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# EFFECTS OF ANTHROPOMETRICS AND BODY SIZE CHANGES ON THE DEVELOPMENT OF PERSONAL PROTECTIVE EQUIPMENT (PPE) SIZING SYSTEMS IN THE US ARMY

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**14. ABSTRACT**

Understanding body size and shape information of military personnel is critical for the design and development of clothing and individual equipment, and especially personal protective equipment. Recently, the U.S. Army performed an Army wide anthropometric survey of the current U.S. Army population. The previous data set was collected in 1988. When the body dimensions from the ANSUR 1988 and ANSUR II 2012 datasets were compared, there were clear increases in weight and circumferences since 1988 for both males and females, but no meaningful increases in heights. These increases in weight and circumferences have a significant impact on the development of sizing systems. The impact of these changes are (as theoretically demonstrated here) that legacy size charts, based on the ANSUR 1988 data, would not accommodate the current U.S. Army population. Based on previous sizing system methodologies, a customized process was developed focusing on the unique requirements of the military acquisition lifecycle and the requirements for PPE. This methodology was made up of three steps: 1) investigate the design problems related to design concept and function of the item along with the interrelationship among the population anthropometrics, the fit of the item, and the target accommodation rate; 2) develop a prototype and perform iterative testing, where each size of the prototype is developed and modified as the sizing system is completed; and 3) produce final products related to sizing systems, including prototypes in all sizes that accommodate the target population, the sizing chart for the item, and the size tariff for the production of the item. This optimization process should result in high accommodation rates for a combined male and female population, with a reduced number of sizes.

**15. SUBJECT TERMS**

| | | | | |
|---|---|---|---|---|
| SIZING | CLOTHING | HUMAN BODY | ANTHROPOMETRY | ANTHROPOMETRICS |
| WIDTH | THICKNESS | MEASUREMENT | ARMY EQUIPMENT | BODY MEASUREMENTS |
| HEIGHT | PROTOTYPES | CIRCUMFERENCE | SIZES (DIMENSIONS) | PROTECTIVE EQUIPMENT |
| SURVEYS | COMPARISON | DESIGN CRITERIA | HUMAN FACTORS ENGINEERING | |
| BODY SIZE | BODY WEIGHT | ARMY PERSONNEL | PPE (PERSONAL PROTECTIVE EQUIPMENT) | |

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# Effects of anthropometrics and body size changes on the development of personal protective equipment (PPE) sizing systems in the US Army

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**Abstract.** Understanding body size and shape information of military personnel is critical for the design and development of clothing and individual equipment, and especially personal protective equipment. Recently, the U.S. Army performed an Army wide anthropometric survey of the current U.S. Army population, the previous data set was collected in 1988. When the body dimensions from the ANSUR 1988 and ANSUR II 2012 datasets were compared, there were clear increases in weight and circumferences, since 1988, for both males and females; but no meaningful increases in heights. These increases in weight and circumferences have a significant impact on the development of sizing systems. The impact of these changes are (as theoretically demonstrated here) that legacy size charts, based on the ANSUR 1988 data, would not accommodate the current U.S. Army population. Based on previous sizing system methodologies, a customized process was developed focusing on the unique requirements of the military acquisition lifecycle and the requirements for PPE. This methodology was made up of three steps: 1) Investigate the design problems, related to design concept and function of the item along with the interrelationship among the population anthropometrics, the fit of the item, and the target accommodation rate, 2) Develop a prototype and perform iterative testing, where each size of the prototype is developed and modified as the sizing system is completed, and 3) Produce final products related to sizing systems, including prototypes in all sizes that accommodate the target population, the sizing chart for the item, and the size tariff for the production of the item. This optimization process should result in high accommodation rates for a combined male and female population, with a reduced number of sizes.

Keywords: ANTHROPOMETRY, SECULAR CHANGES, PERSONAL PROTECTIVE EQUIPMENT (PPE), MILITARY SIZING, SIZING SYSTEM DEVELOPMENT

# Effects of anthropometrics and body size changes on the development of personal protective equipment (PPE) sizing systems in the US Army

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## 1. INTRODUCTION

Understanding user body size and shape is critical for the design of clothing and individual equipment (CIE), and especially so for personal protective equipment (PPE) [1]. The U.S. military has been gathering anthropometric data (i.e., traditional heights, breadths, depths, and circumferences) since the 1940's to ensure that contemporary body size and shape data are reflected in equipment design for the military [2].

Recently, the U.S. Army (Army) performed a service wide anthropometric survey of the current Army population, Anthropometric Survey II (ANSUR II 2012) [3]. Unlike many of the previous studies, this survey also included Army Reservists and Army National Guard personnel along with the Active Duty force. ANSUR II 2012 collected data on 4082 males and 1986 females at 12 Army bases in the United States. The last major Army anthropometric survey was undertaken in 1988 (ANSUR 1988) [4]. In 2009, a pilot study was conducted, showing secular increases in the Army population for weight and circumferences, although heights and lengths remained similar to those from ANSUR 1988 [5, 6]. These trends in body size changes are consistent to other recent studies by the U.S. Air Force [2, 7] and the Center for Disease Control (CDC) [8].

