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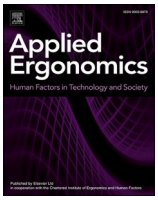

A cluster-based law enforcement body armor sizing system: Concept, procedure, and design practice

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ABSTRACT

Given the evolution of human body dimensions, the increasing diversity within the law enforcement workforce, the growing risks of assault faced by law enforcement officers (LEOs), and the absence of a national standard for body armor sizing, there is a critical need to explore LEO body size classification. This exploration will facilitate the development of an armor sizing structure that adequately accommodates the current LEO population. This study aimed to address this need by developing a LEO body armor sizing scheme and creating a sizing chart/app. Additionally, a plan was devised for a series of 'sizing vests' that would enhance LEO armor accommodation and facilitate fit assessment. Torso anthropometric data pertaining to body armor sizing were collected from 756 male and 218 female LEOs across different regions of the United States. Based on the collected data, a nine-size system for male LEOs and an eight-size scheme for female LEOs were suggested. Furthermore, a sizing chart/app was proposed to enable LEOs to swiftly identify an armor size that is most likely to fit an individual, considering a few anthropometric characteristics known to LEOs. To supplement the sizing chart/app, a series of 'sizing vests' were recommended. These vests would provide LEOs with a physical means to assess and determine the best-fitting armor size, offering an alternative to relying solely on the sizing chart/app. We recommend that armor manufacturers adopt these new sizing systems and create prototypes of armor that can be evaluated within this sizing structure. This evaluation process will facilitate improved fit and enhanced protection for LEOs.

1. Introduction

According to the Federal Bureau of Investigation (FBI), a total of 56,034 law enforcement officers (LEOs) were assaulted out of the 475,848 employed officers in 2019 (FBI, 2022). To protect LEOs from these assaults, LEO body armor plays a crucial role. This equipment provides defense against various types of weapons, including gun ammunition, knives, and spikes (Greene, 2019).

The most commonly used body armor by officers during their daily duties is soft body armor, often referred to as a "vest." This type of armor is designed to safeguard the vital organs, such as the heart, lungs, and kidneys (Fig. 1a). The vest consists of two ballistic resistant panels that are held in place on the wearer's torso. These panels protect the front and back of the torso (Fig. 1b) and overlap to provide additional protection to the sides of the torso (National Institute of Justice – NIJ, 2014). The front and back panels are typically enclosed within a plate-holding pouch known as a carrier, which securely hold the ballistic resistance materials (Fig. 1c). These materials are often comprised of multiple layers for enhanced protection.

LEOs have the option to wear the vest either under their uniform or over it (Hsiao, 2023). This choice allows for flexibility in terms of comfort and operational requirements. By wearing soft body armor, law enforcement officers can significantly reduce the risk of injury and potentially save their lives while carrying out their duties.

1.1. Needs for LEO body size classification for body armor sizing development

Given the evolving human body dimensions (Hsiao et al., 2021), the increasing diversity within the law enforcement workforce (Hsiao, 2022; Hsiao et al., 2022, Fig. 2), and the alarming rise in assaults against LEOs in recent decades (FBI, 2022), there is an urgent imperative to

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conduct comprehensive research on issues related to armor fit, coverage, and sizing. It is crucial to understand how body measurements are translated into effective body armor to enhance the protection provided to LEOs. Furthermore, existing literature has underscored the significance of considering the anthropometry of women (e.g., chest circumference, chest depth, and chest width) in the design and sizing of armor (Brisbine et al., 2022; Coltman et al., 2022). This is particularly essential to ensure the well-being of the growing number of female LEOs who actively serve in the patrolling workforce (Niemczyk et al., 2020).

In a recent market survey conducted by the National Institute for Occupational Safety and Health (NIOSH), it was found that there is a lack of consistent armor sizing structure and criteria for selecting sizes in the U.S. LEO armor marketplace (Hsiao, 2023). This inconsistency is likely due to the absence of comprehensive national LEO anthropometry data. NIOSH surveys of 15 vendors and 9 sellers revealed that current body armor sizing in the market varies widely, with the number of sizes ranging from 6 to 25, based on one or two body dimensions such as Chest Circumference, Chest Circumference by Waist Front Length, Waist Circumference by Waist Front Length, or Body Height by Body Weight. These significant variations in sizing structure and torso dimensions used by different body armor manufacturers pose challenges when selecting and fitting body armor to LEOs.

Compounding the issue of inconsistent sizing structure and selection criteria in the marketplace is the absence of a national standard or guideline for body armor sizing. While the ASTM E3003-20 standards "Body Armor Wearer Measurement and Fitting of Armor" provide guidance on body measurement techniques for assessing body armor fit (American Society for Testing and Materials - ASTM International, 2020), they do not cover information on armor sizing or dimensions. The NIJ Selection & Application Guide 0101.06 to Ballistic-Resistant Body Armor describes five panels (templates) to guide armor suppliers in submitting test samples that represent a range of sizes for ballistic resistance tests (National Institute of Justice - NIJ, 2014). However, the guide states that these template dimensions are not indicative of service armor design (pages 53–57).

Furthermore, the most recent national LEO anthropometry study conducted by NIOSH (Hsiao et al., 2021) reported that the average values of LEO body dimensions have increased over the past four decades (e.g., by 120 mm in waist circumference and 12.2 kg in body weight for men). The study also highlighted differences in body dimensions between the LEO workforce and military personnel on which LEO armor design has historically been based. Considering these findings, it is crucial to utilize the most updated anthropometric database of LEOs and systematically specify armor dimensions and sizing structure to enhance LEO protection.

1.2. Challenges and directions in specifying LEO armor sizing structure

It is widely acknowledged that the design of personal protective equipment (PPE), including body armor sizing, is a complex process. The use of a single measurement or only two dimensions to determine fit and sizing structure, as commonly observed in traditional marketplaces, has been deemed inadequate (Hsiao, 2013). In a recent study conducted by NIOSH, several body dimensions were identified as significant factors associated with body armor fit and comfort, including Chest Breadth, Chest Circumference, Chest Depth, Stature, Waist Breadth (Sitting), Waist Circumference at Omphalion, Body Weight, Body Mass Index, and Waist Front Length (Sitting) (Hsiao, 2023). This study, combined with the availability of newly obtained national LEO anthropometry data (Hsiao et al., 2021), establishes a foundational basis for developing a data-driven, multivariate LEO body armor sizing system.

1.3. Objective

The objectives of this study were as follows.

1. Develop a comprehensive LEO body armor sizing concept and scheme for each sex group, aiming to enhance LEO protection and well-being.
2. Establish dimension boundaries for each armor/vest size, enabling armor manufacturers to produce a range of multivariate-based armor options.
3. Create a practical sizing chart or sizing app that enables LEOs to quickly and accurately select the most appropriate armor size based on a few key body characteristics known to the individuals.
4. Establish dimension ranges for a series of "sizing vests" (Fig. 3) that LEOs can physically try on to determine the best-fitting vest/armor size, providing an alternative to relying solely on a sizing chart.

The study's overarching goal is to provide LEOs with effective tools and options to ensure optimal fit and sizing of body armor, resulting in enhanced comfort, mobility, and overall performance in the field.

2. Methods

2.1. Participants

This study utilized torso anthropometric data obtained from 756 male and 218 female LEOs who participated in a NIOSH anthropometry study conducted between 2018 and 2020. The recruitment of these LEO participants was based on the geographic distribution of racial and ethnic groups as derived from the 2010 U.S. Census (U.S. Census Bureau, 2012). The research protocol underwent approval from the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board (IRB #14-DSR-02XP) and the U.S. Office of Management and Budget (OMB #0920–1232). These rigorous ethical and regulatory clearances were obtained to ensure the proper and responsible conduct of the study.

Fig. 1. Soft body armor serves as essential protective gear for LEOs, providing defense against a range of threats encountered during their daily duties (1a). This type of armor comprises two panels that overlap to safeguard the wearer's vital organs from the front, back, and sides (1b). Each panel consists of ballistic materials enclosed within a protective casing and held together by a carrier (1c) (Picture credits: TurboSquid.com; NIJ, 2014; Hsiao, 2023).

2.2. Key Dimension Selection

In a comprehensive NIOSH study involving a sample size of 974 participants, the investigation focused on the relationship among LEO armor fit, armor discomfort, armor-induced body pain, and LEO anthropometric characteristics, all of which are relevant to armor sizing and design considerations (Hsiao, 2023). The study identified eight LEO body dimensions associated with armor fit for each sex group. These dimensions included Chest Breadth, Chest Circumference, Chest Depth, Waist Breadth (Sitting), Waist Circumference at Omphalion, Body Weight, and Body Mass Index, which were common to both sexes. Additionally, Stature was considered as the eighth dimension for female LEOs, while Waist Front Length (Sitting) was the eighth dimension for male LEOs. These measurements were utilized as the primary dimensions for each sex in the subsequent analyses (Table 1).

2.3. Cluster procedure

Body armor sizing poses a complex challenge that requires a multivariate approach. Among the available statistical techniques, "cluster analysis" is the most suitable for this sorting problem. This approach allows for the grouping of LEOs based on their torso dimensions and shapes, ensuring that individuals within each group are more similar to each other than to those in other groups. However, determining the optimal number of clusters is not straightforward and necessitates practical armor design criteria to guide the selection of cluster numbers and the best sizing options.

One consideration is the trade-off between cluster overlap and precision in size prediction. Having fewer clusters reduces the overlap between groups on primary torso dimensions, enhancing the accuracy of size prediction. This minimizes the likelihood of a person's body dimensions falling between two adjacent sizes. However, assigning a size to each cluster in this scenario would result in substantial differences in torso dimension means between adjacent armor sizes, making fitting and adjustment of body armor challenging.

On the other hand, selecting a high number of clusters would lead to significant overlap on multiple torso dimensions between clusters. This would result in considerable misassignment of sizes, as an officer's torso dimensions are likely to fit into more than one size. Such an option would be cost-ineffective for manufacturing and ineffective for armor sizing selection for LEOs.

In garment or protective equipment sizing, the gradations between sizes are typically incremental and evenly spaced, although manufacturers may introduce larger differences for the smallest or largest sizes. We established initial criteria for size grading, setting ranges of 89 mm (3.5 inches) for chest circumference, 102 mm (4 inches) for waist circumference, and 25 mm (1 inch) for waist front length (corresponding to vest length) to explore optimal sizing options. These values were derived from our market survey of armor sizing, in conjunction with common garment grading practices.

To ensure cost-effectiveness, the second criterion aimed to limit the number of clusters containing a small percentage (4%) of the overall number of participants. Additionally, the third criterion involved establishing a target dimension span (e.g., 10th percentile to 90th percentile) within each LEO cluster. We proposed spans of 102 mm (4 inches) for chest circumference and 127 mm (5 inches) for waist circumference, using a military armor sizing plan as a reference (NIOSH, 2022). This would define the accommodation range of a cluster of LEOs and further refine potential sizing options.

The military body armor sizing scheme, based on Chest Circumference and Waist Front Length, utilizes a five-size system, with two Waist Front lengths for size X-Small and three Waist Front lengths for size Small, resulting in a total of 8 sizes (Associated Press, 2021). Their chest circumference spans range from 89 mm (3.5 inches) to 178 mm (7 inches) for different body armor sizes (NIOSH, 2022).

This study explored various cluster numbers. But, due to space limitations, we condensed the information in this paper to cover the most significant alternatives, ranging from 4 to 8 clusters for male LEOs and 3 to 7 clusters for female LEOs. Given that body weight (in kg) and body mass index (in kg/m^2) have different scales compared to other body dimensions (in mm), we standardized the anthropometric data by transforming them into unitless measures before conducting cluster analyses. Specifically, for each variable in the model, we subtracted the associated mean and divided by the associated standard deviation to obtain unitless measures. These standardized measures were then utilized in the cluster analysis. The SAS FASTCLUS procedure was employed for the analyses (SAS, 2014).

3. Results

3.1. Clustering body dimensions for armor sizing scheme development

3.1.1. Clustering male LEOs

Table 2 presents a summary of the cluster analysis results for male LEOs based on eight torso dimensions, considering four, five, six, seven, and eight clusters. Among these options, the "six clusters" alternative emerged as the most favorable choice. This option exhibits the fewest overrates (values above the criteria set below) for each dimension, and the observed overrates are minor, aligning with criteria #1 and #3 outlined in the cluster procedure (section 2.3).

