Body Models of Law Enforcement Officers for Cruiser Cab Accommodation Simulation

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Objectives: This study developed multivariate law enforcement officer (LEO) body models for digital simulation of LEO accommodation in police cruiser cabs.

Background: Anthropometrically accurate digital LEO body models, representing the United States LEOs, for computerized LEO cruiser interface simulations are lacking.

Methods: Twenty body dimensions (with and without gear combined) of 756 male and 218 female LEOs were collected through a stratified national survey using a data collection trailer that traveled across the US. A multivariate Principal Component Analysis (PCA) approach was used to develop digital LEO body models.

Results: Fifteen men and 15 women representing unique body size and shape composition of the LEO population were identified. A combined set of 24 male and female models (removal of 6 redundant models for which female and male models overlapped) is suggested.

Conclusions: A set of 24 digital LEO body models in 3-dimensional form, along with their anthropometric measurements, were developed to facilitate LEO cruiser cab design.

Application: Digital modeling software developers can use the models and their anthropometric data to build digital avatars for simulated evaluation of LEO cruiser cab configuration, console communication-equipment fitting, and cruiser ingress/egress access arrangement. LEO vehicle and equipment designers also can use eight key body dimensions (i.e., stature, buttock-popliteal length, eye height sitting, knee height sitting, shoulder-grip length, popliteal height, sitting height, and body weight) of the body models to recruit 24 human subjects to physically evaluate their vehicle prototypes for improved vehicle and equipment design.

Keywords: police, body size, diversity and inclusion, digital modeling, simulation

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INTRODUCTION

Approximately 812,000 law enforcement officers (LEOs) serve in the US (Data USA, 2021). During 2017–2021, 1289 officers died in the line-of-duty; 43% to 46% of the fatalities were associated with traffic-related crash incidents each year (Officer Down Memorial Page, 2021). In addition, LEOs had the highest non-fatal injury incidence rate (498 cases per 10,000 full-time workers) among all occupations in 2015 and 15.7% of the injuries were associated with transportation incidents (U.S. Bureau of Labor Statistics, 2016).

Several studies have suggested some aspects of improvement to reduce LEO vehicle crashes and increase incident survivability, including patrol vehicle cab and equipment configurations (International Association of Chiefs of Police, 2011; Molenbroek, Vossebeld, & Naagen, 2009), seatbelt use (NHTSA, 2011; Oron-Gilad, Szalma, Stafford, & Hancock, 2005), seat design (Donnelly, Callaghan, & Durkin, 2009), and vehicle ingress and egress arrangement (McKinnon, Callaghan, & Dickerson, 2011). While transportation incidents are a multi-faceted issue, these suggestions pointed out that the human-cab interface is a critical issue in reducing LEO risk of transportation incidents and injuries. Subject to federal, state, and local laws, LEO cruisers typically are modified from existing lines of commercial vehicles, and most are modified by manufacturers or specialized companies (Chavez, 2017) (Figure 1). Moreover, LEO cruisers are currently more fully equipped with an array of electronic and safety gear than before; all of which occupy valuable space within the vehicle.

Safe human-cab interface design and workspace accommodation become even more critical than before in reducing LEO risk exposures of vehicle crash incidents and protecting LEOs from injuries if a crash occurs.

A significant knowledge gap to effectively advance patrol vehicle cab and equipment configurations, seatbelts, seats, and ingress/egress access in LEO vehicles is the lack of anthropometrically accurate 3-dimensional (3D) digital LEO body models representing current United States LEOs for computerized LEO cruiser cab interface simulations. First, existing civilian and military population-based anthropometric data for general vehicle applications are not suitable for LEO vehicle designs; LEOs were reported to be on average bigger in body dimensions than the civilian population (Hsiao et al., 2021b), military personnel (Hsiao et al., 2021a), and all occupations combined (Hsiao, Long, and Snyder, 2002) (Figure 2). Second, patrol vehicle cab-space accommodation and equipment configuration are 3-dimensional in nature. Use of physical or digital LEO body models rather than single dimensional anthropometric data for cab prototype testing is needed to assure adequacy of designs. Third, it is costly and impractical to recruit a large group of LEOs for each LEO vehicle modification evaluation. A series of digital LEO body models representing the current LEO population for computerized accommodation simulation would fill this gap. The body models and their body dimensions also can be used as the templates to recruit representative human subjects rather than random samples to cost effectively evaluate physical vehicle prototypes.

Proper visibility of external environments and internal equipment, easy to operate vehicle controls, sufficient cab overhead and side clearances, and adequate seatbelt restraints are crucial functions of LEO body size and position in the cruiser cab. LEOs with long limbs and a short torso would position themselves in a cab differently from those with short limbs and a long torso to effectively see through the windshield while operating the vehicle. The accommodation challenge is further compounded when multiple body dimensions are required in the driver-cab interface to tackle the arrangement of seats, seatbelts, and communication equipment. A multivariate accommodation approach is a resolution to address the multi-degree anthropometry concerns for designing LEO cruiser cabs. This paper presents development of multivariate LEO body models representing the United States LEO population to address the need for improving LEO cruiser cab accommodation for safer and more efficient cruiser design and operation.

OBJECTIVE

This study aimed to develop a set of multivariate LEO digital anthropometric body

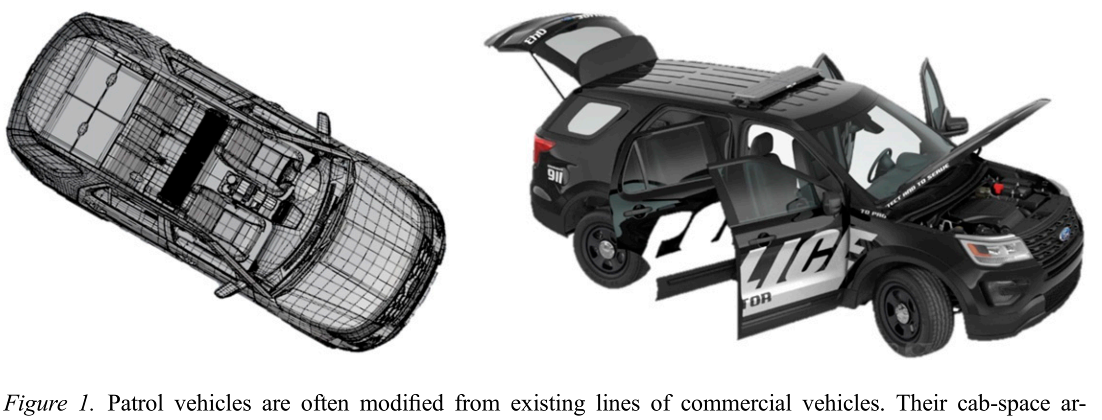


Figure 1. Patrol vehicles are often modified from existing lines of commercial vehicles. Their cab-space arrangement and equipment configuration are 3-dimensional in nature and need to accommodate LEOs with diverse body size variations, which is an important matter in reducing LEO risk exposure of transportation incidents and injuries.

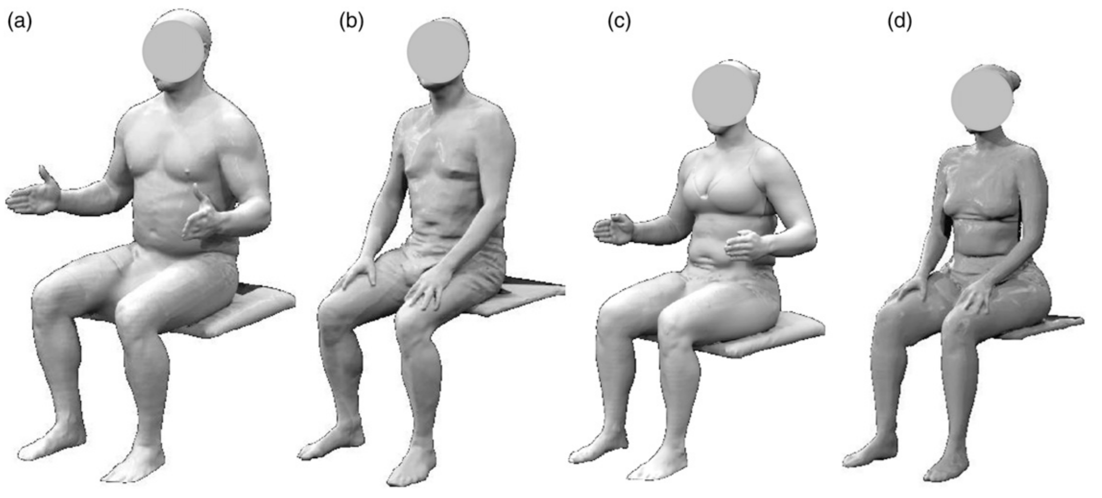


Figure 2. LEOs are in general heavier than the general population and have a larger upper torso build: an average male LEO (a) comparing to an average male civilian (b) and an average female LEO (c) comparing to an average female civilian (d) as reported by Hsiao et al., (2021b).

models, which represents 95% of the current LEO population for cruiser cab design or retrofitting. Specifically, the study (1) determined the theoretical multivariate LEO body models using a series of anthropometry dimensions relevant to the design of LEO cruiser cabs, and (2) identified the 3-dimensional (3D) digital body scans of real LEOs and their body dimensions that are at the closest neighbor of the theoretical representative models.

METHODS

Participants

This LEO body model research is part of a national anthropometry study of LEOs conducted by the National Institute for Occupational Safety and Health (NIOSH) that includes three major components: collection of anthropometric data, 3D body-surface scanning, and LEO equipment assessment (Hsiao et al., 2021b). The anthropometric data and 3D body-surface scans were used in this paper. Seven hundred and fifty-six (756) male and 218 female LEOs across the US participated in the study. The LEO sample considered the geographic density of racial/ethnic distributions calculated from the 2010 U.S. Census by four census regions (U.S. Census Bureau, 2012). The LEO weighted average body height was 177.6 cm (SD = 7.1 cm) and mass was 95.4 kg (SD = 17.3 kg) for men; and 165.1 cm (SD = 6.4 cm) and 74.9 kg (SD = 14.1 kg) for women (Hsiao et al., 2021b). The research protocol and participant consent form were approved by the NIOSH Institutional Review Board (IRB #14-DSR-02XP) and the United States Office of Management and Budget (OMB #0920-1232).