Given that clothing design and sizing is closely tied to body dimensions [1], it is critical to understand how these changes in the Army population have affected the fit, and in turn, the development of military CIE, including PPE. In this paper we have given a theoretical approach, interspersed with examples, of how to determine if a new sizing system is needed, to understand the changes in the target population, and how to approach creating a new sizing system. The paper has been divided into the following three parts:

1. An investigation and exploratory analysis of potential secular changes between the ANSUR 1988 and ANSUR II 2012 populations. This will allow for extrapolating changes in body size distribution for PPE related measurements.
2. With a secular change identified, an investigation was conducted to better understand how body size changes in the Army population affect a PPE sizing system. This will be illustrated using ANSUR II 2012 and an Army body armour system to investigate the theoretical coverage for the current Army population and provide an estimated accommodation range for this armour system.
3. As the coverage and accommodation range are determined, a sizing system can be developed. A customized process will be introduced focusing on the unique requirements of the military acquisition lifecycle and the requirements for PPE.

## 2. CHANGES IN BODY SIZE OVER TIME

Before any changes in secular trends of body dimensions could be explored, it was necessary to control for age and population distributions, as both can have a significant influence on overall body size [9]. Caucasians were selected for secular trend analysis, as they made up the largest population group in both the ANSUR 1988 and 2012 datasets and across all age groups. An age range of 20 to 39 was chosen. Test participants up to age 20 were potentially still growing, where typically after the age of 20 little or no observable changes in linear growth are seen [9]. Those over the age of 40 were dropped from this analysis because the ANSUR 1988 dataset was statistically too small (N=67) relative to other age groups (N=224 or greater).

For this analysis, ANSUR 1988 and ANSUR II 2012 datasets are compared to each other. However, neither Army Reservists nor National Guard was included in ANSUR 1988. Since the start of Operation Enduring Freedom and Operation Iraqi Freedom, both Reservists and National Guard members have played an active role in Army operations, and must also be accommodated by PPE. Therefore, they were included as subgroups in the ANSUR II 2012. Bradtmiller et al. [6] had already determined that the body sizes of Army Reservists and National Guard members were, as a population, broader than Active Duty Soldiers and that difference needed to be accounted for in the development of clothing and equipment. Normally, when comparing two datasets, only the similar populations (i.e., Active Duty) can fairly be compared. However, in this case, because the purpose was to estimate the magnitude of the body size change for the target population who must be accommodated by the PPE sizing system, which included Reservists and National Guard, it was decided to include these subgroups in the analysis.

When both datasets are plotted, the ANSUR 1988 data are represented by dotted lines and the ANSUR II 2012 data by solid lines. Male data are represented in blue and female data are represented in red. All ellipsoids capture the central 98% of the population for these two datasets.

### 2.1 Body size comparison between ANSUR 1988 and ANSUR II (2012)

A comparison of Stature (mm) versus weight (kg) between ANSUR 1988 and ANSUR II 2012, for males and females is provided in Figure 1. In general, the distribution shows that there is very little change in Stature over time, but substantial changes in the distribution of weight for both males and females, as indicated by the pull of the solid ellipsoids to the right (as compared to the dashed line ellipsoids).

This change in weight can be further shown by evaluating the distribution of body mass index (BMI) between the two studies (Table 1). There are significant shifts in the calculated BMI values between the two datasets, with increased percentages of the population classified as overweight and obese based on their BMI levels in the ANSUR II 2012 dataset compared to the earlier 1988 Army survey. For males in 1988, 45.7% were classified as normal weight, 48.2% overweight, and 5.9% class I obesity, while in 2012 the proportion of those classified as normal weight was reduced to 27.6% and class I obesity increased to 20.7%. A similar trend was found for females where the proportion of the normal weight group was reduced from 75.1% in 1988 to 53.4% in 2012 and the proportion of the overweight group doubled from 20.8% (1988) to 40.4% (2012). In order to understand these weight increases, additional comparisons of height and circumference are presented in the following two sections.