Criterion #1 pertains to the anthropometric difference in means between grades (i.e., the six clusters) for the three primary dimensions: 89 mm (3.5 inches) for chest circumference, 102 mm (4 inches) for waist circumference, and 25 mm (1 inch) for front waist length. The analysis shows that the "six clusters" option meets this criterion, with only one between-grades difference having a minor overrate of 13 mm over the desired 102 mm for waist circumference.

Criterion #3 focuses on the anthropometric measurement span (10th percentile to 90th percentile) of two primary dimensions within each cluster: 102 mm (4 inches) for chest circumference and 127 mm (5 inches) for waist circumference. Among the six clusters, only two exhibit minor overrates in the 10th percentile to 90th percentile span. One cluster shows a minor overrate of 3 mm over the desired 102 mm for chest circumference, while another cluster has a minor overrate of 5 mm over the desired 127 mm for waist circumference. Nonetheless, these overrates are preferable compared to those of the alternative cluster options.

Furthermore, the examination of the second criterion confirms that the "six clusters" option satisfies the requirement of no more than one cluster containing less than 4% of the overall number of participants. In

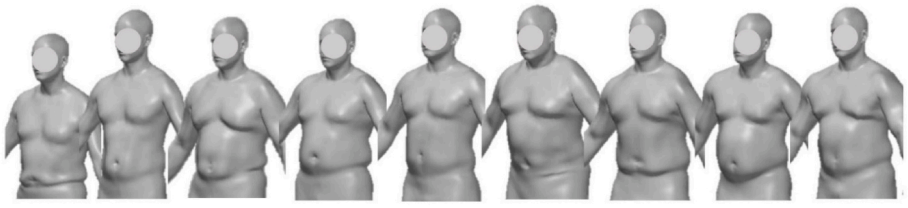


Fig. 2. Representative samples of diverse LEO torso sizes and shapes (Hsiao et al., 2022).

Fig. 3. Sizing vests incorporating integrated tapes for measuring necessary adjustments in front width, front length, back width, and back length have been implemented to assist officers in accurately determining appropriate armor sizes (side view - standing, front view - seated, and back view - standing) (adapted from Hsiao, 2023). Please note that sizing vests are not actual armor; they serve as tools for measuring body dimensions and shape, resembling armor for assessment purposes.

this case, the "six clusters" option accommodates 2.8% of the total participants, which meets the criterion effectively (Table 3).

3.1.2. Clustering female LEOs

Appendix A provides an overview of the cluster analysis results for female LEOs, considering three, four, five, six, and seven clusters based on eight torso dimensions. Among these options, both the "seven clusters" and "six clusters" alternatives emerged as the most suitable choices. Both options will be further explored in the "3.2. Exploring body dimension boundaries" section to advance the development of our sizing scheme.

3.2. Exploring body dimension boundaries in clusters to determine sizing schemes

The Cluster Analysis method offers the advantage of considering all relevant anthropometric dimensions for the initial development of an armor sizing structure. However, to translate the cluster analysis results into a practical sizing system useable by body armor manufacturers, further investigation into primary human torso dimensions corresponding to physical product design is necessary.

In armor design and configuration, human torso size and shape can be summarized by chest circumference, waist circumference, and torso length. For physically fit male officers, accommodating chest circumference is crucial, while for heavier male officers, containing waist circumference is significant. For female officers, accommodating bust size (chest circumference) is a crucial factor. Additionally, many individuals are already aware of their chest circumference and waist circumference since these measurements are associated with shirt and trouser sizing. Therefore, chest circumference and waist circumference can be practical dimensions for establishing armor sizes and sizing boundaries.

Regarding the length dimension, there are two sensible choices: Waist Front Length (torso length) and Stature. Waist Front Length correlates with body armor fit for male LEOs, while Stature is relevant for female LEOs (Hsiao, 2023). Considering the diverse populations in the LEO workforce, torso lengths and their ratios to chest and waist circumferences may vary among LEOs. Therefore, using Waist Front Length as the governing length dimension for male LEOs and Stature for female LEOs, along with chest circumference and waist circumference, would be a sensible approach for establishing a practical armor sizing structure. It is understandable that in armor physical design practice, waist front length needs to be included in armor specifications for both male and female LEOs. However, in sizing selection, stature would be more practical than waist front length because stature is more readily obtainable for anyone unless assistance is available to measure waist front length for LEOs.

In general, sizing systems aim to include as many people as possible within reasonable limits. Typically, this is achieved by setting boundary percentiles for the primary dimensions. For many products, the lower limit is set at the 5th percentile, and the upper limit at the 95th percentile. For PPE with multiple incremental sizes, using the 10th percentile as the lower limit and the 90th percentile as the upper limit would be more practical. In this study, the latter alternative (10th-90th percentiles) was employed to define the boundaries among the clusters, reducing the impact of outliers within each cluster and resulting in more well-defined boundaries. Additionally, individuals falling in the 91st to 99th percentile of a cluster would already be covered by the higher grade, while those in the 1st to 9th percentile would be covered by the lower grade (Fig. 4a). For the smallest grade cluster, the 5th percentile can be considered as the lower limit instead of the 10th percentile, and for the largest grade cluster, the 95th percentile can be considered as the upper limit instead of the 90th percentile (Fig. 4b).

3.2.1. Sizing system by chest and waist circumferences and waist front length for male LEOs

Based on the three criteria outlined in the Cluster Procedure section, the cluster analysis of eight torso dimensions of male LEOs suggests that the "six clusters" option is the best choice. With the inclusion of two circumferential dimensions and waist front length (or torso length), it is possible to specify the design values for each armor size. When designing a product, the target for each size should be near the upper end of the dimension range to ensure that the product can accommodate all individuals within that size bracket. Smaller individuals can use a product that is slightly too big, whereas the opposite is typically not true. Therefore, for the two circumferential dimensions, we used the 90th percentile value of each dimension within a given size/cluster (refer to Table 4). For instance, in the male size 36–40 (the smallest grade) based on chest circumference, the armor/vest dimension at the chest circumference would be 1018 mm. The corresponding waist circumference grade is 31–36, and the vest dimension at the waist circumference is 920 mm (Table 4). Another example is the male size 49–53 grade for chest circumference, where the vest dimension at the chest circumference is 1348 mm. The corresponding waist circumference grade is 47–51, and the vest dimension at the waist circumference is 1304 mm.

Regarding the inclusion of length variation in sizing systems, our survey of commercial sizing systems revealed that some vendors produce body armor in only one length, while others offer short and long versions. A few vendors provide short, regular, and long versions. The range of length for each size varied among vendors, ranging from 25 to 64 mm (1″ to 2.5″). In our approach, we used 60 mm (2.3 inches) as a benchmark to determine whether a single-length or two-length (short and long) version should be offered within each cluster. If the span of 10th to 90th percentile Waist Front Length within a cluster is no more

Table 1
Body dimensions relevant to LEO body armor configuration (adapted from Hsiao et al., 2021; Hotzman et al., 2011).

Item	Variable	Description	
1	Chest Breadth		The maximum horizontal breadth of the chest at the level of the chest point anterior landmark.
2	Chest Circumference (Chest/Bust Girth)		The maximum circumference of the chest at the fullest part of the breast.
3	Chest Depth		The horizontal distance between the right chest point anterior landmark and the back at the same level.
4	Waist Breadth, Sitting		The horizontal breadth of the waist at the level of omphalion.
5	Waist Circumference at Omphalion		The horizontal circumference of the waist at the level of omphalion encompassing the waist (omphalion) landmarks.
6	Weight (kg)		Participant stands on the platform of the scale with weight distributed evenly on both legs. Stand in front of the participant and take the weight of the participant to the nearest tenth of a kilogram.
7	Body Mass Index (BMI)		$BMI = Weight/Stature^2$
8	Stature		The vertical distance from a standing surface to the top of the head.
9	Waist Front Length (WFL), Sitting		The surface distance between the suprasternale landmark at the lowest point of the notch at the top of the breastbone and omphalion while seated.

than 60 mm, a single length is deemed sufficient. If the span falls between 60 mm and 110 mm (2.3–4.3 inches), two sizes are proposed for that cluster. No cluster exhibited a span of 10th to 90th percentile Waist Front Length exceeding 110 mm. For the single length, we used the mean value of Waist Front Length for each circumferential size cluster. In this case, assuming the Waist Front Length data are normally distributed, the maximum "deviation" of the length for any individual would be 30 mm. For the short and long versions, we utilized the 25th and 75th percentiles of Waist Front Length, resulting in a maximum "deviation" of the length for any individual of approximately or less than 30 mm. These outcomes yield a 9-size system for male LEOs, where three chest-and-waist grades have one vest length per grade, while the other three chest-and-waist grades have two vest lengths per grade. It is important to note that in the initial Cluster Analyses (Section 3.1), we established the first criterion for grades of three primary dimensions, which included 25 mm (1 inch) for waist front length. The aim was to differentiate the means of Waist Front Length between two clusters, and it should not be confused with the span of 10th to 90th percentile Waist Front Length within a cluster, as described here.

Fig. 4a and b presents two graphical plots illustrating the relationship between Waist Front Length (sitting) and Chest Circumference in six clusters with 80% and 90% confidence ellipses centered around each cluster, respectively. These figures demonstrate the extent of overlap between clusters, highlighting the requirement for two Waist Front Length sizes in the three larger grade vests. This necessity arises from the scattered distribution of Waist Front Length data within these three larger grades.

3.2.2. Sizing system by chest and waist circumferences and front waist length for female LEOs

Based on the three criteria outlined in section "2.3. Cluster Procedure," the cluster analysis of eight body dimensions for female LEOs suggests two potential sizing options: seven clusters and six clusters (see Appendix A for details). By employing the same procedure described in section 3.2.1, it is feasible to determine the specific design values for each size within the framework of either seven or six clusters. The process and outcomes are detailed in Appendix B. Upon careful analysis of the grade distribution for both chest circumference and waist circumference, it is evident that the grades are more evenly distributed in the "seven clusters" option compared to the "six clusters" option (Appendix B). Consequently, we recommend adopting an 8-size system for female LEOs based on the "seven clusters" option with six chest-and-waist grades having one vest length per grade, while one chest-and-waist grade (Cluster #6) necessitates two vest lengths.

3.3. Dimensions for each grade of vests/armor

3.3.1. Dimensions of each vest/armor grade (size) for male LEOs

As discussed in the "3.2. Exploring sizing system boundaries to identify sizing schemes" section, the design target for each armor size should align with the upper range of body dimensions within each cluster of LEOs. This ensures that the armor can accommodate all individuals within the size bracket, as smaller individuals can wear a slightly larger vest, while the opposite is not feasible. Table 5 provides an overview of the 90th percentile values for relevant body dimensions used in armor configuration, along with the 50th percentile value of waist front length for each cluster (or size). For male LEOs, a total of nine sizes are proposed. The first three clusters (clusters #4, #5, and #6) have a single waist front length each and can be designated as sizes XS, S, and M. The remaining three clusters (clusters #1, #2, and #3), which represent the larger grades, have two waist front lengths (short and long) and can be named sizes L(S), L(L), XL(S), XL(L), XXL(S), and XXL (L) (Fig. 5). For example, in the grade range of 36–40 (Size XS) for chest circumference (or 31–36 for waist circumference), the dimensions for the armor/vest would be as follows: 348 mm for chest breadth, 1018 mm for chest circumference, 262 mm for chest depth, 330 mm for waist breadth, 920 mm for waist circumference at omphalion, and 381 mm for waist front length (sitting). Additionally, vest manufacturers should account for additional space for clothing, such as 25 mm for light dress (e.g., summer or fall attire). In the case of winter clothing, there may not be a need for additional space as the winter coat would be worn over the armor.

Table 2
Cluster analysis results on eight torso dimensions of male LEOs by four, five, six, seven, and eight clusters.