Procedure

Upon arrival to a national LEO anthropometry study site (Hsiao et al., 2021b), each officer was given a consent form to read, which described the study. Each participant had the opportunity to ask questions before signing an informed consent. For the whole-body anthropometry measurement and 3-D scan study component, the participant was taken to a dressing room, where males changed from street clothes into bicycle shorts and females changed into bicycle shorts with a sport bra. Wig caps were used to compress participants' hair which minimized the effect of hair on body height measurement and scan results. Body landmarks were placed with eyeliner pencils or adhesive dots and the body measurements were taken. After completing the body measurements, each participant was scanned standing and seated within a Cyberware WBX 3-D whole-body scanner (Cyberware Inc., Monterey, CA; Hsiao et al., 2021b). Finally, the participant was reimbursed for their time and dismissed.

Data Process

Twenty-five of 34 collected anthropometric dimensions from the national LEO Anthropometry study are relevant to LEO cruiser cab configuration and equipment adjustment (Hsiao, 2022). Fifteen of the dimensions were measured without gear (traditional measurements) and ten dimensions were measured with gear (encumbered measurements) (Table 1); of them, 5 dimensions were measured both without and with gear. The graphical descriptions of the twenty-five dimensions are summarized in Appendix 1 of this paper.

Literature has shown that existing digital human models were typically developed based on traditional (without-gear) measurements of a group of people (Hudson & Choi, 2006; Hsiao, 2013). This LEO body modeling study used a total of 20 measurements (a combination of 10 with-gear and 10 without-gear measurements) out of the 25 available measurements. The with-gear measurements were included for the 5 dimensions measured for both without and with gear (see Table 1). Technically speaking, this process may be considered an "equipped data" based body modeling as the 10 included without-gear measurements (mainly sitting height-related dimensions) would have only minor increases if they were measured with gear, while the 10 with-gear measurements are known to be significantly larger than the measurements without gear (Hsiao et al., 2021b).

TABLE 1: Measurements Relevant to LEO Cruiser Cab Design

Item	Variable	Application for LEO Cruiser Cab Design	Without Gear	With Gear
1	Bideltoid breadth, sitting	Seat back width	X	X
2	Buttock-knee length	Dashboard-seat/seat back clearance	X	
3	Buttock-popliteal length	Seat depth	X	
4	Chest breadth	Middle seat back width	X	X
5	Chest depth	Driving wheel clearance	X	X
6	Elbow rest height	Seat arm rest height	X	
7	Eye height, sitting	Wind shield height	X	
8	Hip breadth, sitting	Seat pan width	X	X
9	Knee height, sitting	Driving wheel/dashboard clearance	X	
10	Popliteal height	Seat height	X	
11	Sitting height	Cruiser cab ceiling height	X	
12	Stature	Egress and ingress configuration	X	
13	Thumbtip reach	Control panel reach	X	
14	Waist breadth, sitting	Space between arm rests	X	X
15	Waist circumference at omphalion	Driving wheel clearance	X	
16	Abdominal extension depth, sitting	Driving wheel clearance		X
17	Acromion-trochanter surface length, sitting	Seatbelt (shoulder belt)		X
18	Bi-trochanter surface length, sitting	Seatbelt (lap belt)		X
19	Shoulder-grip length	Equipment control		X
20	Thigh clearance	Driving wheel clearance		X

To simultaneously and effectively consider the 20 body dimensions (i.e., overall body size variance and body segment proportional variability) of the LEOs in cab accommodation evaluations, a principal component analysis (PCA) approach was used (Hsiao, 2013). The ultimate goal for a principal component analysis is to utilize a small number of principal components to explain the anthropometry variations of a population, in this case LEOs. The 20 measurements relevant to this LEO cruiser cab accommodation application were stratified into male and female categories and standardized with respect to their weighted mean and standard deviation first. PCA was then applied separately to these standardized values using Statistical Analysis System software (SAS Institute, Cary, NC). The decision to use the standardized (or Correlation Matrix) method over a Covariance Method for PCA Analysis is elucidated in the Discussion section. This PCA procedure reduced the 20 dimensions to three principal components (PCs) to define body models. The selection of 3 principal components was based on a screen plot where the eigenvalues for the PCs were greater than 1 (Cattell, 1966). These three PCs were orthogonal to one another and can be described as approximating a spheroid, with enclosed data points, which covered a desired percentage of LEO anthropometry variances.

Determining the Theoretical Multivariate LEO Body Models

With three principal components, the transformed data in Eigen-coordinators can be described as approximating a spheroid. The Bonferroni method was used with a radius value $r = 2.60$ for males and $r = 2.61$ for females as the 95% data enclosure criterion to achieve the 95% confidence level enclosure for each gender (Johnson & Wichern, 2007). There are 14 points on the spheroidal surface representing the most diverse body size and shape combinations based on three principal components (Figure 3)—the six intercept points on the spheroidal surface by the three axes (points U, V, W, X, Y, and Z) and the eight octant midpoints located at the surface center of each of eight sections (octants) divided by the three axes of this spheroid (points A, B, C, D, E, F, G, and H) (Figure 4). These 14 points along with the centroid of spheroid (point O) were the basis for the selection of the theoretical anthropometric models.

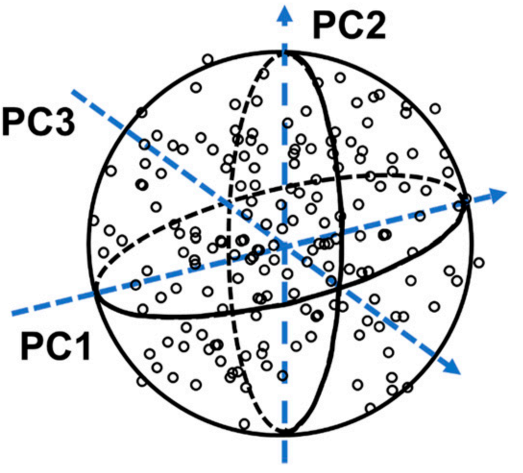


Figure 3. The three principal component factors (PC1, PC 2, and PC 3) were orthogonal to one another and can be described as approximating a spheroid, enclosing data points.

Identifying Real LEOs (the 3D Body Scans) Who Match the Theoretical Models

From a design point of view, the statistically created theoretical PCA case models serve as useful design targets. To facilitate practical LEO cruiser cab design evaluation, either real subjects or virtual subjects (digital avatars) are needed for cab accommodation tests. They are the closest neighbor "real persons" to the theoretical LEOs. The closest neighbor "real persons" also offer other dimensions not in the theoretical PCA analysis. For instance, foot length and hand length are useful dimensions to consider when evaluating the human-cab interface. Due to their correlation with other length measurements and less sensitivity in the PCA process, they were not included in the original dimensions for the PCA process. The PCA case models would not have the foot length and hand length information. The closest neighbor "real person" models fill in this gap. Similarly, the 5 traditional measurements excluded in the "Theoretical Multivariate LEO Body Models" (see Table 1) would become available from the closest neighbor models.

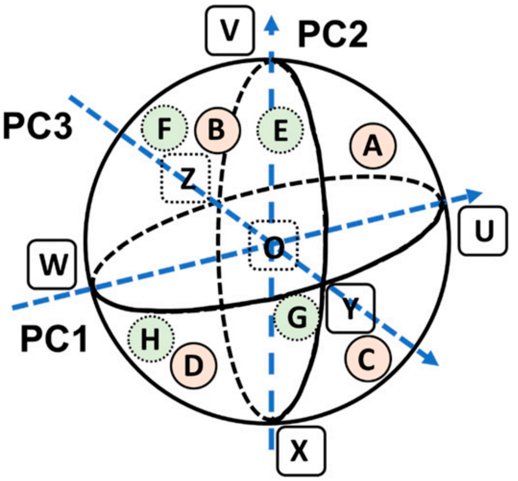


Figure 4. There were 14 points on the spheroid surface representing the diverse body size and shape combinations within each gender group: models X, Y, Z, W, U, and V locate at axis intercept points and models A, B, C, D, E, F, G, and H are models that locate at surface-center octant points. In addition, the center of the spheroid or "average" model center is at the point O with the Eigen-coordinate {0, 0, 0}, defined by the mean for each dimension. The hypothetical models on the axes intercept points are at the Eigen-coordinates: U{1, 0, 0}, V{0, 1, 0}, W{−1, 0, 0}, X{0, −1, 0}, Y{0, 0, 1}, and Z{0, 0, −1}. The hypothetical models on the octants center points are at the Eigen-coordinates: A{1/2, 1/2, √1/2}, B{−1/2, 1/2, √1/2}, C{1/2, −1/2, √1/2}, D{-1/2, −1/2, √1/2}, E{1/2, 1/2, −√1/2}, F{−1/2, 1/2, −√1/2}, G{1/2, −1/2, −√1/2}, H{-1/2, −1/2, −√1/2}.

RESULTS

Theoretical Multivariate Law Enforcement Officer Body Models

The percentage of variation with the 20 variables can be explained for 75.8% for men and 73.8% for woman by the first three principal components (PCs). The remaining 24.2% of variation for males and 26.2% for females were described by the other 17 non-primary components (Table 2). Specifically, the first three PCs for males accounted for 46%, 24%, and 9.8% of the total variation, respectively. PC1 predicted the overall body size. PC2 represented a contrast between dimensions correlated with body length against those correlated with body width/depth and circumferences (i.e., volume indicator). PC3 contrasted the measurements of 5 sitting height–related dimensions (i.e., Elbow Resting Height Sitting, Eye Height Sitting, Sitting Height, Stature, and Acromion-Trochanter Surface Length with gear) together with the Chest Breadth with Gear (a minor effect) against the remaining 14 body dimensions (Table 2). The first three PCs for females followed similar patterns as in the male sample, accounting for 41.7%, 21.2%, and 11% of the total variation, respectively.

These three PCs were orthogonal to one another and can be described as approximating a spheroid, enclosing data points (Figure 3). The Bonferroni method was used with a radius value as the 95% enclosure criterion to achieve the 95% confidence level enclosure for each gender (Johnson & Wichern, 2007). The center of the spheroid or "average" model center is at the point defined by the mean for each dimension (Tables 3 and 5).

With a radius value of $r = 2.60$ for males and $r = 2.61$ for females, 90.6% of data points for males and 90.3% for females were enclosed in the spheroid by the 3 PCs. With the enclosed data, 12 of the 20 measurements for men and 13 measurements for women actually accommodated a broader range (95% or more) of people rather than just 90.6% or 90.3% (Tables 4 and 6). The waist breadth with gear (sitting) dimension within the enclosed data represented only the 20.6th percentile –78.8th percentile of men and 8.9th percentile–90.8th percentile of women (Tables 4 and 6) because the measurement includes the duty belt and thus the percentile values were skewed.