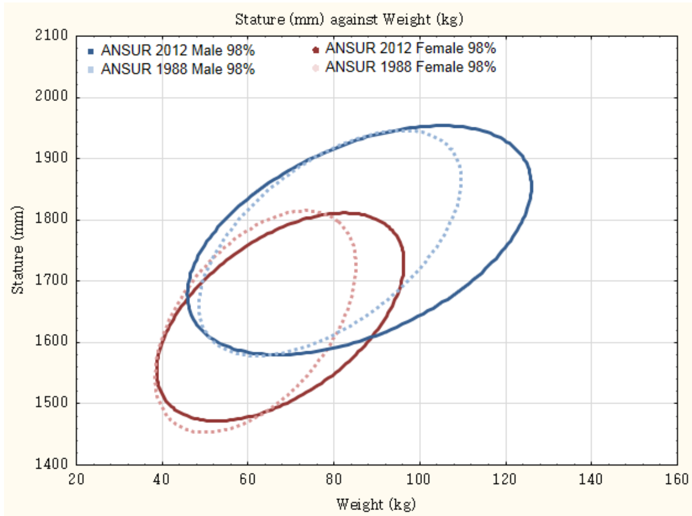


**Figure 1.** 98% ellipses of Stature by Weight distribution for ANSUR 1988 and ANSUR II 2012

**Table 1.** Frequencies of BMI classification for ANSUR 1988 and ANSUR II 2012

| BMI (Kg/m$^2$) | | Males | | | | Females | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ANSUR 1988 | | ANSUR II 2012 | | ANSUR 1988 | | ANSUR II 2012 | |
| | | Count | Percent | Count | Percent | Count | Percent | Count | Percent |
| Underweight | <18.5 | | | 6 | 0.3 | 27 | 2.7 | 2 | 0.3 |
| Normal weight | <25 | 448 | 45.7 | 564 | 27.6 | 746 | 75.1 | 381 | 53.4 |
| Overweight | <30 | 472 | 48.2 | 967 | 47.3 | 207 | 20.8 | 288 | 40.4 |
| Class I Obesity | <35 | 58 | 5.9 | 423 | 20.7 | 14 | 1.4 | 38 | 5.3 |
| Class II Obesity | <40 | 2 | 0.2 | 78 | 3.8 | | | 3 | 0.4 |
| Class III Obesity | >=40 | | | 7 | 0.3 | | | 1 | 0.1 |
| Total | | 980 | 100 | 2045 | 100 | 994 | 100 | 713 | 100 |

### 2.1.1 Height dimensions

There were no meaningful differences between Stature (mm) and Sitting Height (mm), for either males or females, in the ANSUR 1988 and ANSUR II 2012 datasets (Figure 2). This trend continued when lengths (Arm Span and Sleeve Outseam) were evaluated. For all dimensions, the mean differences were within allowable measurement error (6mm for Stature, Sitting Height, and Sleeve Outseam and 10mm for Arm Span [10]) (Table 2 and 3).

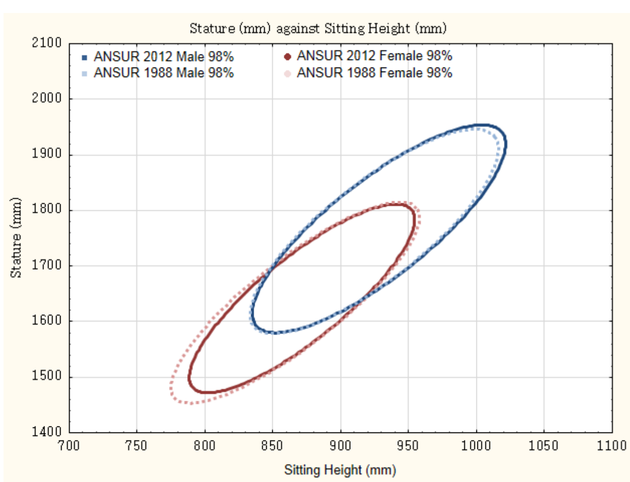


**Figure 2.** 98% ellipses for Stature by Sitting Height distribution for ANSUR 1988 and ANSUR II 2012

**Table 2.** Descriptive statistics for four height and length dimensions for ANSUR 1988 and ANSUR II 2012 (Male)

| Male (Unit:mm) ANSUR 1988 (N=980) ANSUR II 2012 (N=2045) | | Mean | SD | Percentiles | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1st | 5th | 25th | 50th | 75th | 95th | 99th |
| **Stature** | ANSUR 1988 | 1762 | 66 | 1611 | 1658 | 1719 | 1762 | 1806 | 1871 | 1907 |
| | ANSUR II 2012 | 1767 | 67 | 1629 | 1660 | 1720 | 1766 | 1810 | 1879 | 1937 |
| | **Delta** | **5** | **-** | **18** | **3** | **2** | **4** | **5** | **8** | **30** |
| **Sitting Height** | ANSUR 1988 | 925 | 33 | 850 | 872 | 902 | 925 | 947 | 977 | 999 |
| | ANSUR II 2012 | 928 | 33 | 857 | 874 | 905 | 928 | 950 | 985 | 1010 |
| | **Delta** | **3** | **-** | **7** | **3** | **3** | **3** | **3** | **8** | **11** |
| **Span** | ANSUR 1988 | 1814 | 75 | 1638 | 1693 | 1765 | 1812 | 1863 | 1941 | 1983 |
| | ANSUR II 2012 | 1811 | 81 | 1630 | 1684 | 1754 | 1808 | 1865 | 1948 | 2008 |
| | **Delta** | **-3** | **-** | **-8** | **-9** | **-11** | **-4** | **2** | **8** | **25** |
| **Sleeve Outseam** | ANSUR 1988 | 599 | 29 | 533 | 553 | 581 | 597 | 620 | 645 | 671 |
| | ANSUR II 2012 | 593 | 30 | 527 | 546 | 573 | 593 | 612 | 645 | 666 |
| | **Delta** | **-6** | | **-6** | **-7** | **-8** | **-4** | **-8** | **0** | **-5** |