Dimension (Mean; mm)	Number of Clusters: 4 (C2, C3, C1, and C4)				Mean Body Size Changes between Clusters *(Criterion#1)*		
	C2	C3	C1	C4	C2 –C3	C3 –C1	C1 – C4
Chest Breadth	336	368	401	443	32	33	42
Chest Cir.	1001	1103	1196	1318	**102**	**93**	**122**
Chest Depth	250	279	306	340	29	27	34
Waist Breadth	319	354	393	442	35	38	49
Waist Cir.	893	1010	1136	1292	**117**	**126**	**156**
Waist Front L.	386	409	426	451	23	17	25
Weight (kg)	78.9	93.0	108.5	133.7	14.1	15.5	25.2
BMI	25.5	29.4	34.2	40.1	3.9	4.8	5.9
10th - 90th Span	***Criterion #3***						
Chest Cir	**110**	94	97	**122**			
Waist Cir.	**155**	**131.5**	**132.5**	**151**			

Dimension (Mean; mm)	Number of Clusters: 5 (C5, C4, C3, C2, and C1)					Mean Body Size Changes between Clusters *(Criterion#1)*			
	C5	C4	C3	C2	C1	C5 – C4	C4 – C3	C3 – C2	C2 –C1
Chest Breadth	330	358	381	411	447	28	23	29	36
Chest Cir.	984	1068	1143	1221	1330	84	74	79	**109**
Chest Depth	246	268	291	313	343	22	23	22	30
Waist Breadth	312	342	369	405	446	30	27	36	42
Waist Cir.	872	968	1061	1173	1308	96	93	**113**	**134**
Waist Front L	383	401	416	431	455	18	15	15	23
Weight (kg)	76.3	88.1	98.9	113.6	137.2	11.8	10.9	14.7	23.6
BMI	24.8	28.1	31.2	35.4	40.8	3.2	3.2	4.2	5.4
10th - 90th Span	***Criterion #3***								
Chest Cir	**107**	82	87	101	**123**				
Waist Cir.	**136**	115	121	**148**	**167**				

Dimension (Mean; mm)	Number of Clusters: 6 (C4, C5, C6, C1, C2, and C3)						Mean Body Size Changes between Clusters *(Criterion #1)*				
	C4	C5	C6	C1	C2	C3	C4 –C5	C5 –C6	C6 –C1	C1 – C2	C2 –C3
Chest Breadth	327	355	378	405	433	459	28	23	27	27	26
Chest Cir.	977	1059	1133	1207	1291	1362	82	74	74	84	71
Chest Depth	244	265	288	308	333	351	21	23	20	25	18
Waist Breadth	309	339	367	397	426	467	30	28	31	29	41
Waist Cir.	858	960	1049	1150	1249	1364	101	89	101	99	**115**
Waist Front L	381	400	413	427	451	448	18	14	14	24	−3
Weight (kg)	75.2	86.5	97.7	110.7	126.4	145.9	11.3	11.2	13.0	15.7	19.5
BMI	24.5	27.7	30.8	34.6	38.5	42.8	3.2	3.1	3.7	3.9	4.3
10th - 90th Span	***Criterion #3***										
Chest Cir	97	83	80	75	**105**	94					
Waist Cir.	**132**	112	121	125	119	127					

Dimension (Mean; mm)	Number of Clusters: 7 (C6, C5, C1, C3, C2, C4, and C7)							Mean Body Size Change between Clusters *(Criterion #1)*					
	C6	C5	C1	C3	C2	C4	C7	C6 – C5	C5 –C1	C1 –C3	C3 – C2	C2 –C4	C4 – C7
Chest Breadth	324	351	374	396	416	431	456	27	22	22	20	15	25
Chest Cir.	969	1049	1119	1185	1239	1281	1351	80	70	66	55	41	70
Chest Depth	242	263	283	302	319	329	348	21	20	19	16	11	19
Waist Breadth	307	335	361	388	408	431	457	29	25	27	20	23	26
Waist Cir.	853	947	1030	1119	1189	1253	1338	93	83	89	71	64	86
Waist Front L	382	396	414	416	462	414	466	14	18	3	**46**	**−48**	**53**
Weight (kg)	73.9	85.7	95.2	105.7	118.3	124.6	143.0	11.8	9.5	10.4	12.7	6.2	18.5
BMI	24.1	27.4	30.0	33.6	35.4	39.5	41.7	3.3	2.6	3.6	1.8	4.1	2.2
10th - 90th Span	***Criterion #3***												
Chest Cir	89	76	80	83	**103**	**145**	93						
Waist Cir.	**139**	113	109	115	**157**	**133**	**204**						

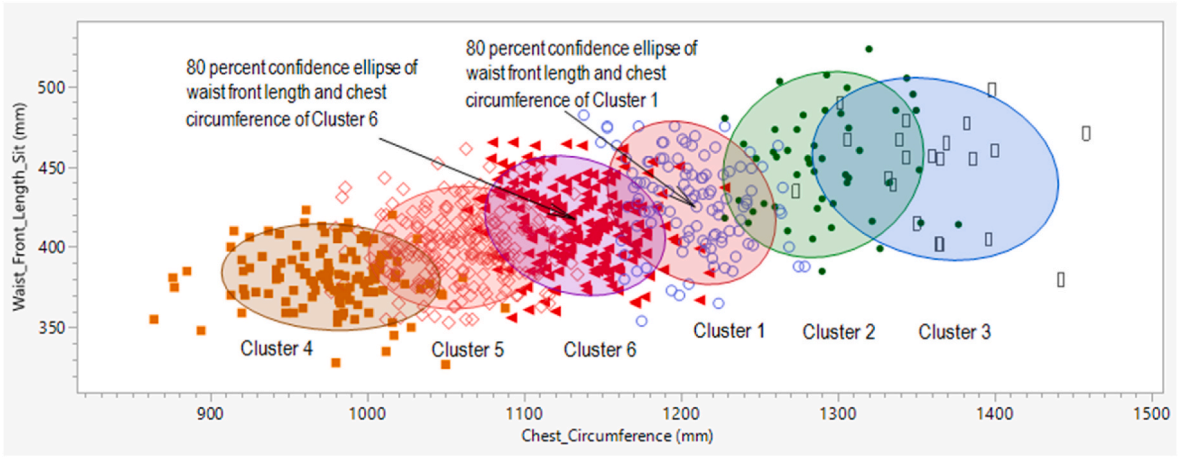
Dimension (Mean; mm)	Number of Clusters: 8 (C5, C7, C4, C6, C2, C8, C3, C1)								Mean Body Size Change between Clusters *(Criterion #1)*						
	C5	C7	C4	C6	C2	C8	C3	C1	C5 –C7	C7 – C4	C4– C6	C6– C2	C2 –C8	C8 – C3	C3 –C1
Chest Breadth	323	349	367	381	395	420	426	457	27	18	14	14	25	5	31
Chest Cir.	964	1041	1096	1146	1182	1250	1270	1356	76	55	50	36	67	20	86
Chest Depth	241	260	276	292	301	321	327	350	20	15	16	10	20	5	23
Waist Breadth	305	333	352	372	385	416	419	461	28	19	19	14	31	3	42
Waist Cir.	847	937	1006	1061	1114	1208	1223	1351	90	69	56	53	94	15	**128**
Waist Front L	383	389	423	393	441	408	465	453	7	**33**	**−30**	**48**	**−33**	**57**	−12
Weight (kg)	73.2	84.6	92.0	98.9	105.9	118.3	124.0	143.7	11.4	7.5	6.8	7.0	12.4	5.7	19.7
BMI	23.9	27.1	28.9	31.8	33.1	37.4	36.7	42.5	3.3	1.8	2.9	1.3	4.3	−0.7	5.8
10th - 90th Span	***Criterion #3***														
Chest Cir	81	77	74	80	84	95	**120**	95							
Waist Cir.	**146**	112	105.5	**128**	119	127	116	**176**							

C: Cluster #. For instance, C5 stands for Cluster #5.
C5 – C7: Body size change in mean between two clusters. For instance, C5 – C7 stands for difference in means between clusters 5 and 7.
Bolded Numbers: The difference in means for the measurement between two clusters is greater than the preset criterion (*Criterion 1*) or the measurements are greater than the criterion set for the 10th - 90th span (*Criterion 3*) within a cluster. All dimensions are in mm except for weight in kg and BMI in kg/m^2.

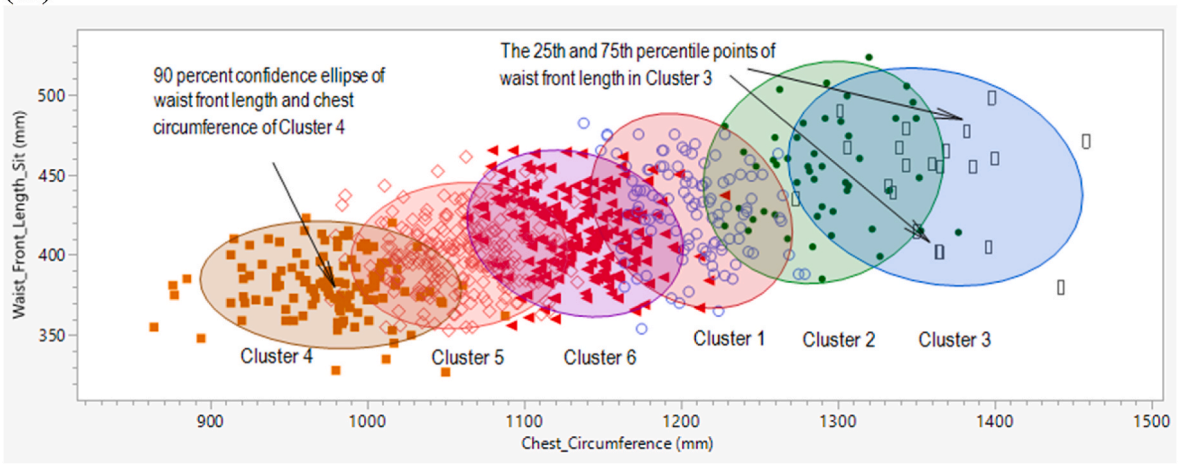
Table 3
The Number and percentage of male participants in each cluster when four, five, six, seven, and eight clusters were applied for classification (Criterion #2).

Total Number of Clusters	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6		Cluster 7		Cluster 8	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Four	160	21.2	223	29.5	310	41.0	63	8.3								
Five	49	6.5	110	14.6	204	27.0	241	31.9	152	20.1						
Six	110	14.6	49	6.5	21	**2.8**	125	16.5	240	31.8	211	27.9				
Seven	201	26.6	47	6.2	121	16.0	34	4.5	221	29.2	106	14.0	26	**3.4**		
Eight	26	**3.4**	8.7	11.5	38	5.0	160	21.2	94	12.4	120	15.9	185	24.5	46	6.1

Percentage in Bold: Percentage of participants in a cluster is less than 4% of the overall participants (***Criterion 2***).



(4a)



(4b)

Fig. 4. Scatter plots of Waist Front Length against Chest Circumference. The first plot (4a) includes the 80 percent confidence ellipses centered around each cluster, and the second plot (4b) includes the 90 percent confidence ellipses centered around each cluster. Both plots highlight the wider range of waist front length in Clusters 1, 2, and 3 compared to the other clusters, emphasizing the necessity for two Waist Front Length sizes in the three larger grade vests designed for male LEOs.

It is important to note that a vest comprises two ballistic-resistant panels that protect the front and back of the torso, with an overlap of at least 50 mm required to safeguard the sides of the torso (National Institute of Justice – NIJ, 2014). The dimensions presented in Table 5 represent solely the torso configurations and do not include the 50 mm overlap requirement pertain to the vest designs and materials.

It is important to highlight that the three larger grade clusters (clusters #1, #2, and #3) consist of two waist front lengths, namely short and long. These lengths were determined based on the 25th and 75th percentile values obtained during the initial clustering process (as shown in Table 4). To provide more precise specifications for the dimensions of the six vest sizes derived from these three clusters, each of clusters #1, #2, and #3 was further divided into two subclusters using the 50th percentile value of waist front length from each cluster as the dividing point. This approach enabled a simultaneous consideration of multiple body dimensions within each subcluster, rather than solely relying on the waist front length (resulting in clusters #1A, 1B, #2A, 2B, #3A, and 3B, corresponding to L(S), L(L), XL(S), XL(L), XXL(S), and XXL (L) sizes, respectively). Consequently, the vest length was determined as the 50th percentile value of waist front length within each of the six subclusters, providing more accurate specifications for the dimensions of the vests (as presented in Table 5 and Fig. 5).

3.3.2. *Dimensions of each vest grade/size for female LEOs*

Table 6 summaries body dimensions relevant to armor configuration for female LEOs based on the seven-cluster with eight-size concept

Table 4
Proposed sizing system by Chest and Waist Circumferences and Waist Front Length for male LEOs.