As mentioned in the Methods section, there were 14 unique data points on the spheroid surface representing the diverse body size and shape combinations within each gender group (Figure 4). Points (or Models) X, Y, Z, W, U, and V situated at axis intercept points and points A, B, C, D, E, F, G, and H located at surface-center octant points. The corresponding 20 anthropometric values of these 14 models were calculated through reverse processes of the eigenvalues and eigenvectors (Tables 3 and 5). The center of the spheroid (point/model O) was at the point defined by the mean for each dimension.

Since LEO cruiser cab workspaces are designed for both men and women, a combined set of male and female models is needed for the design to be relevant. To achieve the goal of minimizing the number of models in the combined set, the models of each gender were introduced into the other gender's 95% enclosure space, and those who were identified to be within the enclosure space of the opposite gender were considered redundant and discarded. For example, to identify whether a female model was a redundant model, the 15 derived body dimensions of that female model were first converted into z scores using the means and standard deviations of the corresponding variables in the male sample. Then, the three PCs were derived by multiplying the set of z scores with the matrix of component score coefficients. The Euclidean distance of this female model to the centroid of the 95% male enclosure was determined using the three PCs. If the distance was smaller than the r = 2.6

TABLE 2: Eigenvalues, Percent of Variation, and Eigenvectors of 20 Measurement Variables Reduced to Three Principal Components (N = 755[a] for Men and N = 217[a] for Women)

		Male Population			Female Population		
		Principal Component (PC)			Principal Component (PC)		
	Variables	PC 1	PC 2	PC 3	PC 1	PC 2	PC 3
Body length	2. Buttock-knee length, sit	0.28	0.16	−0.16	0.29	0.13	−0.17
	3. Buttock-popliteal length, sit	0.24	0.23	−0.20	0.26	0.19	−0.21
	7. Eye height, sit	0.19	0.20	0.48	0.18	0.21	0.47
	9. Knee height, sit	0.26	0.26	−0.10	0.24	0.30	−0.07
	10. Popliteal height, sit	0.16	0.39	−0.09	0.11	0.40	−0.07
	11. Sitting height	0.19	0.20	0.47	0.18	0.23	0.46
	12. Stature	0.24	0.32	0.10	0.23	0.35	0.11
	13. Thumbtip reach length	0.23	0.19	−0.17	0.19	0.22	−0.26
	19. Shoulder-grip length with gear, sit	0.24	0.18	−0.20	0.21	0.23	−0.22
Volume indicator	1. Bideltoid breadth with gear, sit	0.26	−0.19	−0.01	0.26	−0.19	0.00
	4. Chest breadth with gear	0.25	−0.21	0.00	0.25	−0.20	−0.01
	5. Chest depth with gear	0.22	−0.22	−0.09	0.23	−0.23	−0.06
	8. Hip breadth with gear, sit	0.23	−0.16	−0.03	0.23	−0.18	−0.02
	14. Waist breadth with gear, sit	0.10	−0.14	−0.02	0.18	−0.11	−0.02
	15. Waist circumference at omphalion	0.25	−0.28	−0.05	0.28	−0.22	−0.08
	16. Abdominal extension depth with gear, sit	0.22	−0.28	−0.07	0.19	−0.27	−0.04
	18. Bi-trochanter surface length with gear, sit	0.23	−0.23	−0.05	0.24	−0.20	0.00
	20. Thigh clearance with gear, sit	0.22	−0.14	−0.02	0.22	−0.13	−0.04
Location indicator	6. Elbow rest height, sit	0.09	−0.13	0.59	0.09	−0.10	0.58
	17. Acromion-trochanter surface length with gear, sit	0.26	−0.17	0.13	0.28	−0.14	0.14
	Eigenvalues	9.19	3.99	1.97	8.34	4.23	2.20
	Percent of variation	46.0%	20.0%	9.8%	41.7%	21.2%	11.0%
	Total percent of variation explained by the first 3 PCAs	75.8%			73.8%		

[a]Two (1 male and 1 female) participants were excluded in the analysis for missing 1 of the 20 measurements.

TABLE 3: Theoretical Anthropometric Models of Male Law Enforcement Officers (Weighted; N = 755 for Men; Unit in mm)

Variable	(Men) Variable Description	Centroid	Hypothetical Model on the Octants Center Points								Hypothetical Model on the Axes Intercept Points					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
1	Bideltoid breadth with gear (sitting)	543	561	486	598	522	564	488	600	525	618	506	468	580	541	545
2	Buttock-knee length (sitting)	631	669	594	640	565	697	622	668	593	706	660	555	602	611	651
3	Buttock-popliteal length (sitting)	514	545	488	510	453	575	518	540	483	571	549	457	479	492	536
4	Chest breadth with gear	385	400	336	435	370	400	335	434	370	449	351	320	419	385	384
5	Chest depth with gear	326	329	273	365	309	343	287	379	323	382	290	270	362	316	336
6	Elbow rest height (sitting)	254	299	279	319	299	210	190	230	210	274	234	234	274	317	191
7	Eye height (sitting)	809	893	843	858	809	810	760	775	726	859	844	760	775	868	750
8	Hip breadth with gear (sitting)	506	520	454	551	486	526	460	557	491	571	474	440	537	501	510
9	Knee height (sitting)	566	609	549	568	509	624	564	583	524	626	607	507	526	556	577
10	Popliteal height (sitting)	432	470	436	416	382	482	448	428	394	466	487	398	377	423	441
11	Sitting height	930	1018	965	981	927	932	878	894	841	983	967	876	892	991	868
12	Stature	1776	1922	1786	1803	1667	1885	1749	1767	1631	1912	1895	1640	1657	1802	1750
13	Thumbtip reach length,	830	876	789	828	741	918	831	870	783	917	877	743	782	800	859
14	Waist breadth with gear (sitting)	451	449	410	485	446	455	416	491	452	490	415	411	486	446	455
15	Waist circumference at omphalion	1026	1042	792	1227	977	1075	825	1260	1010	1276	841	776	1211	1003	1049
16	Abdominal extension depth with gear (sitting)	351	351	270	416	336	367	286	433	352	432	286	270	417	340	363
17	Acromion-trochanter surface length, with gear (sitting)	837	886	776	933	823	851	741	898	788	947	790	726	884	862	812
18	Bi-trochanter surface length, with gear (sitting)	719	731	615	807	691	747	631	822	707	835	643	603	794	708	730
19	Shoulder-grip length, with gear (sitting)	803	839	764	801	725	880	805	842	766	878	841	727	764	774	832
20	Thigh clearance, with gear (sitting)	197	205	175	218	188	206	177	219	189	227	185	168	210	196	198

TABLE 4: Percentage Coverage of Theoretical Anthropometric Models of Male Law Enforcement Officers (Weighted; unit: mm, Except for the Lower %Tile and Upper %Tile Which are in %)

		PCA Results (15 Men Models)					Percentile Values of Each Signal Dimension Individually (N = 755)							
Variable	(Men) Variable Description	Lower	Upper	Lower percentile	Upper percentile	L to U Range	2.5th percentile Value	5th percentile Value	95th percentile Value	97.5th percentile Value	90% Range	95% Range	PCA Range –90% Range	PCA Range −95% Range
1	Bideltoid breadth with gear (sitting)	468	618	2.1	97.9	150	470	482	604	616	122	145	28	5
2	Buttock-knee length (sitting)	555	706	1.3	98.6	151	564	575	687	698	112	133	39	18
3	Buttock-popliteal length (sitting)	453	575	2.1	97.9	122	455	465	563	573	99	118	23	4
4	Chest breadth with gear	320	449	2.1	97.7	129	322	332	438	448	105	125	24	4
5	Chest depth with gear	270	382	4.1	95.9	112	263	273	379	389	105	125	7	−13
6	Elbow rest height (sitting)	190	319	1.4	98.7	129	197	206	302	311	95	114	34	15
7	Eye height (sitting)	726	893	0.7	99.3	167	742	753	865	876	112	133	55	34
8	Hip breadth with gear (sitting)	440	571	3.8	96.1	131	433	445	567	579	122	145	9	−14
9	Knee height (sitting)	507	626	2.4	97.7	119	507	517	615	625	99	118	20	1
10	Popliteal height (sitting)	377	487	2.1	97.9	110	379	388	476	485	89	106	21	4
11	Sitting height	841	1018	0.6	99.4	177	861	872	988	999	115	137	62	40
12	Stature	1631	1922	2.1	98	291	1637	1659	1893	1915	234	278	57	13
13	Thumbtip reach length,	741	918	3.2	96.6	177	736	751	909	924	158	188	19	−11
14	Waist breadth with gear (sitting)	410	491	20.6	78.8	81	353	369	533	549	165	196	−84	−115

(Continued)

TABLE 4: (Continued)

		PCA Results (15 Men Models)					Percentile Values of Each Signal Dimension Individually (N = 755)						PCA	PCA
Variable	(Men) Variable Description	Lower	Upper	Lower percentile	Upper percentile	L to U Range	2.5th percentile Value	5th percentile Value	95th percentile Value	97.5th percentile Value	90% Range	95% Range	Range –90% Range	Range –95% Range
15	Waist circumference at omphalion	776	1276	2.5	97.5	500	773	814	1238	1279	424	506	76	−6
16	Abdominal extension depth with gear (sitting)	270	433	3.9	96.2	163	261	275	427	441	151	180	12	−17
17	Acromion-trochanter surface length, with gear (sitting)	726	947	1.8	98.1	221	733	750	924	941	174	208	47	13
18	Bi-trochanter surface length, with gear (sitting)	603	835	3.3	96.7	232	596	615	823	842	207	247	25	−15
19	Shoulder-grip length, with gear (sitting)	725	880	2.9	97	155	723	736	870	883	135	161	20	−6
20	Thigh clearance, with gear (sitting)	168	227	4.5	96.1	59	164	169	225	230	56	67	3	−8

TABLE 5: Theoretical Anthropometric Models of Female Law Enforcement Officers (Weighted; N=217; Unit in mm)