**Table 3.** Descriptive statistics for four height and length dimensions for ANSUR 1988 and ANSUR II 2012 (Female)

| Female (Unit:mm) ANSUR 1988 (N=994) ANSUR II 2012 (N=713) | | Mean | SD | Percentiles | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1st | 5th | 25th | 50th | 75th | 95th | 99th |
| **Stature** | ANSUR 1988 | 1634 | 64 | 1478 | 1532 | 1590 | 1634 | 1676 | 1740 | 1785 |
| | ANSUR II 2012 | 1642 | 60 | 1495 | 1555 | 1600 | 1637 | 1680 | 1748 | 1782 |
| | **Delta** | **8** | | **17** | **23** | **10** | **3** | **4** | **8** | **-3** |
| **Sitting Height** | ANSUR 1988 | 866 | 33 | 785 | 812 | 844 | 867 | 889 | 920 | 942 |
| | ANSUR II 2012 | 871 | 30 | 804 | 824 | 851 | 870 | 890 | 920 | 938 |
| | **Delta** | **5** | | **19** | **12** | **7** | **3** | **1** | **0** | **-4** |
| **Span** | ANSUR 1988 | 1648 | 74 | 1473 | 1532 | 1597 | 1648 | 1697 | 1774 | 1817 |
| | ANSUR II 2012 | 1652 | 73 | 1476 | 1532 | 1604 | 1648 | 1699 | 1780 | 1828 |
| | **Delta** | **4** | | **3** | **0** | **7** | **0** | **2** | **6** | **11** |
| **Sleeve Outseam** | ANSUR 1988 | 540 | 28 | 472 | 496 | 520 | 539 | 560 | 585 | 604 |
| | ANSUR II 2012 | 542 | 27 | 480 | 500 | 525 | 540 | 559 | 589 | 610 |
| | **Delta** | **2** | | **8** | **4** | **5** | **1** | **-1** | **4** | **6** |

### 2.1.2 Circumference dimensions

Chest Circumference (mm) increased dramatically from 1988 to 2012. Figure 3 shows Chest Circumference relative to Stature (mm), for males and females, from ANSUR 1988 and ANSUR II 2012. There was a mean increase of 58mm for males and 37mm for females (Tables 4 and 5). Comparisons of other influential circumferential dimensions show similarly dramatic increases between the 1988 and 2012 datasets. Tables 4 and 5 show the mean differences for these dimensions, which all significantly exceed their allowable measurement error range (Buttock Circumference=12mm, Chest Circumference=14mm, and Waist Circumference=12mm [10]). With the male data, there is a larger increase in Chest Circumference ($M$=58mm) compared to the Buttock Circumference ($M$=36mm), while the female data indicates that Buttock Circumference ($M$=55mm) increased more than Chest Circumference ($M$=37mm). For the measurement of Waist Circumference, a similar increase was observed for both males ($M$=66mm) and females ($M$=62mm).

The increases in body dimensions were even more dramatic at the 95$^{th}$ and 99$^{th}$ percentiles. Accommodation ranges for military acquisition are typically set at either 90% (5$^{th}$ to 95$^{th}$ percentiles) or 98% (1$^{st}$ to 99$^{th}$ percentiles); the values for 95$^{th}$ percentile and 99$^{th}$ percentile represent the maximum values that should be accommodated. A case in point, for Chest Circumference, the 95$^{th}$ percentile increased by 84mm and the 99$^{th}$ percentile by 117mm for males in the ANSUR II 2012 dataset. Therefore, if using the guidelines created from 1988 dataset, and attempting to accommodate 98% of the current Army population, 117mm or 4.6 inches of circumference are not accounted for in the size ranges. Thus, a new guideline is required so that the item appropriately accommodates the target population.