DIMENSION	Cluster	Lower Boundary (mm)[a]	Upper Boundary (mm)[b]	Lower Boundary (inches)[a]	Upper Boundary (inches)[b]	Design size (mm)[c]	Grade (inches)
Chest	4	921	1018	36.3	40.1	1018	36–40
Circumference	5	1018	1100	40.1	43.3	1100	40–43
	6	1091	1171	43.0	46.1	1171	43–46
	1	1170	1245	46.1	49.0	1245	46–49
	2	1243	1348	49.0	53.1	1348	49–53
	3	1306	1400	51.4	55.1	1400	51–55[d]
Waist	4	788	920	31.0	36.2	920	31–36
Circumference	5	902	1014	35.5	39.9	1014	36–40
	6	988	1109	38.9	43.7	1109	39–44[d]
	1	1084	1209	42.7	47.6	1209	43–48[d]
	2	1185	1304	46.7	51.3	1304	47–51[d]
	3	1323	1451	52.1	57.2	1451	52–57
Waist Front Length	4	359	407	14.1	16.0	381	
	5	373	427	14.7	16.8	400	
	6	385	445	15.2	17.5	413	
	1	388	465	15.3	18.3	Mean:428; 25th-406 75th - 449 (2 sizes)	
	2	412	499	16.2	19.6	Mean: 451; 25th-425 75th – 474 (2 sizes)	
	3	402	479	15.8	18.9	Mean: 449; 25th-435 75th - 467 (2 sizes)	

[a] The 10th percentile values of chest circumference, waist circumference, and waist front length for each cluster.
[b] The 90th percentile values of chest circumference, waist circumference, and waist front length for each cluster.
[c] The 90th percentile values of chest circumference and waist circumference and the 50th percentile value of waist front length for each cluster. Note: the 25th and 75th percentile values of waist front length are offered for the three upper grade clusters (i.e., Clusters 1, 2, and 3).
[d] The grades exhibit a slight overlap with the adjacent grade, and the specific covered ranges are outlined in the "Lower Boundary (inches)" and "Upper Boundary (inches)" columns. Further elaboration on the distribution of the final grades can be found in Tables 9 and 10.

outlined in Table B1 and Figure B1 of Appendix B. The table includes the 90th percentile values of each body dimension and the 50th percentile value of waist front length within each size. For example, in the grade of 32–36 (XS Size) based on chest circumference (or grade 28–32 based on waist circumference), the armor dimensions would be 296 mm for chest breadth, 910 mm for chest circumference, 245 mm for chest depth, 300 mm for waist breadth, 805 mm for waist circumference at omphalion, and 360 mm for front waist length (sitting). It is common practice for vest makers to include additional space for clothing, such as 25 mm for summer dress.

Similar to the process for dimensions of vests for male LEOs, there is a grade (Cluster #6) that requires two waist front lengths (short and long). These lengths were specified at the 25th and 75th percentile values in the initial clustering process described in Table B1 (see Appendix B). To provide more precise dimensions for these two vest sizes, LEOs in Cluster #6 were regrouped into two subclusters using the 50th percentile value of waist front length from Cluster #6 as the partition. This approach allows for simultaneous consideration of multiple body dimensions within each subcluster (Clusters #6A and #6B), corresponding to sizes L(S) and L(L), respectively. The vest length is now specified at the 50th percentile value of waist front length within each of these two subclusters.

3.3.3. *Selecting the armor size that is most likely to fit an individual*

Tables 5 and 6 provide valuable information for LEOs to determine the most suitable armor size based on their body dimensions. While the selection process may be challenging due to multiple body measurements, LEOs can use chest circumference and waist circumference as the primary parameters to guide their size selection. If an LEO's measurements fall between two grades, it is advisable to choose the larger grade.

To facilitate the size selection process and minimize effort for LEOs, the development of a sizing app or machine-learning algorithm, such as a logistic regression approach, could be beneficial. Such tools can utilize commonly known body measurements among LEOs, including waist circumference, chest circumference, body weight, and stature, which are often obtained during annual physical examinations and in the context of daily uniform usage. Additionally, waist circumference, chest circumference, body weight, and BMI (body weight/stature^2) are key dimensions associated with armor fit and comfort ratings (Hsiao, 2023). Leveraging these dimensions effectively, an app, chart, or algorithm can be developed to assist LEOs in making initial size selections with greater convenience and accuracy.

One sensible option is to develop a simplified app or chart that utilizes Chest Circumference and BMI (calculated by entering body weight and stature) to determine the appropriate sizes. These two variables, when combined, can effectively differentiate between sizes better than other combinations.

For male LEOs, the grades XS, S, and M consist of one waist front length for each grade. On the other hand, the grades L, XL, and XXL include both a short size and a long size of waist front length for each grade, resulting in L(S), L(L), XL(S), XL(L), XXL(S), and XXL(L) subgrades (Fig. 7). To establish the size boundaries and the probability of wearing a size over an adjacent size, a logistic regression model can be employed. Mathematically, the logistic regression equation with Chest Circumference and BMI as the primary predictor variables can be expressed as:

$$p(x) = 1 / (1 + e^{(-z)})$$

where:

p(x) is the probability of the outcome variable being 1 for a given set of predictor variable values.

e is the base of the natural logarithm (approximately 2.71828).

z represents the linear combination of the predictor variables, weighted by their corresponding coefficients:

$z = \beta_0 + \beta_1 x_1 + \beta_2 x_2$

β_0, β_1, and β_2 are the intercept and coefficients associated with the predictor variables Chest Circumference and BMI, respectively.

x_1 and x_2 are the predictor variable values of Chest Circumference

Table 5
Dimensions of each of the proposed nine vest sizes for male LEOs.

Body Dimension (mm)	Grade (inches)[c]		
	CC: 36-40	CC: 40-43	CC: 43-46
	WC: 31-36	WC: 36-40	WC: 39-44
Cluster	#4 [XS]	#5 [S]	#6 [M]
Chest Breadth	348	372	394
Chest Circumference	1018	1101	1172
Chest Depth	262	280	304
Waist Breadth	330	358	386
Waist Circumference Omphalion	920	1016	1109
Waist Front Length, Sitting[b]	**381**	**399**	**411**
Weight (kg)	83.6	93.7	106.2
Body Mass Index (BMI)	27.0	29.9	33.4
Stature[a]	1830	1858	1868
Body Dimension (mm)	Grade (inches)		
	CC: 46-49	CC: 46-49	CC: 49-53
	WC: 43–48[d]	WC: 43–48[d]	WC: 47–52[d]
Cluster	#1A [L(S)]	#1B [L(L)]	#2A [XL(S)]
Chest Breadth	427	426	459
Chest Circumference	1255	1244	1353
Chest Depth	328	324	353
Waist Breadth	428	419	456
Waist Circumference Omphalion	1223	1207	1311
Waist Front Length, Sitting[b]	**405**	**449**	**425**
Weight (kg)	121.4	122.6	136.4
Body Mass Index (BMI)	38.1	36.3	42.4
Stature[a]	1857	1899	1910
Body Dimension (mm)	Grade (inches)		
	CC: 49-53	CC: 50–57[d]	CC: 51–57[d]
	WC: 47–52[d]	WC: 49–57[d]	WC: 52–58[d]
Cluster	#2B [XL(L)]	#3A [XXL(S)]	#3B [XXL(L)]
Chest Breadth	458	471	502
Chest Circumference	1346	1442	1435
Chest Depth	349	393	366
Waist Breadth	450	487	513
Waist Circumference Omphalion	1314	1451	1464
Waist Front Length, Sitting[b]	**474**	**410**	**467**
Weight (kg)	139.3	162.7	165.1
Body Mass Index (BMI)	42.8	46.1	47.5
Stature[a]	1949	1970	1995

CC: Chest Circumference. WC: Waist Circumference.
[a] Body dimension "Stature" was not included in the cluster analysis. It is included in this table for reference.
[b] Waist front length is set at the 50th percentile value. All other dimensions are set at the 90th percentile values for each of the CC/WC grades.
[c] The grades are defined as round offs in inches for the 10th to 90th values of Chest Circumference and Waist Circumference. For the smallest grade (Cluster 4 in this table), the 5th Chest Circumference and Waist Circumference values were set as the lower boundary. For the largest grade, the 95th Chest Circumference and Waist Circumference values were set as the upper boundary.
[d] The grade values for L(S), L(L), XL(S), XL(L), XXL(S), and XXL(L) sizes are slightly different from those in Table 6 as their values were recalculated after the L, XL, and XXL sizes (i.e., Clusters #1, #2, and #3) were further divided into two subclusters each based on their waist front length.

and BMI.

The size boundaries can be determined by setting the probability in the model to p = 0.5 (i.e., the decision boundary line separating the predicted adjacent size is the solution of $\beta_0 + \beta_1 x_1 + \beta_2 x_2 = 0$). Below are the details of the statistical models:

The probability of wearing XS size instead of S size = 1/(1 + exp (-(83.2930143–0.0670323 * chest circumference – 0.5940142 * body mass index))). —— [Equation 1]

The probability of wearing S size instead of M size = 1/(1 + exp (-(96.0799394–0.0691642 * chest circumference – 0.6924783 * body mass index))). —— [Equation 2]

The probability of wearing M size instead of L size = 1/(1 + exp (-(110.179805–0.0749385 * chest circumference – 0.6663894 * body mass index))). —— [Equation 3]

The probability of wearing L size instead of XL size = 1- 1/(1 + exp (-(-132.8653 + 0.08543117 * chest circumference + 0.70193733 * body mass index))). —— [Equation 4]

The probability of wearing XL size instead of XXL size = 1 - 1/(1 + exp (-(-70.668517 + 0.03812644 * chest circumference + 0.47468396 * body mass index))). —— [Equation 5]

The probability of wearing L(S) size instead of L(L) size = 1/(1 + exp (-(-21.474477 + 0.00948736 * chest circumference + 0.28881846 * body mass index))). —— [Equation 6]

The probability of wearing XL(S) size instead of XL(L) size = 1/(1 + exp (-(-9.0985686 + 0.00162699 * chest circumference + 0.18085574 * body mass index))). —— [Equation 7]

The probability of wearing XXL(S) size instead of XXL(L) size = 1/(1 + exp (-(5.63504698 - 0.0049179 * chest circumference + 0.01341174 * body mass index))). —— [Equation 8]

This logistic regression prediction (equation (8)) may exhibit instability due to the limited number of samples available in the XXL(S) and XXL(L) sizes.

For female LEOs, the L grade is divided into two subgrades: L(S) and L(L), representing short and long sizes of waist front length. The remaining six grades, namely XS, S, M, R (Regular), XL, and XXL, have a single waist front length assigned to each grade (Fig. 8). To determine the probability of wearing a size over an adjacent size, the statistical models are described in detail below:

The probability of wearing XS size instead of S size = 1/(1 + exp (-(34.3724658–0.0398985 * chest circumference + 0.0617037 * body mass index))). —— [Equation 9]

The probability of wearing S size instead of M size = 1/(1 + exp (-(58.9955738–0.0238746 * chest circumference – 1.4509423 * body mass index))). —— [Equation 10]

The probability of wearing M size instead of R (Regular) size = 1 - 1/(1 + exp (-(-25.599146 + 0.02268202 * chest circumference + 0.09404183 * body mass index))). —— [Equation 11]

The probability of wearing R size instead of L size = 1/(1 + exp (-(66.872991–0.0309138 * chest circumference – 1.128404 * body mass index))). —— [Equation 12]

The probability of wearing L(S) size instead of L(L) size = 1/(1 + exp (-(24.1851021 - 0.0279275 * chest circumference + 0.18940401 * body mass index))). —— [Equation 13]

The probability of wearing L size instead of XL size = 1 - 1/(1 + exp (-(-10969.753 + 5.00088322 0.0309138 * chest circumference + 147.725679 * body mass index))). —— [Equation 14]

This logistic regression prediction (equation (14)) may exhibit instability due to the limited number of samples available in the XL size.

The probability of wearing XL size instead of XXL size = 1 - 1/(1 + exp (-(-5.9165412 – 0.0465981 * chest circumference + 1.68435377 * body mass index))). —— [Equation 15]

This logistic regression prediction (equation (15)) may exhibit instability due to the limited number of samples available in the XL and XXL sizes.