		Centroid	Hypothetical Model on the Octants Center Points								Hypothetical Model on the Axes Intercept Points					
Variable	(Women) Variable Description	O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
1	Bideltoid breadth with gear (sitting)	484	500	432	535	468	500	432	535	468	551	448	416	519	484	484
2	Buttock-knee length (sitting)	600	631	562	609	541	660	591	638	569	669	622	531	578	580	620
3	Buttock-popliteal length (sitting)	493	518	465	490	438	548	495	521	468	545	520	440	466	471	514
4	Chest breadth with gear	347	357	308	384	336	358	309	386	337	395	319	298	375	346	347
5	Chest depth with gear	309	312	261	348	297	322	271	358	307	360	273	258	345	302	316
6	Elbow rest height (sitting)	248	292	273	306	287	209	190	223	204	267	234	230	262	307	190
7	Eye height (sitting)	761	839	798	803	762	759	719	724	683	802	796	720	726	817	705
8	Hip breadth with gear (sitting)	489	503	438	537	473	506	442	541	476	554	455	425	524	487	492
9	Knee height (sitting)	522	561	513	520	471	572	523	530	482	570	563	473	480	514	529
10	Popliteal height (sitting)	393	424	405	372	352	433	413	381	361	412	445	373	341	386	399
11	Sitting height	875	955	912	917	874	876	833	837	794	918	913	832	836	931	819
12	Stature	1651	1783	1674	1665	1556	1746	1637	1628	1519	1760	1769	1542	1533	1677	1625
13	Thumbtip reach length,	759	784	725	736	676	842	782	793	733	819	807	699	710	718	799
14	Waist breadth with gear (sitting)	449	465	398	495	428	470	403	500	433	516	419	381	479	445	452
15	Waist circumference at omphalion	915	946	673	1098	825	1004	731	1156	883	1187	762	642	1067	873	956
16	Abdominal extension depth with gear (sitting)	318	314	257	371	314	322	266	379	323	374	261	262	375	312	324
17	Acromion-trochanter surface length, with gear (sitting)	790	841	740	877	776	805	704	841	740	891	754	690	826	816	765
18	Bi-trochanter surface length, with gear (sitting)	672	696	582	763	649	695	581	762	648	786	605	558	739	673	672
19	Shoulder-grip length, with gear (sitting)	741	772	712	724	663	818	758	770	710	801	789	680	693	708	773
20	Thigh clearance, with gear (sitting)	181	188	159	199	171	191	162	203	174	210	169	152	193	178	183

TABLE 6: Percentage Coverage of Theoretical Anthropometric Models of Female Law Enforcement Officers (Weighted; unit: mm, Except for the Lower %Tile and Upper %Tile Which are in %)

		PCA Results (15 Women Models)					Percentile Values of Each Signal Dimension (N = 217)							
Variable	(Women) Variable Description	Lower (mm)	Upper (mm)	Lower %Tile	Upper %Tile	L to U Range	2.5th % Value	5th % Value	95th % Value	97.5th % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range –95% Range
1	Bideltoid breadth with gear (sitting)	416	551	2.4	97.5	135	417	428	540	551	113	134	37	16
2	Buttock-knee length (sitting)	531	669	1.4	98.6	138	538	548	652	662	103	123	48	28
3	Buttock-popliteal length (sitting)	438	548	2.1	97.9	110	440	449	537	546	89	106	33	16
4	Chest breadth with gear	298	395	2.7	97	97	297	305	389	397	84	100	45	29
5	Chest depth with gear	258	360	4.5	95.5	102	250	260	358	368	98	117	14	−5
6	Elbow rest height (sitting)	190	307	1.4	98.7	117	196	205	291	300	87	103	42	26
7	Eye height (sitting)	683	839	0.6	99.4	156	700	710	812	822	102	121	65	46
8	Hip breadth with gear (sitting)	425	554	4.1	96.1	129	417	428	550	561	121	144	10	−13
9	Knee height (sitting)	471	572	2.6	97.1	101	470	479	565	574	87	103	32	16
10	Popliteal height (sitting)	341	445	1.6	98.4	104	345	353	433	441	80	95	30	15
11	Sitting height	794	955	0.6	99.4	161	813	823	927	937	104	124	73	53
12	Stature	1519	1783	1.9	98.1	264	1526	1546	1756	1776	210	250	81	41
13	Thumbtip reach length	676	842	2.2	97.8	166	679	691	827	839	135	161	42	16
14	Waist breadth with gear (sitting)	381	516	8.9	90.8	135	350	366	532	548	166	198	−85	−117

(Continued)

TABLE 6: (Continued)

		PCA Results (15 Women Models)					Percentile Values of Each Signal Dimension (N = 217)							
Variable	(Women) Variable Description	Lower (mm)	Upper (mm)	Lower %Tile	Upper %Tile	L to U Range	2.5^{th} % Value	5^{th} % Value	95^{th} % Value	97.5^{th} % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
15	Waist circumference at omphalion	642	1187	1.9	98.1	545	658	699	1131	1172	432	515	68	−15
16	Abdominal extension depth with gear (sitting)	257	379	6.3	93.7	122	240	252	384	396	131	156	32	7
17	Acromion-trochanter surface length, with gear (sitting)	690	891	1.7	98.3	201	697	712	868	883	156	186	65	35
18	Bi-trochanter surface length, with gear (sitting)	558	786	3.4	96.6	228	550	570	774	794	205	244	27	−12
19	Shoulder-grip length, with gear (sitting)	663	818	2.1	97.8	155	666	678	804	816	126	150	29	5
20	Thigh clearance, with gear (sitting)	152	210	4.7	95.3	58	147	153	209	215	57	68	2	−9

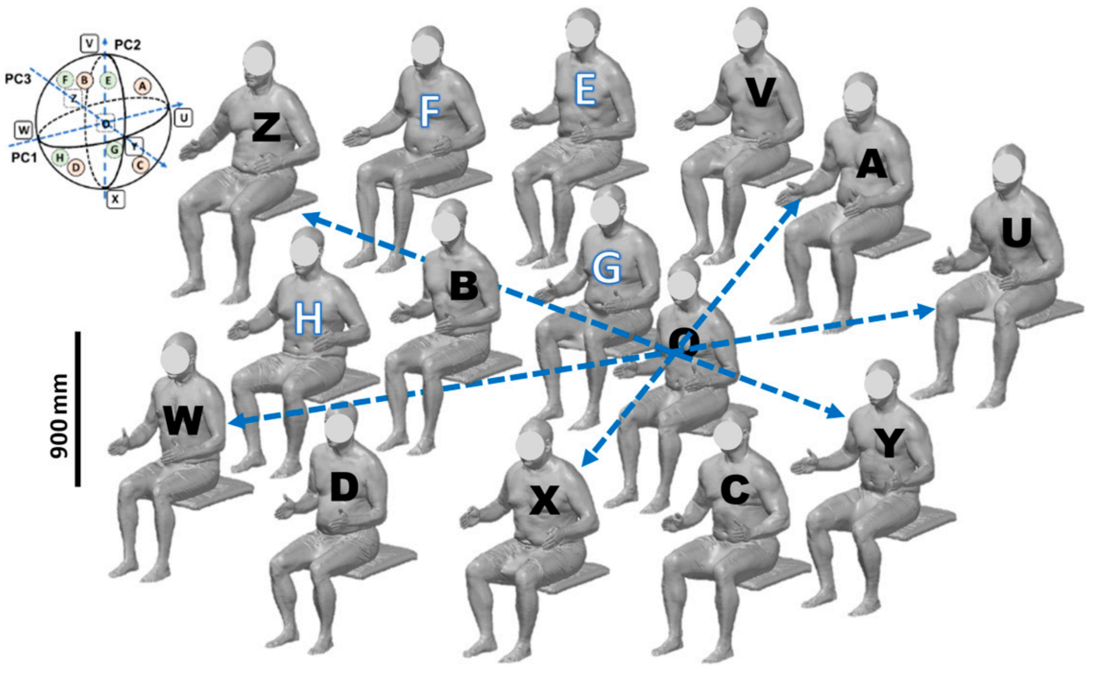


Figure 5. The closest neighbor male participating law enforcement officers corresponding to multivariate anthropometric models. Models W, U, X, V, Z, and Y are at the axes intercept points with the 95% male enclosure space, surrounding the average male model O. Models A, B, C, and D are on the octants center points at the front side of the 95% male enclosure space (see Figure 4), while models E, F, G, and H are on the octants center points at the rear side of the 95% male enclosure space (see Figure 4).

enclosure criterion, this female model was considered redundant and discarded. Otherwise, the model was retained for the joint male and female space. The male models were evaluated for redundancy in the same manner by placing each of them into the female 95% enclosure with $r = 2.61$ and following identical accept and reject procedures.

Six out of 15 female models (O, A, C, E, U, and V) were found to coincide with the male space because their respective Euclidian distance to the centroid of the 95% male enclosure was smaller than the r = 2.6 criterion. In addition, the Euclidian distance of five male models (O, D, H, W, and X) to the centroid of the 95% female enclosure was smaller than the r = 2.61 criterion. In all, the female models O, A, C, E, U, and V were redundant to male models; the male models O, D, H, W, and X were redundant to female models. The recombination procedure resulted in a joint male and female enclosure space of 24 models which included 15 models for men (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O) and 9 models for women (B, D, F, G, H, W, X, Y, and Z). The dimensions of these models are presented in Tables 3 and 5. Alternatively, a combined set of 25 models can include 10 models for men (A, B, C, E, F, G, U, V, Y, and Z) and 15 models for women (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O). (Tables 3–6.)

Identifying Real LEOs (the 3D body scans) Who Match the Theoretical Models

The corresponding 20 anthropometric values of these 15 models for each gender were calculated through reverse processes of the eigenvalues and eigenvectors. The Euclidean distance from each participant to each model point was then evaluated; one closest neighbor participant for each model was chosen and their corresponding closest neighbor human participants (Figures 5 and 6) and dimensions are summarized in Tables 7–10. The

Euclidean distance from each participant to each model point ranged from 0.07 to 0.25 for male models and 0.07 to 0.42 for female models. The joint male and female enclosure space of 24 models are presented in Figure 7a which included 15 models for men (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O) and 9 models for women (B, D, F, G, H, W, X, Y, and Z). An alternative with 25 models is also presented (Figure 7b) which included 10 models for (A, B, C, E, F, G, U, V, Y, and Z) and 15 models for women (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O).

It should be noted that in the theoretical anthropometric models with radius value of r = 2.60 for males and r = 2.61 for females, 90.6% of data points for males and 90.3% for females are enclosed in the spheroid by the first 3 PCs. When we accommodate a real person, we are accommodating a range of people around that person who are similar, just like accommodating a fit model for apparel accommodates larger and smaller people near that person. That means we will be accommodating a broader range (e.g., 95% in lieu of 90.6% or 90.3%) of people than the ellipse used to find them, and this helps mitigate some of the central tendency of the body size distribution.

DISCUSSION

Accounting Overall Body Size and Segment Proportional Variances

In vehicle cab space design and equipment arrangement, multiple measurements (such as seated eye height for external visibility, popliteal height for seat pan height, thumbtip reach for clearance between control units and driver body, and knee height sitting for driving wheel to body clearance) must be considered. 'When each dimension is prescribed sequentially to cover the 2.5th to 97.5th percentile population, the design would include 95% of the user population for each specific function but suffer from a compounded decrease in the level of overall accommodation, which would result in design inefficiency' (Hsiao, 2013).