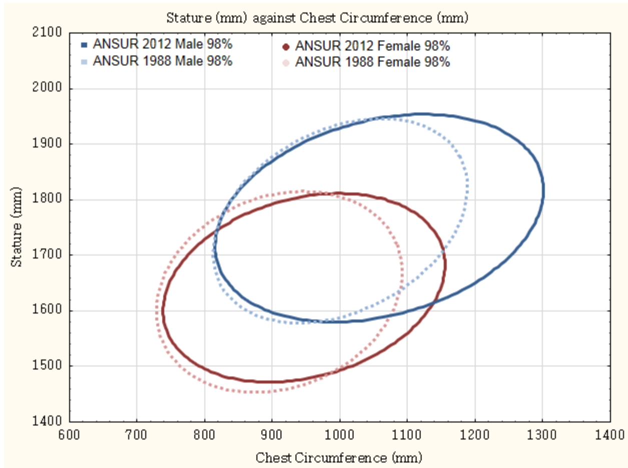


**Figure 3.** 98% ellipses for Stature by Chest Circumference distribution for ANSUR 1988 and ANSUR II 2012

**Table 4.** Descriptive statistics for three circumferences for ANSUR 1988 and ANSUR II 2012 (Male)

| Male (Unit:mm) ANSUR 1988 (N=980) ANSUR II 2012 (N=2045) | | Mean | SD | Percentiles | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1st | 5th | 25th | 50th | 75th | 95th | 99th |
| Buttock Circumference | ANSUR 1988 | 988 | 60 | 861 | 897 | 942 | 986 | 1028 | 1092 | 1133 |
| | ANSUR II 2012 | 1024 | 77 | 865 | 903 | 971 | 1022 | 1073 | 1153 | 1217 |
| | **Delta** | **36** | | **4** | **7** | **29** | **36** | **45** | **61** | **84** |
| Chest Circumference | ANSUR 1988 | 1000 | 67 | 874 | 899 | 954 | 994 | 1044 | 1122 | 1161 |
| | ANSUR II 2012 | 1058 | 87 | 873 | 923 | 997 | 1054 | 1115 | 1205 | 1278 |
| | **Delta** | **58** | | **-1** | **25** | **43** | **60** | **71** | **84** | **117** |
| Waist Circumference | ANSUR 1988 | 877 | 84 | 726 | 751 | 810 | 869 | 935 | 1025 | 1086 |
| | ANSUR II 2012 | 943 | 109 | 731 | 777 | 859 | 939 | 1014 | 1135 | 1222 |
| | **Delta** | **66** | | **5** | **26** | **49** | **71** | **79** | **110** | **136** |

**Table 5.** Descriptive statistics for three circumferences for ANSUR 1988 and ANSUR II 2012 (Female)

| Female (Unit:mm) ANSUR 1988 (N=994) ANSUR II 2012 (N=713) | | Mean | SD | Percentiles | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 1st | 5th | 25th | 50th | 75th | 95th | 99th |
| Buttock Circumference | ANSUR 1988 | 968 | 60 | 842 | 876 | 927 | 965 | 1008 | 1070 | 1126 |
| | ANSUR II 2012 | 1023 | 70 | 871 | 913 | 974 | 1022 | 1067 | 1147 | 1200 |
| | **Delta** | **55** | | **29** | **37** | **47** | **57** | **59** | **77** | **74** |
| Chest Circumference | ANSUR 1988 | 910 | 65 | 777 | 811 | 865 | 905 | 950 | 1029 | 1076 |
| | ANSUR II 2012 | 947 | 74 | 795 | 838 | 895 | 941 | 994 | 1076 | 1152 |
| | **Delta** | **37** | | **18** | **27** | **30** | **36** | **44** | **47** | **76** |
| Waist Circumference | ANSUR 1988 | 796 | 82 | 655 | 679 | 734 | 784 | 843 | 947 | 1025 |
| | ANSUR II 2012 | 857 | 96 | 667 | 713 | 791 | 846 | 916 | 1031 | 1105 |
| | **Delta** | **62** | | **12** | **34** | **57** | **63** | **73** | **84** | **80** |

## 3. THE IMPACT OF BODY SIZE CHANGES ON PPE

Now that it has been determined that there has been a secular change in body dimensions between the two study periods, an assessment of how these changes impact the sizing of PPE needs to be conducted. To illustrate this impact of change between ANSUR 1988 and ANSUR II 2012, a theoretical coverage of a legacy Army body armour sizing chart was used. The body armour sizing chart uses the body dimension Chest Circumference and is graded with four inch intervals between sizes. The body armour system originally had five sizes (X-Small, Small, Medium, Large, and X-Large), but later added an additional size (2X-Large and wider), and so these are the sizes which our example will focus on.

### 3.1 Theoretical coverage of conventional body armour sizes

Figure 4 superimposes the breakdown of the legacy body armour sizing onto Figure 3 to illustrate the theoretical impact of increases in Chest Circumference between the 1988 and 2012 datasets. In general, the 2012 Army population has shifted, theoretically, into one size larger, for the most common sizes (Small, Medium and Large) when compared to the 1988 Army population.