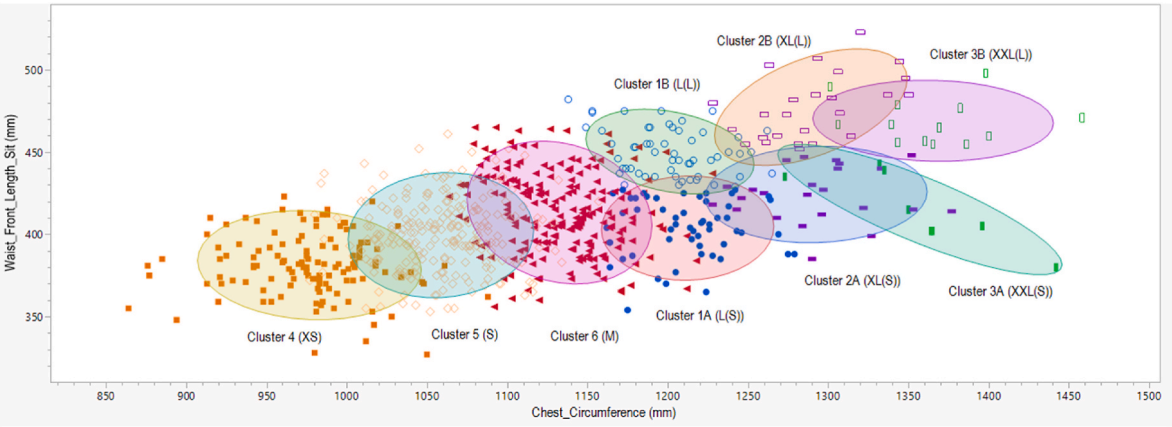


Fig. 5. Scatter plot of Waist Front Length by Chest Circumference for male LEOs in nine groups, including the division of clusters 1, 2, and 3 into two subgroups (Clusters 1A and 1B, 2A and 2B, and 3A and 3B). The plot includes 80% confidence ellipses centered from each cluster center of waist front length and chest circumference.

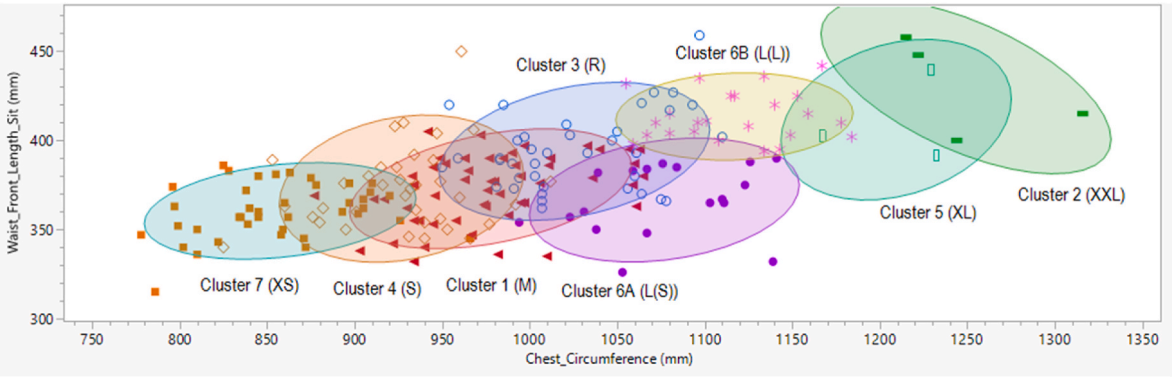


Fig. 6. Scatter plot of Waist Front Length by Chest Circumference of female LEOs in eight size groups with 80% confidence ellipses, where Cluster #6 is divided into two subclusters (Cluster #6A and Cluster #6B).

3.4. Sizes and adjustment ranges of "sizing vests"

Recognizing that armor coverage and fit encompass multiple dimensions rather than being solely a single-dimensional issue, armor manufacturers are adopting the concept of "sizing vests" for assessing armor fit (Fig. 3). Section 7 of the ASTM E3003-20 standard outlines procedures for defining armor fit when using a sizing vest. However, the standard does not specify the dimensions and number of sizes for sizing vests. This study contributes companion information to enhance the standard by providing additional insights and recommendations regarding sizing vests.

Sizing vests serve as measurement tools rather than actual armor and therefore can be designed in various sizes and configurations. The ASTM E3003-20 standard specifies the use of torso girth (waist circumference) and chest girth (chest circumference) measurements to determine the most suitable sizing vest for an individual. By adjusting the front and back panels and shoulder straps and conducting a fit assessment in the shooting stance, the wearer can identify whether a step-down, step-up, or current size is appropriate. A width tape located on the side of the panels (Fig. 3) can be utilized to determine the panel width needed to achieve the required overlap. Likewise, a length tape positioned at the lower part of the panels can assist in determining the necessary front and back panel lengths.

Considering the concept of sizing vests mentioned earlier and the cluster analysis results presented in Section 3.3, "Dimensions for Each Grade of Vests/Armor," a practical approach for the number of sizing vests would be nine for male LEOs and eight for female LEOs. This corresponds to the nine sizes of armor for male LEOs and eight sizes for female LEOs identified in the study. For each sizing vest, the size would be determined by the 90th percentile values of chest circumference and waist circumference for each cluster, while the vest length would be set at the 50th percentile value of the waist front length. To determine the lengths of the front and back panels, a length tape can be attached to the vest panels. Tables 7 and 8 provide an overview of the proposed dimensions of sizing vests for male and female LEOs, respectively. When considering chest circumference, waist circumference, and waist front length simultaneously, a step-down or step-up size can be determined for a better fit assessment.

4. Discussion

4.1. Sizing systems for female LEOs

Male and female torsos exhibit distinct shapes, and considering this anatomical difference, separate designs for body armor can potentially enhance the fit for both sexes (Hsiao, 2023). A study conducted in Australia (Niemczyk et al., 2020) examined the impact of bras on the performance of unisex ballistic armor for female LEOs. The findings indicated that women with larger breasts encountered more difficulties with their armor compared to women with smaller breasts. These insights, along with the understanding of sex-specific considerations, informed our cluster analyses conducted in this study.

It is acknowledged that there are practical considerations that argue against implementing separate armor sizing systems for men and

Table 6
Dimensions of each of the proposed eight vest sizes for female LEOs.

Body Dimension (mm)	Grade (inches)[b]		
	CC: 32-36	CC: 35-38	CC: 37-42
	WC: 28-32	WC: 31-35	WC: 33-37
Cluster	#7 (XS)	#4 (S)	#1 (M)
Chest Breadth	296	317	336
Chest Circumference	910	971	1058
Chest Depth	245	263	285
Waist Breadth	300	330	339
Waist Circumference Omphalion	805	902	944
Front Waist Length, Sitting[a]	360	371	376
Weight (kg)	64.0	73.2	78.0
Body Mass Index (BMI)	24.9	25.9	30.4
Stature	1668	1774	1657

Body Dimension (mm)	Grade (inches)[b]		
	CC: 39-43	CC: 40–45[c]	CC: 42–46[c]
	WC: 35-40	WC: 39–42[c]	WC: 39–44[c]
Cluster	#3 (R)	#6A (L(S))	#6B (L(L))
Chest Breadth	355	366	367
Chest Circumference	1082	1139	1173
Chest Depth	305	322	336
Waist Breadth	355	384	402
Waist Circumference Omphalion	1017	1065	1121
Front Waist Length, Sitting[a]	392	**366**	**410**
Weight (kg)	91.7	96.7	97.9
Body Mass Index (BMI)	30.8	35.3	35.4
Stature	1784	1681	1709

Body Dimension (mm)	Grade (inches)[b]	
	CC: 46-49	CC: 48-52
	WC: 45-49	WC: 48-51
Cluster	#5 (XL)	#2 (XXL)
Chest Breadth	402	434
Chest Circumference	1232	1316
Chest Depth	355	374
Waist Breadth	436	465
Waist Circumference Omphalion	1234	1297
Waist Front Length, Sitting[a]	403	432
Weight (kg)	117.7	117.3
Body Mass Index (BMI)	37.4	44.6
Stature	1789	1658

CC: Chest Circumference. WC: Waist Circumference.

[a] Waist front length is set at the 50th percentile value. All other dimensions are set at the 90th percentile values for each of the CC/WC grades.

[b] The grades are defined as rounded values in inches for the 10th to 90th percentiles of Chest Circumference and Waist Circumference. In the case of the smallest grade (Cluster 4 in this table), the lower boundary was set as the 5th percentile values for Chest Circumference and Waist Circumference. Similarly, for the largest grade, the upper boundary was set as the 95th percentile values for Chest Circumference and Waist Circumference.

[c] The grade values for L(S) and L(L) sizes in Table 4 are slightly different from those in this table (Table 6). This difference occurred because the L size (Cluster #6) was divided into two subclusters based on waist front length, and the grade values were recalculated accordingly in this table.

women. Currently, female officers account for approximately 13%–18% of uniformed officers in the US (Duffin, 2021; U.S. Bureau of Labor Statistics, 2020). For certain vendors, justifying the development of separate female sizes may pose a challenge due to the relatively smaller number of female officers. Additionally, accommodating the diverse body types of female officers would require a significant number of sizes. While this study proposes eight sizes for female LEOs, it should be noted that detailed analyses on bust configurations were not included in this investigation. In light of considerations related to inclusivity and cost, it could be valuable to explore a unisex sizing system for comparison, either within this paper or in a separate publication. Due to the substantial length of this paper, the authors have opted to dedicate a separate paper to the discussion of unisex sizing systems.

However, it is important to recognize the need for a separate design and sizing system to enhance the safety of female officers. Ensuring proper fit and protection for female LEOs is crucial, considering the unique anatomical factors they face. Therefore, while practical challenges may exist, prioritizing the goal of improving safety for female officers warrants the development of a distinct design and sizing approach.

When comparing the proposed armor sizing structures for male and female LEOs, it is evident that there is a greater overlap among clusters in the scatter plots of waist front length versus chest circumference for female LEOs compared to male LEOs (Figs. 5 and 6). This finding highlights the additional challenge involved in classifying female torso sizes and shapes. While waist front length is a significant dimension in armor physical design, it does not correlate as strongly with perceived fit and comfort of armor for female LEOs, unlike in the case of male LEOs (Hsiao, 2023). As mentioned in the "2.2. Key Dimension Selection" section, stature demonstrated a strong correlation with the perceived fit and comfort of armor for female LEOs. Fig. 9a and b further illustrate the benefits of incorporating stature in the initial multivariate clustering process before determining the physical sizing of the armor for the clustered LEO groups.

Given the complexity involved in classifying female torso sizes and shapes, we would recommend that women consider utilizing sizing vests as a particularly useful tool, especially when compared to male LEOs, in selecting a size that offers the best fit for individuals. Sizing vests provide a more comprehensive and accurate assessment of body measurements, enabling a more personalized and tailored fit for female LEOs.

4.2. Dimension boundaries for each vest size

The cluster analyses conducted on LEO anthropometric characteristics served as the foundation for grouping LEOs based on their torso dimensions. This grouping ensured that individuals within each group were more similar to one another in terms of combined torso dimensions compared to individuals in other groups. To translate these cluster analysis results into practical armor design and sizing, the anthropometric dimensions relevant to armor configurations were evaluated. This study focused on chest circumference, waist circumference, and torso length (waist front length) as the key dimensions to refine the LEO grouping, which resulted in the determination of nine armor sizes for men and eight sizes for women.

Tables 5 and 6 outline the dimension boundaries for each proposed armor size, representing the 90th percentile value of each of the eight anthropometric dimensions. It is important to exercise caution when designing the largest grade of armor, such as cluster XXL(S) size for male LEOs and XL and XXL sizes for female LEOs. Due to the relatively smaller number of LEOs in these categories and the larger variations among them in certain dimensions, the fit and accommodation rates in these grades may not be as optimal as in other armor grades. For individuals falling within these grades, customized designs may be necessary to ensure a better fit and comfort.

4.3. Sizing chart, sizing app, and sizing vests

The aim of an armor sizing chart is to aid LEOs in swiftly selecting the most suitable armor size based on a few known body characteristics. Recognizing that armor fit is a multidimensional issue and that a sizing chart must strike a balance between simplicity and practicality, the sizing charts presented in Tables 5 and 6, which focus on chest circumference and waist circumference, fulfill this purpose. These charts serve as a starting point for selecting a size to try on. Individuals with different combinations of anthropometric characteristics should also consider trying adjacent sizes to determine the best fit.