This study relied on three PCs which are linear combinations of 20 individual anthropometric dimensions of LEOs. These PCs are orthogonal to each other and approximate a spheroidal in distribution. A 95% accommodation level designated as this threshold is a sufficient balance for LEO cab efficiency and cost-effectiveness. This approach took into account both the overall LEO body size variance and their body segment proportional variability. The models generated in this study therefore comprise not only overall large and small persons but also individuals of different body shapes (Meindl, Zehner, & Hudson, 1993; Hsiao 2013). For instance, the male Model B has a medium stature (50th percentile; 1776 mm) but a tall eye height sitting (74th percentile; 831 mm) (Table 7). In contrast, the female Model E has an above-average stature (68th percentile; 1682 mm) but a below-average eye height sitting (46th percentile; 758 mm) (Table 9). Their seat positions or seat adjustments would be different when they need to comfortably survey external environments through the windshield. This variability in body sizes and shapes reflect the real-world LEO body models much better than the traditional multiple-tier univariate method and will help improve the conformity of digital human models in LEO cab workspace design. The results in Table 8 and 10 show that not all 20 dimensions of the "real person" body models would accommodate a 95% range of LEOs when each dimension is considered individually. When multi-dimensions are considered simultaneously, the models would accommodate a broader range of LEOs (e.g., 95% or more). It is also worth noting that using a "real person" model (as opposed to a hypothetic/theoretic model), we are accommodating a range of people around that person who are similar—just like accommodating a fit model for attire which accommodates smaller and larger people close to that person. That means we will be accommodating a wider range of people than the ellipse used to find them.

Traditional vs. Encumbered Digital Human Body Models

Existing digital human body models were typically developed based on traditional body measurement data (i.e., without gear). This LEO body modeling study took advantage of newly available data of encumbered (with-gear) LEO body measurements for more realistic applications, which are considered to be the most updated and comprehensive LEO body models. It should be noted that Figures 5–7 display body models in an unencumbered form for better presentation of body shapes and dimension compositions. The corresponding dimensions in Tables 3–10 are encumbered dimensions. Digital modeling users should factor this difference in when they incorporate these data and body models in their digital modeling software for simulation applications. Researchers or vehicle designers who plan to use body dimension data of the representative body models as the templates to recruit human subjects for testing vehicle prototypes should also factor this into their preparation.

To offer an opportunity for comparisons to existing traditional digital civilian and military human models, we have used 15 traditional without-gear measurements relevant to LEO cruiser cab design (see Table 1) and provided both the theoretical (Table 11) and closest neighbor models (Table 12) for discussion below. The percentage of variation with 15 traditional measurements can be explained for 86.4% for men and 84.5% for woman by the first three principal components (PCs). Seven out of 15 female models (O, A, C, E, U, V, and Y) were found to coincide with the male space because their respective Euclidian distance to the centroid of the 95% male enclosure was smaller than the r = 2.6 criterion. In addition, the Euclidian distance of five male models (O, B, F, V, and W) to the centroid of the 95% female enclosure was smaller than the r = 2.61 criterion. In all, the female models O, A, C, E, U, V and Y were redundant to male models; the male models O, B, F, V, and W were redundant to female models. The procedure resulted in a joint male and female enclosure space of 23 models which included 15 models for men (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O)

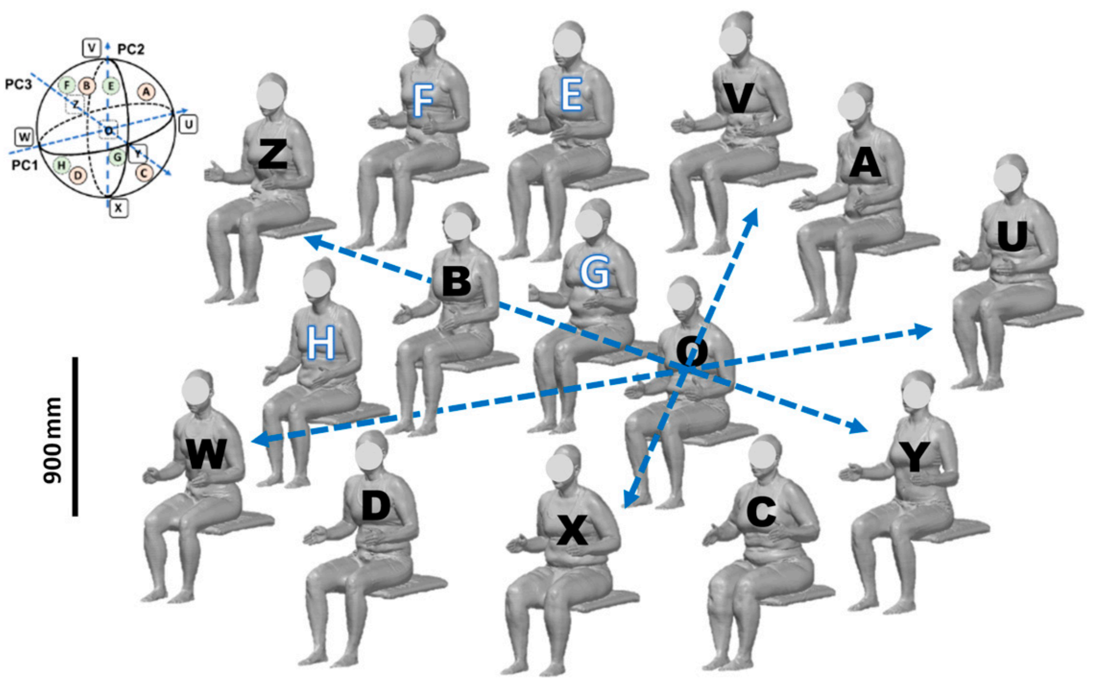


Figure 6. The closest neighbor female participating law enforcement officers corresponding to theoretic multivariate anthropometric models. Models W, U, X, V, Z, and Y are at the axes intercept points with the 95% female enclosure space, surrounding the average female model O. Models A, B, C, and D are on the octants center points at the front side of the 95% female enclosure space (see Figure 4), while models E, F, G, and H are on the octants center points at the rear side of the 95% female enclosure space (see Figure 4).

TABLE 7: Anthropometry of the Closest Neighbor Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models[a] (Men; Unit in mm)

Variable	(Men) Variable Description	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
	Subject ID	S573	S845	S944	S829	S146	S954	S065	S301	S074	S107	S220	S578	S079	S414	S025
1	Bideltoid breadth with gear, sitting	547	572	522	580	533	537	533	540	543	585	556	504	570	572	536
2	Buttock-knee length, sitting	640	664	597	635	615	658	633	627	592	648	641	597	624	637	639
3	Buttock-popliteal length, sitting	514	536	495	504	504	549	522	512	497	530	517	490	511	510	517
4	Chest breadth with gear	382	392	367	377	363	421	390	399	369	406	363	354	418	395	405
5	Chest depth with gear	310	330	293	347	304	309	296	348	326	368	317	310	318	291	314
6	Elbow rest height, sitting	239	278	252	275	276	224	224	260	234	245	220	236	270	300	225
7	Eye height, sitting	814	833	831	834	815	831	777	775	770	852	837	795	790	812	794
8	Hip breadth with gear, sitting	508	502	502	548	510	513	464	518	506	528	492	469	510	489	531
9	Knee height, sitting	576	579	547	578	512	577	570	579	552	579	574	536	532	557	573
10	Popliteal height, sitting	426	431	415	428	397	451	446	446	424	437	446	413	406	420	433
11	Sitting height	932	975	963	953	926	946	894	893	897	969	952	907	908	946	915
12	Stature	1798	1841	1776	1787	1711	1828	1774	1766	1706	1806	1829	1716	1702	1773	1761
13	Thumbtip reach length,	842	854	832	810	864	858	808	820	790	926	846	790	848	838	854
14	Waist breadth with gear (sitting)	498	392	512	533	403	490	404	441	430	402	383	458	458	454	526
15	Waist circumference at omphalion	1024	1096	923	1073	1019	1064	1021	1110	1021	1092	961	962	1093	955	1026
16	Abdominal extension depth w/gear (sitting)	361	357	320	355	334	378	341	372	330	385	310	342	354	302	344
17	Acromion-trochanter surface length, gear (sitting)	835	863	777	890	824	813	835	848	800	888	811	790	835	812	798
18	Bi-trochanter surface length with gear (sitting)	705	713	725	750	680	678	655	777	725	735	709	660	755	727	700

(Continued)

TABLE 7: (Continued)

	(Men)	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
Variable	Variable Description	O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
19	Shoulder-grip length, with gear (sitting)	797	832	809	806	778	844	785	832	783	845	832	804	794	787	809
20	Thigh clearance, with gear (sitting)	193	210	185	210	189	182	179	213	205	216	211	184	213	211	204
Without gear	Bideltoid breadth, sitting	521	553	471	550	489	521	521	508	502	557	518	491	532	533	547
	Chest breadth	368	388	346	409	350	390	368	371	386	401	359	365	412	375	381
	Chest depth	282	279	257	308	252	258	260	301	274	319	254	273	297	272	279
	Hip breadth	419	427	354	441	381	402	380	416	379	421	406	356	427	397	402
	Waist breadth	365	355	314	365	347	362	366	387	364	383	346	336	370	344	369
	Body weight (kg)[a]	107.0	123.0	91.5	122.0	92.1	103.2	94.4	108.3	99.1	123.1	104.9	90.3	107.5	107.5	104.0

[a]Body weight is included in this table for reference.