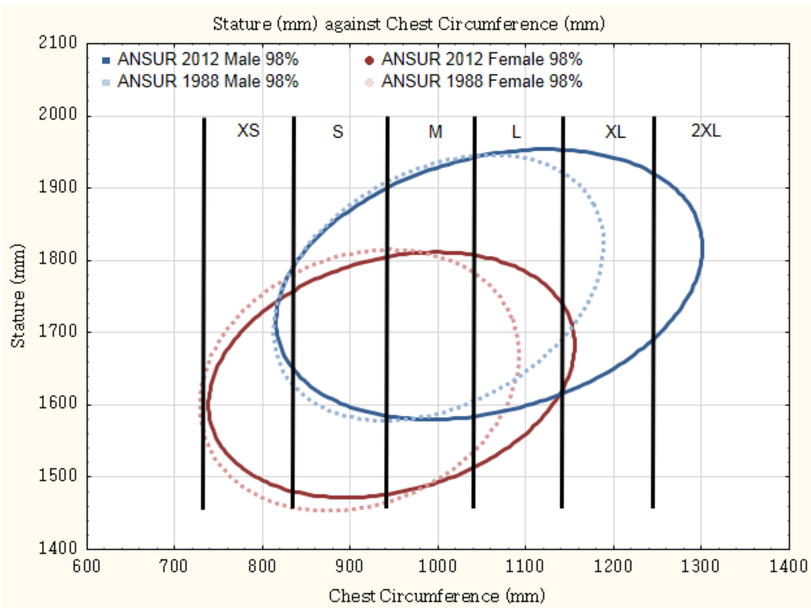


**Figure 4.** 98% ellipses for Stature by Chest Circumference distribution for ANSUR 1988 and ANSUR II 2012 with visualization of size categories of body armour, based on Chest Circumference

The percent increases and frequency counts for the theoretical fit for males and females in the 1988 and 2012 datasets is detailed in Table 6. For male personnel in 1988, 55.0% of Army personnel were predicted to fit a size Medium and 24.1% a size Large body armour system. However, when updated with ANSUR II 2012, the number of males predicting into size Medium has dropped to 35.9%, while size Large has increased to 35.4%. Additionally, the proportion of individuals who predict into the sizes X-large, 2X-large, and 3X-large increased to 17% for ANSUR II 2012, up from 2.5% in ANSUR 1988. It should be noted that neither 2X-Large nor 3X-Large existed in the original size chart.

**Table 6.** Frequencies per body armour size by ANSUR 1988 and ANSUR II 2012

| Body Armour Chest Circ. (Unit:in) | | Males | | | | Females | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | ANSUR 1988 | | ANSUR II 2012 | | ANSUR 1988 | | ANSUR II 2012 | |
| | | Count | Percent | Count | Percent | Count | Percent | Count | Percent |
| **X-small** | **29-33** | 1 | 0.1 | 4 | 0.2 | 129 | 13.0 | 37 | 5.2 |
| **Small** | **33-37** | 179 | 18.3 | 159 | 7.8 | 570 | 57.3 | 312 | 43.8 |
| **Medium** | **37-41** | 539 | 55.0 | 735 | 35.9 | 260 | 26.2 | 288 | 40.4 |
| **Large** | **41-45** | 236 | 24.1 | 805 | 39.4 | 34 | 3.4 | 67 | 9.4 |
| **X-large** | **45-49** | 23 | 2.3 | 293 | 14.3 | 1 | 0.1 | 9 | 1.3 |
| **2X-large** | **49-53** | 2 | 0.2 | 48 | 2.4 | | | | |
| **3X-large** | **53-57** | | | 1 | 0.05 | | | | |
| Total | | 980 | 100 | 2045 | 100 | 994 | 100 | 713 | 100 |

A similar trend was observed for females; in the ANSUR 1988 dataset, 57.3% of females predicted into a size Small and 26.2% into size Medium. However, utilizing ANSUR II 2012, the percentage of personnel who predicted into size Small decreased to 43.8% and those who predicted into a size Medium increased to 40.4%. These major shifts affect not just the sizing tariff, but also require significant modifications to the sizing system itself, requiring the availability of additional sizes to accommodate the required population (i.e., central 90% or 98%). Therefore, as body dimensions shift, there is an impact on the development of current and future sizing for CIE, and for items that require an acceptable level of fit to perform their missions (e.g., PPE), these secular changes become even more critical to monitor and evaluate during the design and development phases of acquisition.

## 4. SIZING SYSTEM DEVELOPMENT

Analysis has shown that secular increases in body size and shape have occurred between 1988 and 2012, and that, theoretically, the previous sizing system does not provide the required accommodation rates. Therefore, a new sizing system should be developed. Because body proportion and shape are expected to continue to change over time, adding additional larger sizes for increased circumferences, graded from the legacy sizing system, does not guarantee the required accommodation rate will be met. Therefore, a newly revised sizing system needs to be developed.

A sizing system is the product of a series of anthropometric analyses that attempts to summarize body shape and size information for a target population. The underlying goal is to define an optimal number of garment sizes that can best accommodate the target population [11]. Therefore, it is crucial to have an anthropometric database that accurately represents the target population for the development of a successful sizing system. For civilian garment design, multiple sizing systems (e.g. junior, misses, petite) are used to accommodate subsets of the entire population. Because these subsets are classified based on body shape information, the individuals within each subset tend to be homogenous in terms of body shape, allowing designers to achieve a high accommodation rate for their target population, but relatively low overall. Conventionally, the accommodation rate of civilian garment sizing systems is between 65% and 85% [11].