The sizing app represents a step forward compared to sizing charts, as it incorporates additional anthropometric dimensions beyond chest

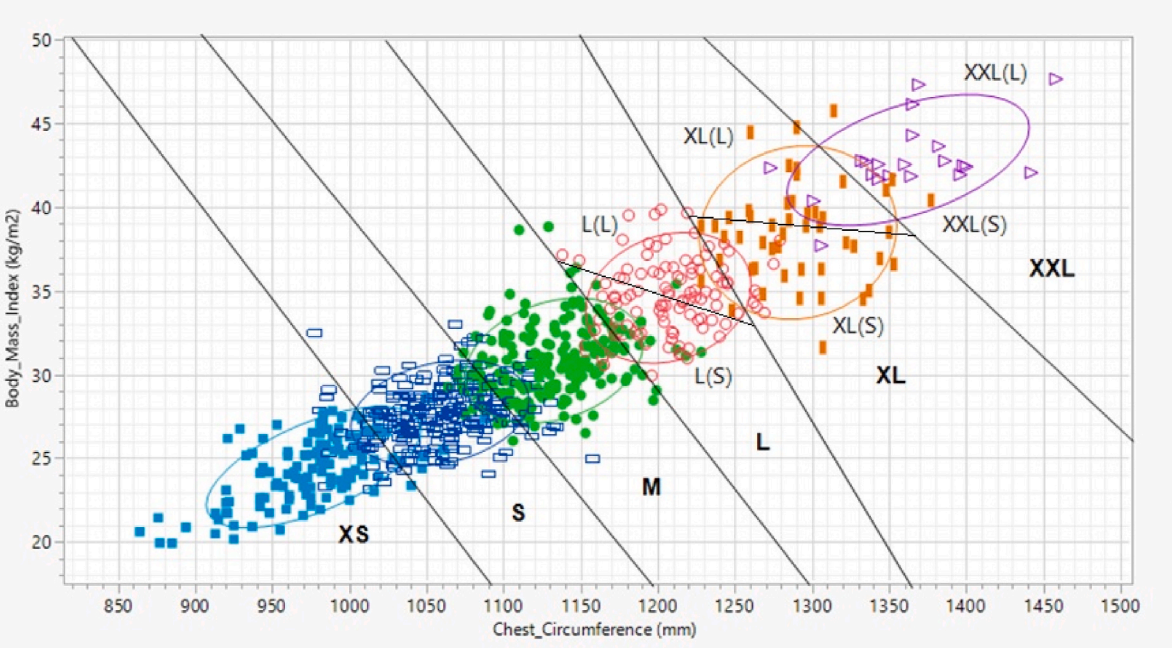


Fig. 7. A simplified sizing chart by BMI and Chest Circumference for male LEOs. The chart consists of six clusters representing different size categories. The grades XS, S, and M each have a single waist front length assigned to them. On the other hand, the grades L, XL, and XXL are further divided into short and long sizes, resulting in L(S), L(L), XL(S), XL(L), XXL(S), and XXL(L) subgrades. The logistic fit prediction between XXL(L) and XXL(S) is insignificant and thus no dividing boundary is shown. It is important to note that the logistic fit prediction between XXL(L) and XXL(S) is not significant, indicating that no clear dividing boundary is applicable in this case. The density ellipses displayed in the chart represent 80 percent confidence ellipses centered around each cluster, providing an overview of the distribution within each size category.

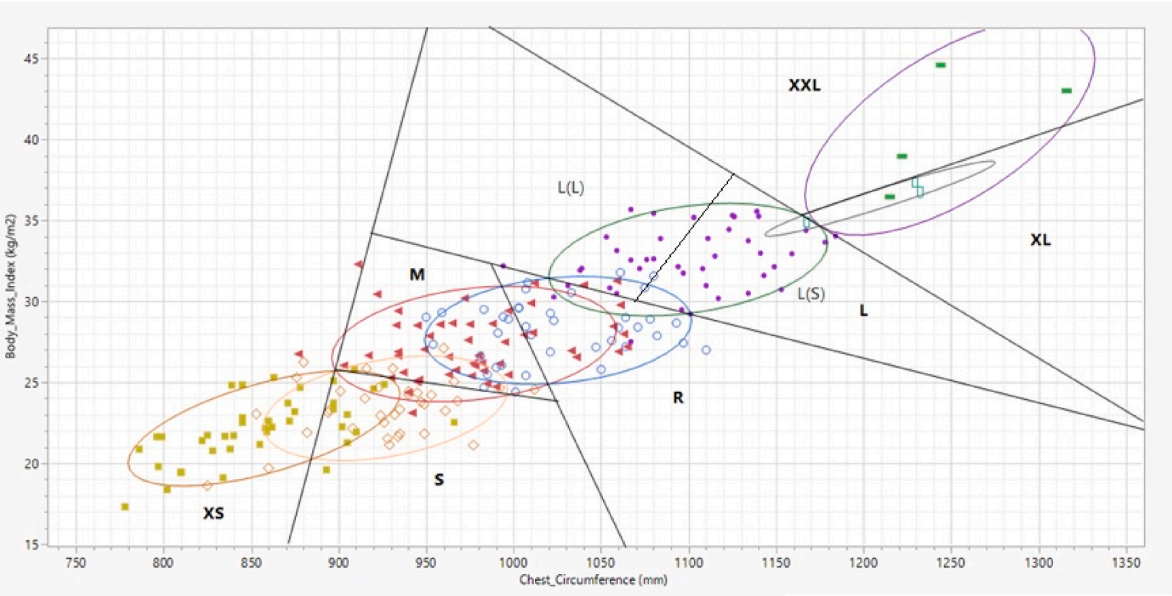


Fig. 8. A simplified sizing chart by BMI and Chest Circumference for female LEOs, containing seven clusters with eight sizes. The grade L includes a short size and a long size of waist front length to form L(S) and L(L) subgrades. The other six grades (XS, S, M, R, XL, and XXL) have one waist front length for each grade. The density ellipses represent 80 percent confidence ellipses centered around each cluster.

circumference and waist circumference in its size prediction. LEOs can utilize the proposed app by inputting their body height, body weight, and chest circumference (or waist circumference) to predict the size that is most likely to provide the best fit. Figs. 7 and 8 demonstrate a conceptual app, accompanied by equations (1)–(8) for men and equations (9)–(15) for women. These equations utilize body weight and stature to calculate body mass index (BMI) along with chest circumference measurement, enabling the prediction of the required size.

Sizing vests offer an alternative to sizing apps. They provide the opportunity for physical try-ons, unlike sizing apps which are virtual sizing prediction tools. Given that armor coverage and fit involve multiple dimensions, sizing vests are a valuable tool for assessing armor fit before LEOs make their final armor selection. It is recommended that LEOs initially use the proposed sizing chart or sizing app to identify the appropriate size and then utilize the corresponding sizing vest for fit assessment to determine the final size needed. This approach allows for a

Table 7
Dimensions of each of the proposed sizing vest for male LEOs (9 sizes).

Body Dimension (mm)	Men Grade (inches)		
	CC: 36-40	CC: 40-43	CC: 43-46
	WC: 31-36	WC: 36-40	WC: 39-44
Size	XS	S	M
Chest Circumference	1018	1101	1172
Waist Circumference Omphalion	920	1016	1109
Waist Front Length, Sitting	381	399	411
Body Dimension (mm)	Men Grade (inches)		
	CC: 46-49	CC: 46-49	CC: 49-53
	WC: 43-48	WC: 43-48	WC: 47-52
Size	L(S)	L(L)	XL(S)
Chest Circumference	1255	1244	1353
Waist Circumference Omphalion	1223	1207	1311
Waist Front Length, Sitting#	405	449	425
Body Dimension (mm)	Men Grade (inches)		
	CC: 49-53	CC: 50-57	CC: 51-57
	WC: 47-52	WC: 49-57	WC: 52-58
Size	XL(L)	XXL(S)	XXL(L)
Chest Circumference	1346	1442	1435
Waist Circumference Omphalion	1314	1451	1464
Waist Front Length, Sitting#	474	410	467

Table 8
Dimensions of each of the proposed sizing vest for female LEOs (8 sizes).

Body Dimension (mm)	Women Grade (inches)		
	CC: 32-36	CC: 35-38	CC: 37-42
	WC: 28-32	WC: 31-35	WC: 33-37
Size	XS	S	M
Chest Circumference	910	971	1058
Waist Circumference Omphalion	805	902	944
Front Waist Length, Sitting*	360	371	376
Body Dimension (mm)	Women Grade (inches)		
	CC: 39-43	CC: 40-45	CC: 42-46
	WC: 35-40	WC: 39-42	WC: 39-44
Size	R (Regular)	L(S)	L(L)
Chest Circumference	1082	1139	1173
Waist Circumference Omphalion	1017	1065	1121
Front Waist Length, Sitting* #	392	366	410
Body Dimension (mm)	Women Grade (inches)		
	CC: 46-49		CC: 48-52
	WC: 45-49		WC: 48-51
Size	XL		XXL
Chest Circumference	1232		1316
Waist Circumference Omphalion	1234		1297
Waist Front Length, Sitting*	403		432

comprehensive evaluation of the armor fit and ensures a better fit for LEOs.

4.4. Study summaries and limitations

NIOSH conducted a comprehensive anthropometric survey of law enforcement officers across the country in 2018, 2019, and 2020. The survey revealed that the body size and shape of LEOs had changed since the previous survey conducted in the 1970s, which focused solely on male officers (Martin et al., 1975). The current survey also highlighted the increasing presence of female officers in law enforcement, although they remain a minority. A significant finding from the NIOSH survey was the prevalence of body armor fit issues among many officers, leading to the development of the body size/shape classification and armor sizing project.

To inform our research, we examined the anthropometric material used in commercially available body armor, as well as military body armor sizing systems and sizing information provided by standards organizations. Our investigation revealed a variety of sizing systems employed by different vendors. While there were some overlaps among the systems, there was no widely used approaches to sizing. In addition, some of them do not adequately cover the NIOSH LEO database. Furthermore, some armor designs still relied on anthropometry data from military personnel, which presented challenges related to width and circumference dimensions (Hsiao, 2023). Given these findings, there is a clear need for a comprehensive overhaul of the existing LEO sizing systems in the market. This paper aims to address this need by leveraging the newly available LEO anthropometry data and proposing improved sizing approaches.

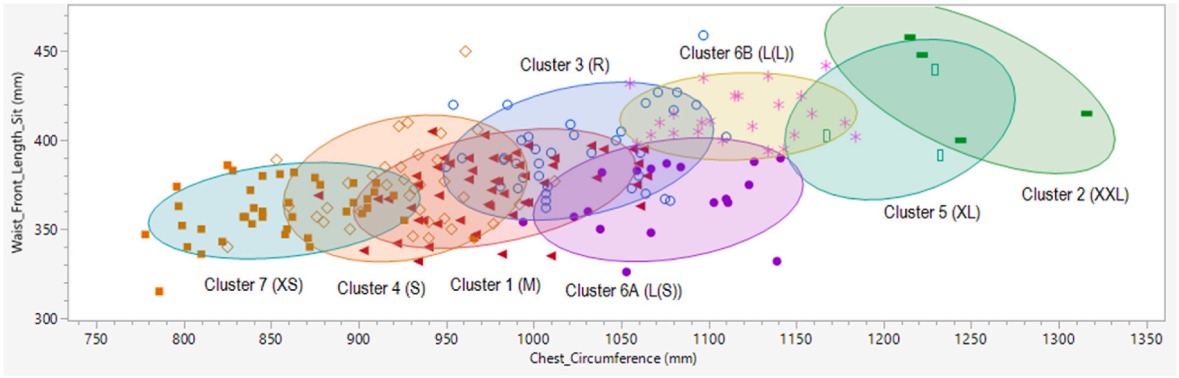
We employed multivariate approaches, specifically cluster analyses, to explore potential solutions for LEO armor sizing. By varying the number of clusters, we obtained valuable insights. In our study, we initially utilized eight body dimensions associated with armor fit and comfort (Hsiao, 2023) for the cluster classification. Subsequently, we reduced the number of dimensions within each cluster to develop the final sizing structure. This represents the first endeavor in the literature to address LEO armor sizing using the cluster procedure on a large-scale national LEO anthropometric dataset, and the outcomes are promising. To complete the innovation loop, it would be desirable to conduct a follow-up study to verify the impact of the proposed sizing structure. This paper does not cover the verification component which is a limitation. However, it is important to note that the clustering method has previously been successfully employed in the development of firefighter structural glove sizing, where it demonstrated improved accommodation and business value (Hsiao et al., 2015). Moving forward, we recommend that one or more vendors embrace these new sizing systems and create prototypes of vests (armor) and sizing vests (fit assessment tools) for each size. Through rigorous anthropometric fit tests, it will be possible to validate the size-to-size grade and the size selection chart, as well as assess whether the prototype designs provide the desired fit and comfort for our law enforcement professionals.