TABLE 8: Percentage Coverage of Anthropometry of the Closest Neighbor Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models* (Unit: mm, Except for the Lower %Tile and Upper %Tile Which are in %)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Men) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5^{th} % Value	5^{th}% Value	95^{th}% Value	97.5^{th} % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
1	Bideltoid breadth with gear (sitting)	504	585	14.5	87.2	81	470	482	604	616	122	145	−41	−64
2	Buttock-knee length (sitting)	592	664	12.6	83.4	72	564	575	687	698	112	133	−40	−61
3	Buttock-popliteal length (sitting)	490	549	21.2	87.8	59	455	465	563	573	99	118	−40	−59
4	Chest breadth with gear	354	421	16.6	87	67	322	332	438	448	105	125	−38	−58
5	Chest depth with gear	291	368	13.8	91.6	77	263	273	379	389	105	125	−28	−48
6	Elbow rest height (sitting)	220	300	9.4	87.9	80	197	206	302	311	95	114	−15	−34
7	Eye height (sitting)	770	852	12.5	89.7	82	742	753	865	876	112	133	−30	−51
8	Hip breadth with gear (sitting)	464	548	12.8	87.2	84	433	445	567	579	122	145	−38	−61
9	Knee height (sitting)	512	579	3.6	66.8	67	507	517	615	625	99	118	−32	−51
10	Popliteal height (sitting)	397	451	9.6	76	54	379	388	476	485	89	106	−35	−52
11	Sitting height	893	975	14.3	90.2	82	861	872	988	999	115	137	−33	−55
12	Stature	1702	1841	15.2	81.8	139	1637	1659	1893	1915	234	278	−95	−139
13	Thumbtip reach length,	790	926	20.2	97.7	136	736	751	909	924	158	188	−22	−52

(Continued)

TABLE 8: (Continued)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Men) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5th % Value	5th% Value	95th% Value	97.5th % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
14	Waist breadth with gear (sitting)	383	533	8.7	94.9	150	353	369	533	549	165	196	−15	−46
15	Waist circumference at omphalion	923	1110	21.2	74.3	187	773	814	1238	1279	424	506	−237	−319
16	Abdominal extension depth with gear (sitting)	302	385	14.3	77	83	261	275	427	441	151	180	−68	−97
17	Acromion-trochanter length, w/gear (sitting)	777	890	12.9	84.1	113	733	750	924	941	174	208	−61	−95
18	Bi-trochanter surface length with gear (sitting)	655	777	15.4	82.1	122	596	615	823	842	207	247	−85	−125
19	Shoulder-grip length, with gear (sitting)	778	845	27.1	84.8	67	723	736	870	883	135	161	−68	−94
20	Thigh clearance, with gear (sitting)	179	585	14.5	89.1	37	164	169	225	230	56	67	−19	−30

(Continued)

TABLE 8: (Continued)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Men) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5th % Value	5th% Value	95th% Value	97.5th % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
Without gear	Bideltoid breadth, sitting	471	557	9.7	91.3	86	449	460	568	579	109	129	−23	−43
	Chest breadth	346	412	22.7	86.2	66	302	314	432	444	118	141	−52	−75
	Chest depth	252	319	16.6	89.8	67	222	232	330	340	99	118	−32	−51
	Hip breadth	354	441	7.1	89.4	87	338	348	454	464	105	125	−18	−38
	Waist breadth	314	387	12.5	75.2	73	282	294	426	438	132	157	−59	−84
	Body weight (kg)*	90.3	123.1	38.2	94.5	32.8	61.5	66.9	123.9	129.3	56.9	67.8	−24.1	−35.0

TABLE 9: Anthropometry of the Closest Neighbor Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models* (Women; Unit in mm)

Variable	(Women) Variable Description	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
	Subject ID	S807	S481	S816	S600	S837	S529	S957	S480	S849	S902	S456	S188	S124	S223	S764
1	Bideltoid breadth with gear (sitting)	482	450	459	500	473	491	471	497	450	512	463	477	522	465	475
2	Buttock-knee length (sitting)	603	601	585	627	576	605	582	624	590	634	610	572	586	599	596
3	Buttock-popliteal length (sitting)	499	503	480	505	468	485	481	520	492	517	519	471	477	484	503
4	Chest breadth with gear	351	349	334	334	332	344	344	365	327	369	332	313	353	341	405
5	Chest depth with gear	293	286	315	325	305	286	286	337	298	315	286	287	315	278	275
6	Elbow rest height (sitting)	244	263	247	263	283	242	224	238	243	256	230	238	280	275	227
7	Eye height (sitting)	767	791	770	783	757	758	747	745	730	786	772	746	754	779	748
8	Hip breadth with gear (sitting)	488	506	484	542	487	490	467	499	504	567	488	476	537	495	470
9	Knee height (sitting)	529	543	520	531	517	559	527	513	487	536	514	494	504	535	526
10	Popliteal height (sitting)	398	424	387	372	387	421	406	399	382	392	405	382	371	407	398
11	Sitting height	881	910	877	897	862	872	872	859	849	903	893	868	863	896	865
12	Stature	1665	1719	1664	1671	1613	1682	1654	1644	1582	1689	1711	1588	1598	1694	1662
13	Thumbtip reach length,	740	758	740	760	732	796	784	786	750	796	780	740	792	728	784
14	Waist breadth with gear (sitting)	490	507	470	511	462	480	464	495	458	528	481	449	397	494	423
15	Waist circumference at omphalion	939	918	824	986	861	858	807	956	921	993	850	788	1004	821	870
16	Abdominal extension depth with gear (sitting)	304	307	272	280	356	357	320	369	303	334	272	294	325	353	322
17	Acromion-trochanter length, with gear (sitting)	810	840	790	845	775	800	780	800	765	814	798	710	797	795	750
18	Bi-trochanter surface length, with gear (sitting)	685	720	630	725	665	670	660	660	710	671	690	600	695	735	615

(Continued)

TABLE 9: (Continued)

	(Women)	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
Variable	Variable Description	O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
19	Shoulder-grip length, with gear (sitting)	753	773	730	736	719	766	743	739	738	764	774	725	703	726	748
20	Thigh clearance, with gear (sitting)	190	149	171	213	176	188	177	161	171	197	180	176	194	159	187
Without gear	Bideltoid breadth, sitting	449	438	440	479	446	463	448	457	400	456	455	444	491	408	444
	Chest breadth with gear	323	305	315	343	329	308	303	326	310	335	302	289	330	288	322
	Chest depth with gear	261	248	262	303	244	260	257	306	256	277	253	234	271	252	257
	Hip breadth	434	393	382	489	424	428	399	412	425	481	392	390	450	419	419
	Waist breadth	321	330	297	377	306	303	305	333	325	347	309	284	369	307	324
	Body weight (kg)*	82.2	81.3	75.6	99.3	77.8	87.1	80.0	89.1	73.8	98.6	76.6	71.9	92.4	76.8	81.3

TABLE 10: Percentage of Coverage of Anthropometry of the Closest Neighbor Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models* (Women; Unit in mm)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Women) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5th % Value	5th% Value	95th% Value	97.5th % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
1	Bideltoid breadth with gear (sitting)	450	522	16.4	87	72	417	427	540	551	113	134	−41	−62
2	Buttock-knee length (sitting)	572	634	18.4	85.8	62	539	548	652	662	103	123	−41	−61
3	Buttock-popliteal length (sitting)	468	520	18.1	84.1	52	440	448	537	546	89	106	−37	−54
4	Chest breadth with gear	313	405	9.5	98.9	92	297	305	389	397	84	100	8	−8
5	Chest depth with gear	275	337	12.7	82.4	62	251	260	358	368	98	117	−36	−55
6	Elbow rest height (sitting)	224	283	18.1	90.7	59	197	205	291	300	87	103	−28	−44
7	Eye height (sitting)	730	791	15.9	83.4	61	700	710	812	821	102	121	−41	−60
8	Hip breadth with gear (sitting)	467	567	27.1	98.3	100	417	429	550	562	121	144	−21	−44
9	Knee height (sitting)	487	559	9.5	92.2	72	470	478	565	573	87	103	−15	−31
10	Popliteal height (sitting)	371	424	18.7	90.1	53	345	353	433	440	80	95	−27	−42
11	Sitting height	849	910	21.2	86.6	61	813	823	927	937	104	124	−43	−63
12	Stature	1582	1719	14	85.5	137	1526	1546	1756	1776	210	250	−73	−113
13	Thumbtip reach length,	728	796	22.7	81.6	68	678	691	826	839	135	161	−67	−93

(Continued)

TABLE 10: (Continued)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Women) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5th % Value	5th% Value	95th% Value	97.5th % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
14	Waist breadth with gear (sitting)	397	528	15.2	94.2	131	350	366	532	548	166	198	−35	−67
15	Waist circumference at omphalion	788	1004	16.9	75.2	216	657	699	1130	1172	432	515	−216	−299
16	Abdominal extension depth with gear (sitting)	272	369	12.3	89.8	97	240	253	384	396	131	156	−34	−59
17	Acromion-trochanter length, with gear (sitting)	710	845	4.6	87.5	135	697	712	868	883	156	186	−21	−51
18	Bi-trochanter surface length, with gear (sitting)	600	735	12.3	84.4	135	550	570	775	794	205	244	−70	−109
19	Shoulder-grip length, with gear (sitting)	703	774	16.4	80.8	71	666	678	804	816	126	150	−55	−79
20	Thigh clearance, with gear (sitting)	179	216	45.6	97.9	37	147	152	209	215	57	68	−20	−31

(Continued)

TABLE 10: (Continued)

		PCA Results					Percentile Values of Each Signal Dimension							
Variable	(Women) Variable Description	Lower	Upper	Lower %Tile (%)	Upper %Tile (%)	L to U Range	2.5^{th} % Value	5^{th}% Value	95^{th}% Value	97.5^{th} % Value	90% Range	95% Range	PCA Range – 90% Range	PCA Range −95% Range
Without gear	Bideltoid breadth, sitting	400	491	3.1	91.8	397	406	498	507	92	110	397	−1	−19
	Chest breadth	288	343	13.6	75.2	261	271	373	383	102	122	261	−47	−67
	Chest depth	234	306	16.6	84.8	198	210	328	340	118	141	198	−46	−69
	Hip breadth	382	489	18.4	95.6	339	352	486	499	135	161	339	−28	−54
	Waist breadth	284	377	15.4	87.3	244	257	399	412	141	169	244	−48	−76
	Body weight (kg)*	71.9	99.3	41.7	95.2	47.3	51.7	98.1	102.5	46.4	55.3	47.3	−19.0	−27.9

