unfamiliar to consumers, foreign to traditional cut-and-sew manufacturing methods, and difficult to clean through traditional washing.

*Managing adjustability:*

These methods of adjustability can be manipulated precisely by the wearer to ensure proper fit through various cues. Traditional visual cues (e.g. numbers, notches) are easy for the wearer to follow, low-tech, inexpensive, easy to accomplish through traditional manufacturing, and can be easily washed; however, they require that the wearer pre-measure their own body dimensions, which can be time consuming and error-prone. Tension / pressure switches are an alternative that are also easy for the wearer to follow *and* set correctly without premeasuring; however, electronics add bulk, require a power source, require modification to traditional manufacturing, and can be difficult to wash [14], [15] Additionally, integrated pressure sensing has many of the same pros and cons as electronic switches. Future researchers should evaluate the pros and cons for each adjustability method and management style appropriate for their wearable application.

### Limitations and Future Work

Our analysis was limited by lack of relevant, pre-measured dimensions available within anthropometric databases and alternative resources should be explored in further studies. Future work will focus on evaluating the efficacy of the previously outlined design and sizing strategies for advanced functional garments. Our approach is applicable to all areas of the body and this anthropometric study should be expanded to other body regions for other product types. For all body areas, a quantitative analysis of topographical variability would help define the parameters of the problem.

## ACKNOWLEDGMENTS

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