5. Conclusion

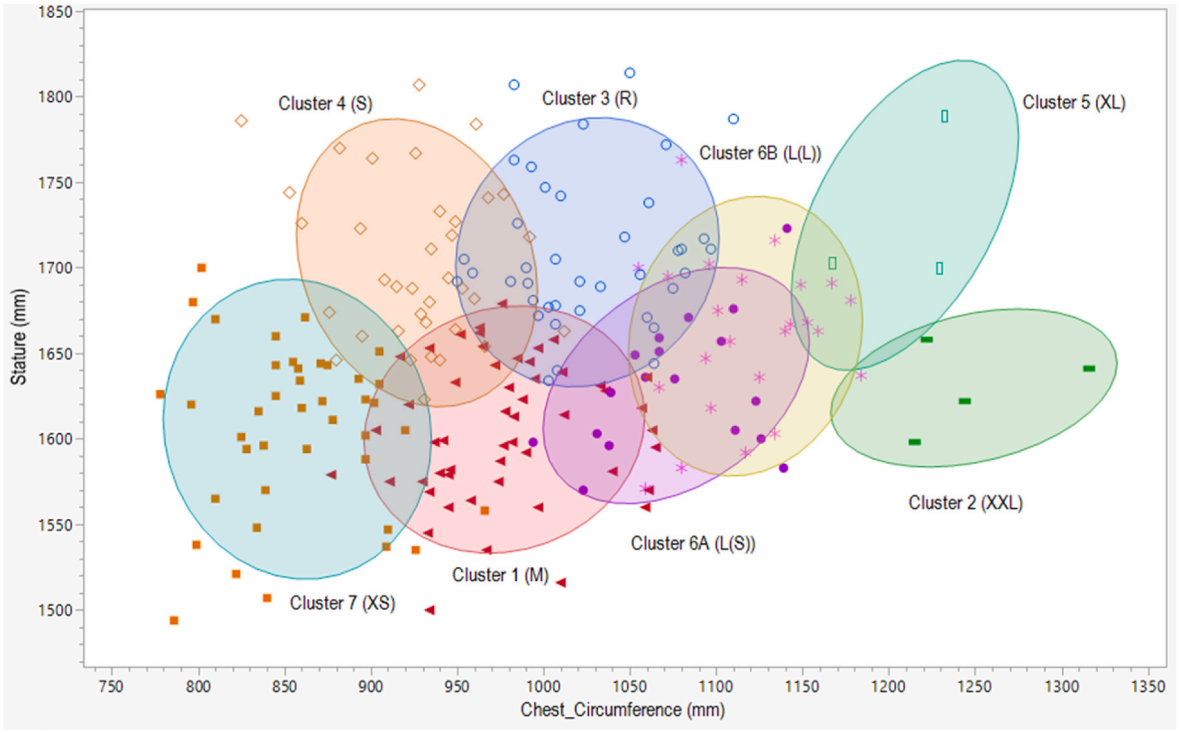
Four key findings emerge from this study. Firstly, cluster analyses of various anthropometric measurements including chest breadth, chest circumference, chest depth, waist breadth (sitting), waist circumference, body weight, body mass index, and waist front length (sitting) were performed on male LEOs. These analyses revealed that these anthropometric data can be effectively classified into six distinct clusters, with individuals within each cluster being more similar to each other than to individuals in other clusters. Similarly, cluster analyses conducted on female LEOs utilizing chest breadth, chest circumference, chest depth, waist breadth (sitting), waist circumference, body weight, body mass index, and stature led to the identification of seven clusters.

Secondly, an examination of the boundaries of body dimensions within each cluster for male LEOs provided valuable insights for armor design applications. This examination resulted in the development of a nine-size system, where three armor grades require one vest length each, while the other three grades necessitate two vest lengths for each grade. Similarly, the evaluation of body dimension boundaries within each cluster for female LEOs led to the creation of an eight-size system, where six grades/clusters require one vest length for each grade/cluster, and one grade/cluster necessitates two armor lengths.

Thirdly, a sizing chart was proposed as a data-driven LEO armor sizing system, which would serve as a valuable resource for armor



(9a)



(9b)

Fig. 9. Scatter plot of Waist Front Length by Chest Circumference (9a) and Stature by Chest Circumference (9b) of female LEOs. The plots include 80% confidence ellipses of waist front length by chest circumference, as well as stature by chest circumference, for each cluster in 7 clusters (8 sizes). It is evident from the plots that the distribution of clusters based on Stature by Chest Circumference is much clearer compared to Waist Front Length by Chest Circumference for female LEOs.

manufacturers, national standard committees, and LEOs in determining appropriate armor sizes. Additionally, a sizing app featuring eight equations for men and seven equations for women was proposed. This app enables LEOs to swiftly select an armor size that is most likely to fit an individual based on readily available body dimensions known to LEOs, such as chest circumference, body weight, and stature.

Finally, a series of 'sizing vests' with defined dimension ranges for each vest was presented. These sizing vests offer a practical solution for armor manufacturers and LEO station representatives. LEOs can utilize these vests to physically try on and determine the best-fitting vest size, providing an alternative to relying solely on a sizing chart or app.

To further advance armor fit and coverage for improved protection of our law enforcement professionals, a collaborative effort among armor manufacturers, national standard entities, LEO stakeholders, and body armor researchers is recommended. It is strongly recommended that armor manufacturers incorporate these sizing systems and create prototypes of vests in each size to evaluate the effectiveness of the sizing structure in improving fit and protection. By working together, we can enhance LEO protection, streamline armor production, and ensure the optimal fit of body armor for our law enforcement personnel.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Clustering female LEOs

Table A1 provides an overview of the cluster analysis results for female LEOs, considering three, four, five, six, and seven clusters based on eight torso dimensions. Among these options, the "seven clusters" alternative emerged as the most suitable choice. This option exhibits the fewest overrates for each dimension, and the observed overrates are minor, aligning with criteria #1 and #3 outlined in the analysis.

Criterion #1 focuses on the anthropometric difference in means between grades for two primary dimensions: 89 mm (3.5 inches) for chest circumference and 102 mm (4 inches) for waist circumference. There were two small overrates under the seven clusters alternative, one for chest circumference and one for waist circumference. It should be noted that Waist Front Length was not included in this analysis since it is not a critical dimension associated with armor fit and comfort for female LEOs (Hsiao, 2023). Criterion #3 refers to the span (10th percentile to 90th percentile) of the two primary dimensions within each cluster: 102 mm (4 inches) for chest circumference and 127 mm (5 inches) for waist circumference. Among the seven clusters, there were three small overrates (8 mm, 25 mm, and 12 mm) in the chest circumference span for clusters #7, #1, and #6. However, no overrates were observed for the waist circumference span.

Upon examining criterion #2, it becomes evident that the "seven clusters" option has two clusters containing a small percentage (1.8% and 1.4%) of the overall number of participants, which can be considered a disadvantage (Table A2). As an alternative, the "six clusters" option becomes the second choice. This option satisfies the second criterion, with only one cluster containing a small percentage (2.8%) of the overall number of participants.

Criterion #1 shows the same practically small between-grades overrates under the “six clusters” option for chest circumference and waist circumference as the "seven clusters" option. In terms of criterion #3, four out of the six clusters have a chest circumference span larger than 102 mm (4 inches), with relatively small overrates (12 mm, 25 mm, 17 mm, and 18 mm). Additionally, one cluster has a waist circumference span of 137 mm, which exceeds the 127-mm criterion. This is not as preferable as the “seven clusters” option.

In summary, based on the three criteria described in the Cluster Procedure section, the optimal options for female LEOs are either six or seven clusters. Both options will be further explored in the "3.2. Sizing system boundaries" section and Appendix B to advance the development of our sizing scheme.

Table A1
Cluster analysis results on 8 torso dimensions of female LEOs using 3, 4, 5, 6, and 7 clusters

Dimension (Mean; mm)	Number of Clusters: 3 (C1, C3, and C2)			Mean Body Size Changes between Clusters *(Criterion #1)*	
	C1	C3	C2	C1 – C3	C3 –C2
Chest Breadth	293	328	361	34	34
Chest Cir.	896	1012	1136	**116**	**124**
Chest Depth	235	273	318	38	45
Stature	1630	1669	1657	39	−12
Waist Breadth	289	334	384	45	50
Waist Cir.	793	934	1088	**142**	**154**
Weight (kg)	62.2	78.1	93.4	15.9	15.2
BMI	23.4	28.1	34.0	4.7	5.9
10th - 90th Span	***Criterion #3***				
Chest Cir	**128**	**111**	**154**		
Waist Cir.	**161**	**149**	**216**		

Dimension (Mean; mm)	Number of Clusters: 4 (C2, C4, C1, and C3)				Mean Body Size Changes between Clusters *(Criterion #1)*		
	C2	C4	C1	C3	C2 – C4	C4 –C1	C1 –C3
Chest Breadth	283	315	345	398	32	31	52
Chest Cir.	863	967	1080	1232	**105**	**113**	**152**
Chest Depth	224	259	298	345	35	38	47
Stature	1624	1653	1665	1673	29	13	8
Waist Breadth	277	317	359	435	40	42	76
Waist Cir.	754	878	1016	1234	**125**	**138**	**218**
Weight (kg)	58.6	71.3	86.5	108.6	12.8	15.2	22.1
BMI	22.2	26.2	31.2	38.9	3.9	5.1	7.6
10th - 90th Span	***Criterion #3***						
Chest Cir.	**108**	88	**135**	**149**			
Waist Cir.	106	**131**	**152**	**156**			

Dimension (Mean; mm)	Number of Clusters: 5 (C2, C5, C3, C4, and C1)					Mean Body Size Changes between Clusters *(Criterion #1)*			
	C2	C5	C3	C4	C1	C2 –C5	C5 –C3	C3 –C4	C4 –C1

(*continued on next page*)

Table A1 (*continued*)

Dimension (Mean; mm)	Number of Clusters: 5 (C2, C5, C3, C4, and C1)					Mean Body Size Changes between Clusters *(Criterion #1)*			
	C2	C5	C3	C4	C1	C2 –C5	C5 –C3	C3 –C4	C4 –C1
Chest Breadth	282	308	321	350	403	26	13	29	53
Chest Cir.	858	949	989	1095	1243	**90**	41	**106**	**148**
Chest Depth	223	253	266	303	349	30	14	37	46
Stature	1614	1707	1617	1672	1668	93	−90	55	−4
Waist Breadth	276	311	325	364	439	35	14	39	75
Waist Cir.	749	854	907	1034	1249	**105**	53	**127**	**216**
Weight (kg)	57.9	70.9	73.1	88.6	109.8	13.0	2.2	15.6	21.2
BMI	22.2	24.3	27.9	31.7	39.5	2.1	3.6	3.8	7.8
10th - 90th Span	***Criterion #3***								
Chest Cir.	**110**	100	**125**	**114**	101				
Waist Cir.	118	**139**	124	**140**	80				

Dimension (Mean; mm)	Number of Clusters: 6 (C6, C1, C5, C3, C2, and C4)						Mean Body Size Changes between Clusters *(Criterion #1)*				
	C6	C1	C5	C3	C2	C4	C6 – C1	C1 –C5	C5 – C3	C3 – C2	C2 –C4
Chest Breadth	275	294	317	329	351	403	19	23	13	22	52
Chest Cir.	849	893	977	1018	1100	1243	44	84	42	82	**143**
Chest Depth	221	234	263	275	306	349	13	29	12	31	44
Stature	1575	1677	1610	1714	1649	1668	102	−67	103	−64	19
Waist Breadth	274	288	317	336	371	439	14	29	19	35	68
Waist Cir.	749	780	882	947	1049	1249	31	102	65	102	**200**
Weight (kg)	54.6	63.9	70.5	81.1	88.5	109.8	9.3	6.6	10.6	7.5	21.3
BMI	22.0	22.7	27.2	27.6	32.5	39.5	0.7	4.5	0.4	4.9	7.0
10th - 90th Span	***Criterion #3***										
Chest Cir.	**114**	95	**127**	**119**	**120**	101					
Waist Cir.	123	**137**	114	114	123	80					

Dimension (Mean; mm)	Number of Clusters: 7 (C7, C4, C1, C3, C6, C5, and C2)							Mean Body Size Changes between Clusters *(Criterion #1)*					
	C7	C4	C1	C3	C6	C5	C2	C7 –C4	C4 –C1	C1–C3	C3 – C6	C6 –C5	C5 –C2
Chest Breadth	281	303	317	332	351	385	407	22	15	15	19	34	22
Chest Cir.	857	927	978	1025	1100	1209	1249	69	51	48	74	**110**	40
Chest Depth	222	245	264	277	306	337	351	23	19	13	29	32	13
Stature	1606	1703	1605	1709	1648	1731	1630	97	−97	104	−61	83	−101
Waist Breadth	276	299	319	339	371	417	448	23	20	20	32	47	30
Waist Cir.	749	820	886	956	1048	1197	1261	71	66	70	92	**150**	64
Weight (kg)	57.1	67.8	70.6	82.4	88.5	109.0	108.3	10.6	2.8	11.8	6.1	20.5	−0.6
BMI	22.2	23.4	27.4	28.2	32.6	36.4	40.8	1.2	4.0	0.8	4.4	3.8	4.4
10th - 90th Span	***Criterion #3***												
Chest Cir.	**110**	92	**127**	101	**114**	65	101						
Waist Cir.	105	117	108	119	121	93	78						

C: Cluster #. For instance, C7 stands for Cluster #7.