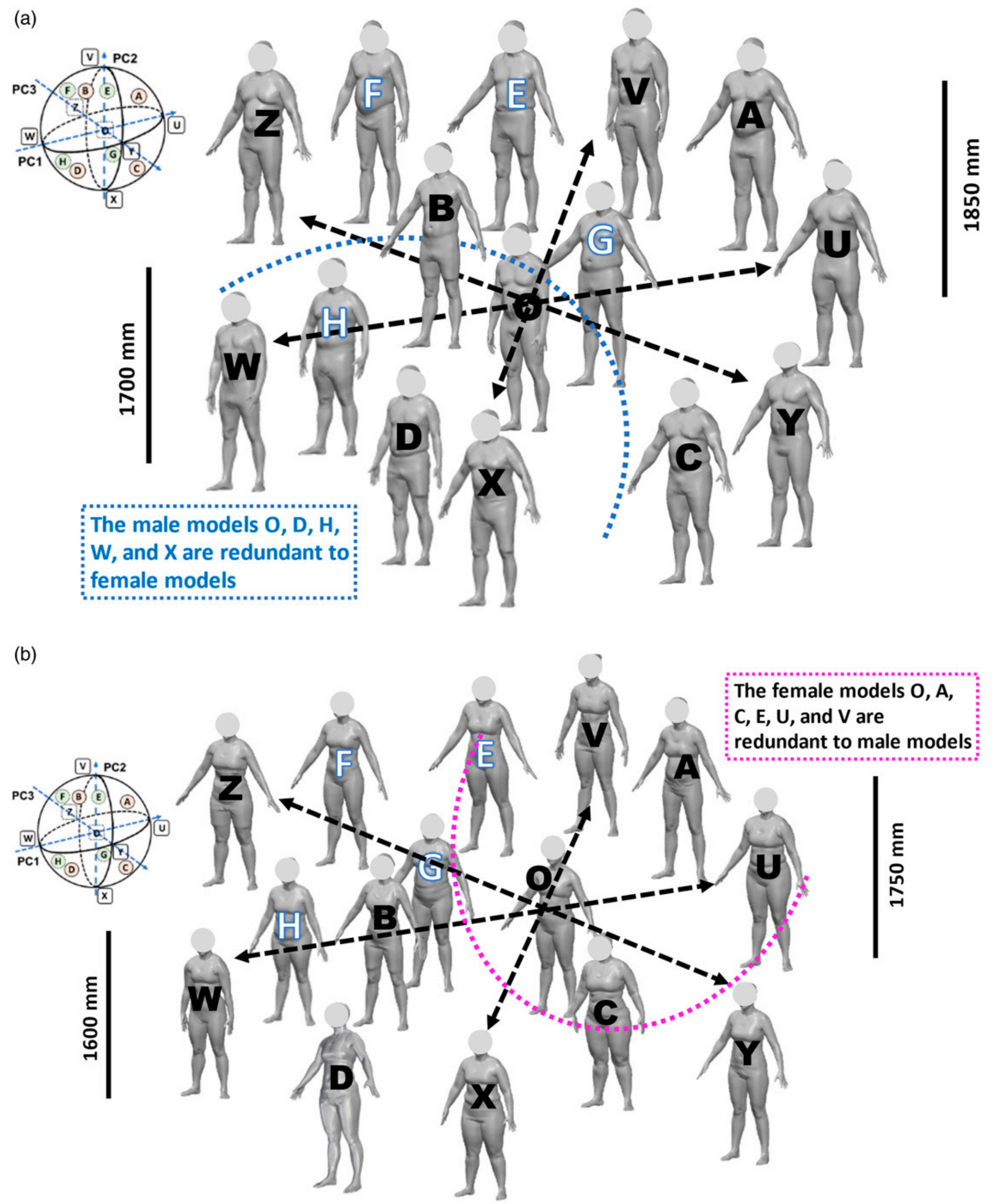


Figure 7. The joint male and female law enforcement officers corresponding to multivariate anthropometric models. Two options can be considered: (1) Twenty-five (25) models are proposed for which the male models O, D, H, W, and X can be considered redundant to female models (7a). (2) Twenty-four (24) female and male law enforcement multivariate anthropometric models can be proposed for which the female models O, A, C, E, U, and V are redundant to male models (7b).

and 8 models for women (B, D, F, G, H, W, X, and Z). The dimensions of these models are presented in Table 12. Alternatively, a combined set of 25 models can include 10 models for men (A, C, D, E, G, H, U, X, Y, and Z) and 15 models for women (A, B, C, D, E, F, G, H, U, V, W, X, Y, Z, and O).

Decision to Use Correlation Matrix for PCA Analysis

Three analysis approaches were considered for the PCA analysis in this study: Correlation Matrix (derived from standardized variables), Covariance matrix (appropriate if all the variables have the same unit or scale), and Covariances of Weighted Variable (weights are chosen to reflect a priori idea of the relative importance of the variables). The Correlation Matrix approach was employed in lieu of the Covariance Matrix because there were major differences of variance among body dimensions (Jolliffe, 1986). For example, the variance of waist circumference is about 27-fold of the popliteal height for women, and about 23-fold for men. In addition, results with covariance matrices will be more challenging to compare from different analyses than with correlation matrices given that both with- and without-gear measurements were used in this study. While this approach is at the expense of size of the larger body dimensions, small body dimensions can be critical to LEO cab design as well; in fact, in a study on seat adjustment needs among patrol LEOs, all body dimensions in Table 1 (except for elbow rest height) were directly associated with seat and equipment adjustment needs (Hsiao, 2022). The option of using Covariance of Weighted Variable requires a good knowledge of the relative importance of the variables (Jolliffe, 1986) and we did not have well-defined information to quantify the relative importance of the dimensions for LEO cab design yet.

.In a multivariate study on defining extreme forms for body armor for soldiers, correlation matrix and covariance matrix methods did not yield substantially different results in terms of the univariate ranges of extreme forms for torso lengths and breadths (Gordon, Corner, & Brantley, 1997). The authors suggested that detailed contrast of these two methodological alternatives be further studied within armor sizing and design applications. The correlation matrix approach may fit workspace design better while the covariance matrix approach may suit a physical product design better as it would be equivalent to a Cluster Analysis (Hsiao, Whitestone, Kau, & Hildreth, 2015).

Using Varimax Rotation to Check Variable Loading and Interpretability

There are several different PCA rotations that can be utilized to arrive at a diverse set of PCs. One of the most common rotations is the Varimax rotation (Kaiser 1958). With the Varimax rotation the total amount of variance explained by the first 3 PCs will be the same as the standard PCA (which does not include rotation), but the amount of variance explained by each PC will be different. It rotates the coordinate system such that each component will have a small number of high loading variables and a larger number of small loading (or zero loading) variables. This process groups variables together which helps scientists see more clearly how the variables cluster. This however is at the expense of the overall size component (i.e., PC1) in the standard PCA. In general, in using Varimax rotation, we would like to see that (a) there are at least three (and preferably more) variables loading on each retained component, (b) most of the variables have relatively high loadings on only one component, and near-zero loadings on the other components, and (c) most components have relatively high loadings for some variables, and near-zero loadings for the remaining variables (SAS Institute, 2022). Our results using Varimax rotation, unfortunately, do not meet all the criteria listed above. Therefore, we kept the design-based variable set and used the standard method of principal component analysis where the first component accounts for a maximal amount of total variance in the observed variables, and the second component extracted accounts for a maximal amount of variance that was not accounted for by the first component, and so forth.

TABLE 11: Hypothetical Anthropometric Models of the Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models Based on 15 Traditional Measurements (Weighted; N= 756 for Men and N = 217* for Women; Unit in mm; 1 Missing Data for Women)

	(Men)	Centroid	Hypothetical Model on the Octants Center Points								Hypothetical Model on the Axes Intercept Points					
Variable	Variable Description	O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
1	Bideltoid breadth, sitting	514	563	501	528	465	563	500	528	465	577	549	451	479	514	514
2	Buttock-knee length	631	641	564	664	586	675	598	698	620	708	608	553	654	607	655
3	Buttock-popliteal length	514	511	451	541	481	547	487	577	517	574	484	454	544	488	540
4	Chest breadth	372	433	365	379	311	434	366	380	312	440	426	305	319	372	373
5	Chest depth	281	324	269	280	225	337	282	293	238	336	325	226	237	272	290
6	Elbow rest height	254	319	298	299	278	230	209	210	189	275	274	233	234	317	191
7	Eye height, sitting	809	860	806	892	839	780	726	813	759	863	776	755	842	866	753
8	Hip breadth, sitting	401	452	388	415	351	450	386	413	349	465	437	336	364	402	399
9	Knee height, sitting	566	569	507	605	543	589	527	625	563	628	530	504	602	552	581
10	Popliteal height	432	416	379	468	431	433	396	485	448	469	380	394	484	420	444
11	Sitting height	929	982	924	1018	960	899	841	935	877	987	894	872	965	988	871
12	Stature	1776	1805	1660	1915	1770	1782	1637	1892	1747	1921	1666	1631	1886	1793	1759
13	Thumbtip reach	830	833	744	871	783	877	789	915	827	918	791	742	868	798	861
14	Waist breadth, sitting	360	424	348	359	284	436	360	371	296	435	425	284	295	351	368
15	Waist circumference at omphalion	1026	1235	993	1021	779	1273	1032	1059	818	1268	1240	785	812	999	1054

	(Women)	Centroid	Hypothetical Model on the Octants Center Points								Hypothetical Model on the Axes Intercept Points					
Variable	Variable Description	O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
1	Bideltoid breadth, sitting	452	464	412	495	444	461	409	492	441	503	421	401	483	454	450
2	Buttock-knee length	600	627	555	615	543	658	586	646	574	672	612	528	588	578	622
3	Buttock-popliteal length	493	513	457	494	438	548	492	529	473	549	512	437	474	468	517
4	Chest breadth	322	333	270	378	314	330	266	374	311	385	277	259	366	324	319
5	Chest depth	269	275	207	328	260	277	210	330	263	336	216	201	321	267	270
6	Elbow rest height	248	296	279	303	286	211	193	217	200	266	241	231	255	309	187
7	Eye height, sitting	761	839	796	798	755	766	723	726	683	804	801	718	721	812	710

(Continued)

TABLE 11: (Continued)

Variable	(Women) Variable Description	Centroid	Hypothetical Model on the Octants Center Points								Hypothetical Model on the Axes Intercept Points					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
8	Hip breadth, sitting	419	446	366	485	404	434	354	473	393	500	381	339	458	427	411
9	Knee height, sitting	522	556	505	520	468	575	523	539	487	573	558	470	485	508	535
10	Popliteal height	393	419	395	369	345	440	416	390	367	416	442	369	343	378	408
11	Sitting height	875	955	910	912	867	883	837	840	794	920	918	829	832	926	824
12	Stature	1651	1772	1654	1661	1543	1760	1641	1649	1530	1770	1762	1532	1540	1660	1642
13	Thumbtip reach	759	777	713	741	677	841	777	804	741	822	795	695	723	714	804
14	Waist breadth, sitting	328	340	254	401	315	341	255	403	317	414	267	242	390	327	329
15	Waist circumference at omphalion	915	946	678	1136	868	961	693	1151	883	1182	725	647	1104	904	925

TABLE 12: Anthropometry of the Closest Neighbor Participating Law Enforcement Officers Corresponding to Multivariate Anthropometric Models Based on 15 Traditional Measurements[a] (unit in mm)