Unlike with civilian clothing systems, military PPE items are generally developed to accommodate the largest number of male and female personnel of diverse age and population background; while doing so with the smallest number of sizes. This is primarily due to the high development and design costs, purchasing, and logistical challenges the military faces [12]. Ironically, most military PPE items are required to accommodate up to central 98% ($1^{st}$ to $99^{th}$ percentiles) of the target population [12, 13] and therefore the development of sizing systems for PPE becomes very complex. Further complicating issues, the consequences of failure of fit are critical in PPE items, as they must fit properly in order to provide the levels of protection required. Because of this complexity, an iterative product development cycle (i.e., design, test, modify and retest) is highly recommended in order to ensure that the largest number of individuals can obtain a proper fit in their predicted size.

### 4.1 Optimal process of sizing system development

The sizing system development for PPE should include the development of prototypes, as well as an evaluation of such prototypes to meet the required accommodation range. These two actions will help developers reduce the potential for developing poorly fit items. By adopting critical elements out of civilian sizing processes, and eliminating or reworking those steps that do not work well, the following three step approach is suggested:

1) Investigate the design problems,
2) Develop a prototype and perform iterative tests through fit mapping of the items, and
3) Produce the final sizing systems product.

#### *4.2.1 Step 1: Investigate the design problems*

When developing a PPE item, the most critical goal is to achieve an optimal fit between the user and the equipment. The design problems, including the design concept and functional requirements of the item, should be identified. At the same time, the interrelationship between the anthropometric characteristics of the target population (e.g., what is the optimal and/or required fit of the item, what is the target accommodation rate) should be investigated and understood. Both need to be done prior to attempting a prototype design.

Design criteria should include requirements (e.g., the body armour must protect the vital organs from all angles) as well as fit guidelines (e.g., the bottom edge of the soft body armour must fall between the line of the Omphalion and the line of the anterior superior iliac spine). Additionally, user experience on fit of the legacy system, as it is related to coverage, mobility, performance and comfort, should be included in the requirements. In all stages of the development of the prototype, it is important to collect the user populations' opinion of the design item and to use these opinions to inform the next phase of the design. If an innovative item is to be developed and no legacy item exists, or no experienced users are available, then it is critical to have potential users don the prototype and collect feedback from them regarding the design.

*4.2.2 Step 2: Develop a prototype and perform iterative testing through fit mapping of the items*

Once the design problems have been thoroughly examined, prototype development can be initiated. It is important that the first prototype is developed based on the centre size of the population in order to accommodate the most populated part of the target population distribution and to capture the maximum and minimum ends of the anthropometric ranges. Since it is rare to develop gender specific PPE in a military environment, the target population must accommodate both (i.e., unisex items). Therefore, testing of the prototypes must include female and male test participants, to ensure adequate accommodation.

When developing a unisex PPE item, the centre size should be based on the centre of the most prominent gender (usually the male), not the centre of the combined population. Otherwise, the average of the combined population is usually far above the 50$^{th}$ percentile for the female population and far below the 50$^{th}$ percentile for the male population. Because most anthropometric population data is normally distributed, means and medians are closely located together at the centre of the distribution; therefore, the values deviated from the 50$^{th}$ percentile are also deviated from the mean value at the centre of the distribution. As demonstrated in Table 7, the mean value of the Chest Circumference for the combined population corresponds to the 35$^{th}$ percentile of the male population and the 82$^{nd}$ percentile for the female population. Similar trends are observed for Stature and weight (Table 7). Since the male personnel represent a larger proportion (approximately 85%) of the target population, the body armour system developed based on the combined mean would not adequately accommodate a large portion of the combined population. The centre size is the key to estimating the values used for the development of adjacent sizes; therefore, any fit issues on the centre size would also have a strong effect on the adjacent sizes as well.

**Table 7. Averages of combined population and its corresponding percentiles in male and female population**

| ANSUR II 2012 (Unit:mm) | | Chest Circumference | Stature | Weight (kg) |
|---|---|---|---|---|
| **Average of Combined population** | | 1022 | 1714 | 79.70 |
| **Percentile** | ***Male population*** | 35$^{th}$ | 27$^{th}$ | 36$^{th}$ |
| | ***Female population*** | 82$^{nd}$ | 90$^{th}$ | 87$^{th}$ |
| **Average of Male population** | | 1059 | 1756 | 85.5 |
| **Percentile** | ***Male population*** | 51$^{st}$ | 50$^{th}$ | 53$^{rd}$ |
| | ***Female population*** | 90$^{th}$ | 97$^{th}$ | 93$^{rd}$ |

Once the centre size is developed, a fit mapping process should be initiated. Fit mapping is a method that quantitatively characterizes the relationship between the garment being tested and its target population [14]. The process of fit mapping applies fit evaluation results in an iterative fashion to improve the fit quality. It identifies gap/overlap between those adjacent sizes, thereby delineating the maximum accommodation rate and the fit quality of the adjacent sizes.