C7–C4: Body size change in mean between two clusters. For instance, C7–C4 stands for difference in means between clusters 5 and 7.

Bolded Numbers: The measurements are great than the criterion set for the 10th - 90th Span within a cluster (criterion 3) or the difference in mean for the measurement between two clusters is greater than the set criterion (criterion 1).

Table A2

The Number and percentage of female participants in each cluster when three, four, five, six, and seven clusters were applied for classification (criterion #2)

Total Number of Clusters	Cluster 1		Cluster 2		Cluster 3		Cluster 4		Cluster 5		Cluster 6		Cluster 7	
	N	%	N	%	N	%	N	%	N	%	N	%	N	%
Three	90	41.3	40	18.4	88	40.4								
Four	69	31.7	51	23.4	7	**3.2**	91	41.7						
Five	6	**2.8**	46	21.1	66	30.3	55	25.2	45	20.6				
Six	45	20.6	44	20.2	43	19.7	6	**2.8**	58	26.6	22	10.1		
Seven	53	24.3	4	**1.8**	39	17.9	36	16.5	3	**1.4**	42	19.3	41	18.8

Percentage in Bold: percentage of participants in a cluster is less than 4% of the overall participants (**criterion 2**).

Appendix B

Sizing system by chest and waist circumferences and front waist length for female LEOs

Based on the three criteria outlined in section "2.3. Cluster Procedure," the cluster analysis of eight body dimensions for female LEOs suggests two potential sizing options: seven clusters and six clusters. By employing the same procedure described in section 3.2.1, it is feasible to determine the specific design values for each size within the framework of either seven or six clusters. For the circumferential dimensions, we utilized the 90th percentile value of each dimension within a given size (refer to Tables B1 and B2). For instance, in the case of the "seven clusters" option, in female size 32–36 for the chest circumference-based grade, the vest dimension at the chest circumference would be set to 909 mm. This pertains to the cluster associated with the smallest grade. Correspondingly, its waist circumference-based grade is 28–32, and the vest dimension at the waist circumference would be 803 mm (Table B1). Another example involves the female size 41–45 for chest circumference, where the vest dimension at the chest circumference would be determined as 1153 mm. In this instance, the associated waist circumference-based grade is 39–44, and the vest dimension at

the waist circumference would be 1112 mm.

For sizing systems that incorporate variations in length, we established 60 mm (2.3 inches) as the benchmark to determine whether a single-length or two-length (short and long) version is needed within each cluster. If the range between the 10th and 90th percentiles of Waist Front Length within a cluster is 60 mm (2.3 inches) or less, a single length is considered sufficient. However, if the range exceeds 60 mm, two sizes are proposed for that cluster. Out of the clusters analyzed, six fall into the single length category, while only one cluster exhibits a Waist Front Length range larger than 60 mm.

For the single length option, we utilized the mean value of Waist Front Length for each circumferential size. In this scenario, assuming the Waist Front Length data follows a normal distribution, the maximum "deviation" in length for any individual would be 30 mm (1.2 inches). As for the cluster requiring two Waist Front Lengths, we used the 25th and 75th percentiles of Waist Front Length. This resulted in a Waist Front Length span of 36 mm (1.4 inches) for each of the two sizes, totaling 72 mm (2.8 inches) for the entire cluster (Figure B1). Consequently, the maximum "deviation" in length for any individual within each size of the cluster would be 18 mm (0.7 inch). Based on these outcomes, we arrived at an 8-size system for female LEOs, with six chest-and-waist grades having one vest length per grade, while one chest-and-waist grade (Cluster #6) necessitates two vest lengths.

Table B1
Proposed sizing system by Chest and Waist Circumferences and Waist Front Length for female LEOs (7 Clusters)

DIMENSION	Cluster #	Lower Boundary (mm)	Upper Boundary (mm)	Lower Boundary (inches)	Upper Boundary (inches)	Design size (mm)	Grade (inches)
Chest	7	799	909	31.5	35.8	909	32–36
Circumference	4	876	968	34.5	38.1	968	35–38
	1	930	1057	36.6	41.6	1057	37–42
	3	981	1082	38.6	42.6	1082	39–43
	6	1039	1153	40.9	45.4	1153	41–45
	5	1167	1232	45.9	48.5	1232*	46–49
	2	1215	1316	47.8	51.8	1316*	48–52
Waist	7	698	803	27.5	31.6	803	28–32
Circumference	4	778	895	30.6	35.2	895	31–35
	1	834	942	32.8	37.1	942	33–37
	3	898	1017	35.4	40.0	1017	35–40
	6	991	1112	39.0	43.8	1112	39–44
	5	1141	1234	44.9	48.6	1234*	45–49
	2	1219	1297	48.0	51.1	1297*	48–51
Front Waist Length	7	343	380	13.5	15.0	360	
	4	346	406	13.6	16.0	373	
	1	342	395	13.5	15.6	373	
	3	367	421	14.4	16.6	394	
	6	354	425	13.9	16.7	Mean: 393; 25th-375 75th −411 (2 sizes)	
	5	392	440	15.4	17.3	412*	
	2	400	458	15.7	18.0	430*	

Small number of participants.

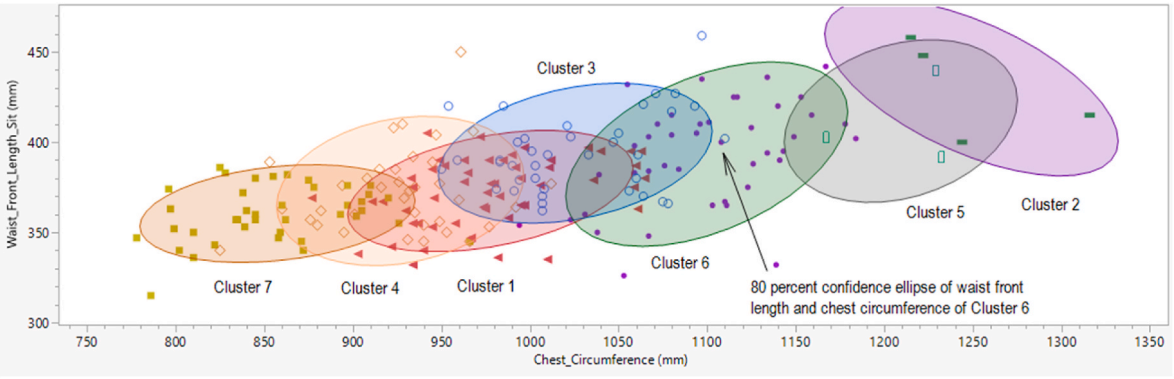

Fig. B1. Scatter plot of Waist Front Length against Chest Circumference of female LEOs in seven clusters with 80% confidence ellipses centered around each cluster. The plot emphasizes the necessity of having two Waist Front Length sizes for Cluster #6, represented by solid circles) for female LEOs. Cluster 6 is the third largest grade vest in chest circumference.

Applying the same procedure to examine the "six clusters" option for the span of 10th to 90th Waist Front Length within a cluster, we observed that four out of six clusters are classified as single length (Table B2; Figure B2). However, two clusters have a span of Waist Front Length exceeding 60 mm, indicating the need for two Waist Front Length sizes (Figure B2). As a result, the findings still lead to an 8-size system for female LEOs, which aligns with the outcome of the "seven clusters" option.

Table B2
Proposed sizing system by Chest and Waist Circumferences and Waist Front Length for female LEOs (6 Clusters)

DIMENSION	Cluster	Lower Boundary (mm)	Upper Boundary (mm)	Lower Boundary (inches)	Upper Boundary (inches)	Design size (mm)	Grade (inches)

(*continued on next page*)

Table B2 (*continued*)

DIMENSION	Cluster	Lower Boundary (mm)	Upper Boundary (mm)	Lower Boundary (inches)	Upper Boundary (inches)	Design size (mm)	Grade (inches)
Chest	6	796	910	31.3	35.8	910	31–36
Circumference	1	845	940	33.3	37.0	940	33–37
	5	930	1057	36.6	41.6	1057	37–42
	3	961	1080	37.8	42.5	1080	38–43
	2	1039	1159	40.9	45.6	1159	41–46
	4	1215	1316	47.8	51.8	1316	48–52
Waist	6	680	803	26.8	31.6	803	27–32
Circumference	1	702	839	27.6	33.0	839	28–33
	5	828	942	32.6	37.1	942	33–37
	3	895	1009	35.2	39.7	1009	35–40
	2	991	1114	39.0	43.9	1114	39–44
	4	1217	1297	47.9	51.1	1297	48–51
Front Waist Length	6	343	382	13.5	15.0	360	
	1	345	389	13.6	15.3	367	
	5	342	395	13.5	15.6	372	
	3	366	421	14.4	16.6	394	
	2	354	425	13.9	16.7	Mean: 393; 25th-75th - 411 (2 sizes)	378
	4	392	458	15.4	18.0	Mean: 426; 25th-75th - 448 (2 sizes)	400

*The 95th and 90th percentile values are the same due to small number of participants.

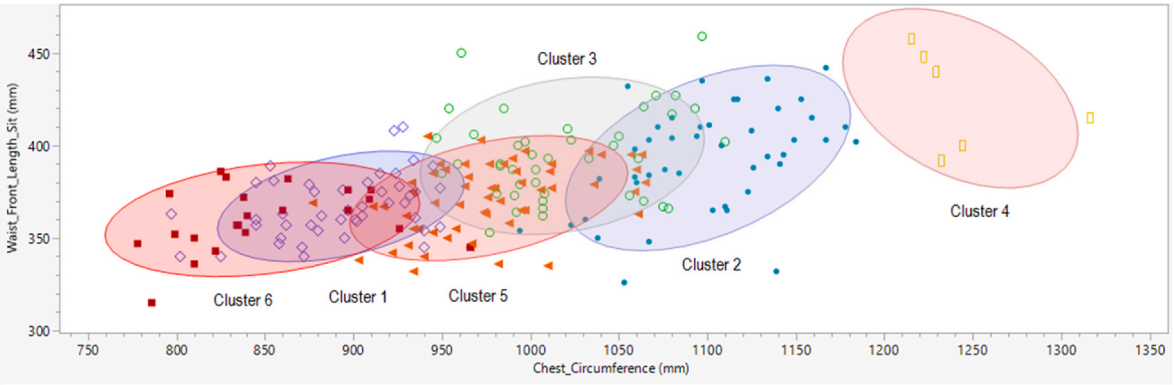

Fig. B2. Scatter plot of Waist Front Length by Chest Circumference for female LEOs in six clusters with 80% confidence ellipses centered around each cluster. These plot demonstrates the requirement for two Waist Front Length sizes to accommodate the two largest grade vests (Cluster #2 and Cluster #4) in the sizing system.

Upon careful analysis of the grade distribution for both chest circumference and waist circumference, it is evident that the grades are more evenly distributed in the "seven clusters" option compared to the "six clusters" option (Tables B1 vs. B2 and Figures B1 vs. B2). Consequently, we recommend adopting the 8-size system for female LEOs based on the "seven clusters" option.

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