The adjacent sizes (one size larger and one size smaller) are developed one at a time, and a fit evaluation should follow each size development. For the initial fit evaluation of the adjacent sizes (including the centre size), it is critical to identify the accommodation range for each developed size, as well as to identify any overlap or gaps between the sizes. Based on the fit evaluation results and user feedback on the fit, performance, and comfort of the developmental system, these prototypes can then be modified (i.e., redesigned) and then retested, as necessary, instituting an iterative design, test, redesign, and retest cycle. This design cycle is repeated until all sizes are developed and positioned correctly in the sizing system, thereby mapping out all the sizes and accommodating the population.

It is recommended that focus groups be conducted following testing events, as a way of identifying any additional issues regarding the fit, performance, and comfort of the prototype item with the future user population for that PPE item. For example, in one fit evaluation conducted, the test PPE sizing chart predicted users into an item that was too large, as compared to their best fit. These fit trials and focus groups highlighted the impact of poor fit on the users' mission duties, comfort, and the potential need for improved sizing and fit of PPE [15]. By collecting users' feedback in the early stages of the development process, issues can be identified earlier and corrected at a lower cost, allowing a finished product that better meets the users' needs.

*4.2.3 Step 3: Produce the final products of sizing systems*

Once all the sizes of the item are developed, a thorough fit mapping, via a fit evaluation, should be conducted to confirm that the appropriate design and size ranges have been developed and that they accommodate the target population. A limited user field evaluation, using realistic mission scenarios should be conducted to determine any remaining fit and design issues in a more dynamic setting than a fit evaluation offers. The results from this testing should be applied to the final products. The final product should include all sizes of the development item, an accurate size prediction chart, and required sizing tariffs with the final accommodation rate.

The size chart is a document that gives the range of body dimensions (e.g., Chest Circumference of 34-38 inches) that should fit into a given size of the item. Some size charts provide the key sizing dimensions, as well as garment ease amounts. A sizing tariff determines the percentage of each size of the garment needed to be produced or procured to meet the target accommodation rate. Once the size chart is updated upon the final fit evaluation, the size tariff can be finalized by applying the values of key dimensions in the size chart to the target population [14]. Recently, NSRDEC, under the Helmet Electronic and Display System – Upgradeable Protection (HEaDS-UP) program successfully applied this process to develop a new helmet system with three sizes, which accommodates up to the 99$^{th}$ percentile of the Army population [16].

## 5. CONCLUSION AND DISCUSSION

In general, when the body dimensions from the ANSUR 1988 and ANSUR II 2012 datasets were compared, there were clear increases in weight based body dimensions (i.e., increases in circumference since 1988), for both males and females. At the same time, there were no meaningful increases in heights. These results were consistent with a previous study which found significant increases in weight and circumferences, but little to no meaningful differences in heights between the 2009 ANSUR II Pilot and ANSUR 1988 datasets [6]. These increments in weight/circumferences have a significant impact on the development of sizing systems for Army CIE, especially PPE. As was illustrated in section 3, PPE that was developed or sized based on circumference dimensions from the ANSUR 1988 dataset significantly disaccommodate the ANSUR II 2012 dataset, and thereby will disaccommodate the current Army population. With this in mind, the execution of a customized process for sizing system development was explored.

Based on previous sizing system methodologies [11, 12], a customized novel process was developed focusing on the unique requirements of the military acquisition lifecycle and the requirements for PPE. This process was made up of three steps: 1) Investigate the design problems, as they related to design concept and the required function of the item along with the interrelationship among the anthropometric characteristics of the target population, the optimal and/or required fit of the item, and the target accommodation rate, 2) Develop a prototype and perform iterative testing to accommodate the entire male/female combined population. During this process each size of the prototype is developed and modified as the sizing system for the item is completed, and 3) Produce final products related to sizing systems that include a set of prototypes that should accommodate the target population, the sizing chart for the prototypes, and the size tariff for the production of the prototype system. This optimization process should result in high accommodation rates for a combined male and female population, with a reduced number of sizes.

As can be seen by looking at the effects of the secular changes in body dimensions between 1988 and 2012 for the U.S. Army population, anthropometry has a critical impact on a sizing system for PPE (and all CIE). Even once a size system has been developed, it needs to continually be monitored and updated based on changes in the user population's body shapes and sizes, to continue to allow for the best fit and performance from the clothing and equipment. It is important for scientists and CIE designers and developers to continue to assess the shape and size of the military population, at regular intervals, so that these changes can be noted and remedies can be quickly put in place. This is especially true in the case of PPE, for which fit is a key component in the ability of the item to perform its job (i.e., protect the user).

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