Variable	(Men) Variable Description	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
	Subject ID	S112	S779	S401	S161	S621	S013	S170	S954	S604	S107	S257	S578	S357	S414	S127
1	Bideltoid breadth, sitting	517	518	520	528	474	521	490	521	466	557	510	491	522	533	485
2	Buttock-knee length	613	640	615	625	615	683	619	658	622	648	630	597	641	637	640
3	Buttock-popliteal length	493	520	499	494	500	575	512	549	518	530	515	490	522	510	529
4	Chest breadth	370	390	364	355	340	396	361	390	337	401	380	365	341	375	378
5	Chest depth	280	293	293	292	269	319	271	258	270	319	304	273	260	272	285
6	Elbow rest height	257	279	279	276	251	247	236	224	222	245	275	236	250	300	239
7	Eye height, sitting	807	826	809	838	829	804	786	831	802	852	789	795	822	812	791
8	Hip breadth, sitting	400	421	407	407	375	447	404	402	385	421	415	356	398	397	387
9	Knee height, sitting	563	577	556	581	553	564	543	577	558	579	543	536	592	557	555
10	Popliteal height	425	435	429	450	421	435	421	451	431	437	412	413	450	420	428
11	Sitting height	923	943	931	953	947	908	893	946	926	969	915	907	937	946	912
12	Stature	1750	1767	1736	1807	1780	1760	1724	1828	1767	1806	1727	1716	1818	1773	1747
13	Thumbtip reach	920	796	784	910	802	736	842	858	852	926	812	790	822	838	898
14	Waist breadth, sitting	355	382	354	358	338	386	385	362	352	383	395	336	334	344	386
15	Waist circumference at omphalion	980	1150	1049	985	1006	1085	1135	1064	977	1092	1158	962	909	955	1037
	Body weight (kg)[a]	104.0	117.8	102.8	107.0	97.9	121.4	96.4	103.2	85.7	123.1	106.1	90.3	104.0	107.5	98.6

Variable	(Women) Variable Description	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
	Subject ID	S807	S203	S781	S729	S590	S860	S957	S526	S602	S789	S448	S188	S687	S300	S936
1	Bideltoid breadth, sitting	449	466	439	473	454	456	448	491	444	467	451	444	468	439	454
2	Buttock-knee length	603	592	587	614	575	635	582	610	607	620	607	572	602	593	615
3	Buttock-popliteal length	499	485	472	497	462	529	481	493	489	509	511	471	490	490	508
4	Chest breadth	323	336	288	343	333	329	303	341	337	357	295	289	334	328	316
5	Chest depth	261	272	242	321	279	273	257	285	307	288	251	234	272	257	273
6	Elbow rest height	244	256	265	288	264	221	224	229	225	254	255	238	232	254	238
7	Eye height, sitting	767	797	755	777	754	759	747	752	736	784	765	746	743	787	741

(Continued)

TABLE 12: (Continued)

Variable	(Women) Variable Description	Centroid	Real LEO Model on the Octants Center Points (mm)								Real LEO Model on the Axes Intercept Points (mm)					
		O	A	B	C	D	E	F	G	H	U	V	W	X	Y	Z
8	Hip breadth, sitting	434	424	406	435	390	430	399	457	397	432	395	390	438	398	434
9	Knee height, sitting	529	524	528	531	509	529	527	539	509	547	521	494	515	506	521
10	Popliteal height	398	404	399	390	391	396	406	386	373	406	404	382	366	385	378
11	Sitting height	881	905	898	889	877	874	872	874	854	891	884	868	851	895	846
12	Stature	1665	1658	1646	1657	1631	1678	1654	1659	1636	1710	1689	1588	1603	1645	1614
13	Thumbtip reach	740	740	740	720	718	774	784	762	750	770	764	740	714	756	806
14	Waist breadth, sitting	321	319	298	344	340	313	305	356	322	351	301	284	352	344	326
15	Waist circumference at omphalion	939	860	847	1011	949	910	807	998	902	1009	839	788	1020	971	915
	Body weight (kg)[a]	82.2	84.1	81.5	97.0	82.5	89.8	80.0	100.7	81.6	95.4	80.3	71.9	89.2	80.1	92.0

[a]Body weight is included in this table for reference.

Practical Implications and Inclusivity

Digital body models of LEOs with unique combinations of body size and physique, considering sex, age, and ethnicity/race factors, were developed and their body dimensions were summarized in this study. These models can be applied to the design or retrofitting of LEO cruiser cabs to accommodate the diverse LEO population. Developers of ergonomics software may apply these models toward generating digital manikins to improve cab simulation capacity and accuracy. "Rather than designing to specific dimensions, designers can use the models as representatives of LEO population that must be accommodated to evaluate different fit issues in cab designs" (Hsiao, 2013; Hsiao et. al 2005). These digital mannequins provide a level of anthropometric variability that cannot be provided by the conventional percentile models. Literature has reported a similar modeling process for farm workers (Hsiao et. al 2005), military personnel (Hudson, Zehner, & Meindl, 1998), and firefighters (Hsiao, 2013). These models can be systematically incorporated into commercial digital human software to assess the safety and effectiveness of equipment and workspaces used by specific occupational groups.

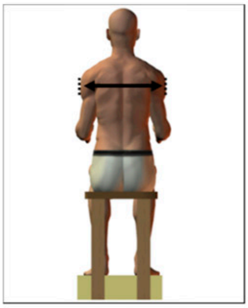
Another practical implication is that LEO vehicle and equipment manufacturers and designers can use the 24 body models and their body dimensions as the templates to recruit human subjects to physically evaluate their vehicle prototypes for improved vehicle and equipment design. Stature, buttock-popliteal length, eye height (sitting), knee height (sitting), shoulder-grip length, popliteal height, and sitting height were identified as seven key parameters associated with seat fore/aft and up/down adjustments in an LEO vehicle accommodation survey (Hsiao, 2022). In addition to the abovementioned 7 dimensions, 12 other dimensions in Table 1 (except for elbow rest high) were also found to affect seat/equipment adjustment needs in the fore/aft direction. Finally, body weight is associated with seat belt adjustment (Hsiao, 2022). LEO vehicle and equipment manufacturers and designers can use the 7 key parameters plus body weight as the initial basis to identify the needed 24 subjects in lieu of random subjects to cost effectively evaluate their vehicle/equipment prototypes/configurations for improved vehicle and equipment design.

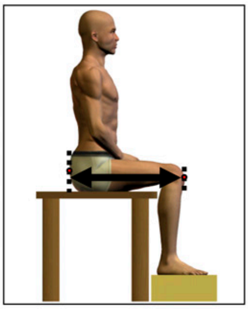
CONCLUSION

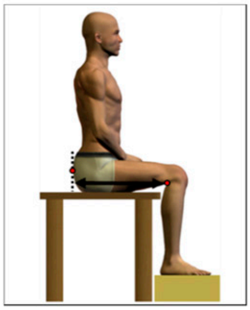
This study developed the first available multivariate digital body models of law enforcement officers (LEOs), representing the current U.S. LEO population. The investigation used a national anthropometry dataset of 756 male and 218 female LEOs and a principal component analysis-based process. It identified fifteen body models for each gender group which represent a unique combination of body size and physique of male and female LEOs. A combination of 24 body models was suggested for cruiser workspace simulation applications. Both male and female body models of the representative LEOs and their body dimensions are presented in this paper. LEO cruiser/equipment designers and retrofitting manufacturers can use these avatars/models for computerized simulations to prototype or verify their driver-cab interface designs. Alternatively, LEO cruiser/equipment designers can use body dimensions of the 24 body models as the templates to recruit the needed 24 subjects in lieu of random subjects to cost effectively evaluate their vehicle prototypes and equipment configurations. Moreover, the LEO body models were developed based on the newly available encumbered (with-gear) LEO body measurements for more realistic applications. LEO cruiser/equipment designers and retrofitting manufacturers are advised to include LEO clothing and gear (body belt) in their computerized simulations.

APPENDIX 1

SEMI-NUDE MEASUREMENTS VS. MEASUREMENTS WITH GEAR (ENCUMBERED MEASUREMENTS)

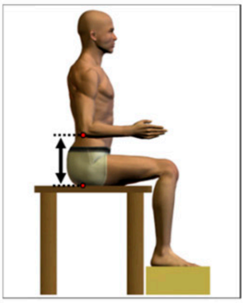

Bideltoid Breadth, Sitting

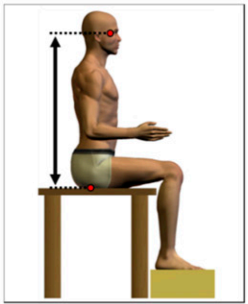

Buttock-Knee Length

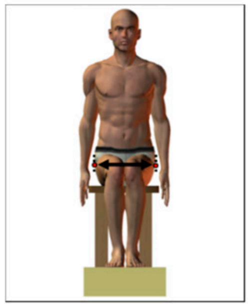

Buttock-Popliteal Length

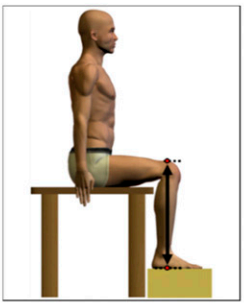

Chest Breadth

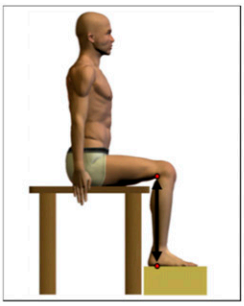

Chest Depth

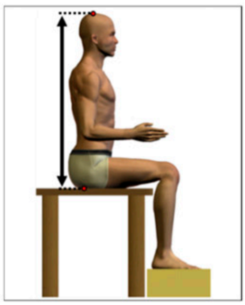

Elbow Rest Height, Sitting

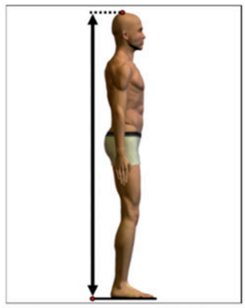

Eye Height, Sitting

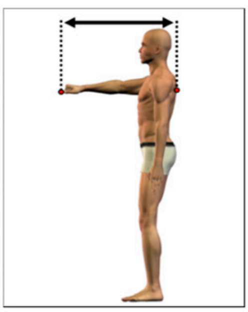

Hip Breadth, Sitting

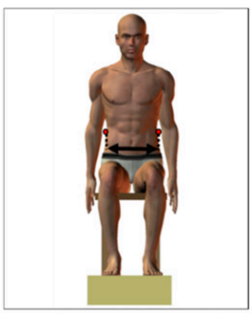

Knee Height, Sitting


Popliteal Height

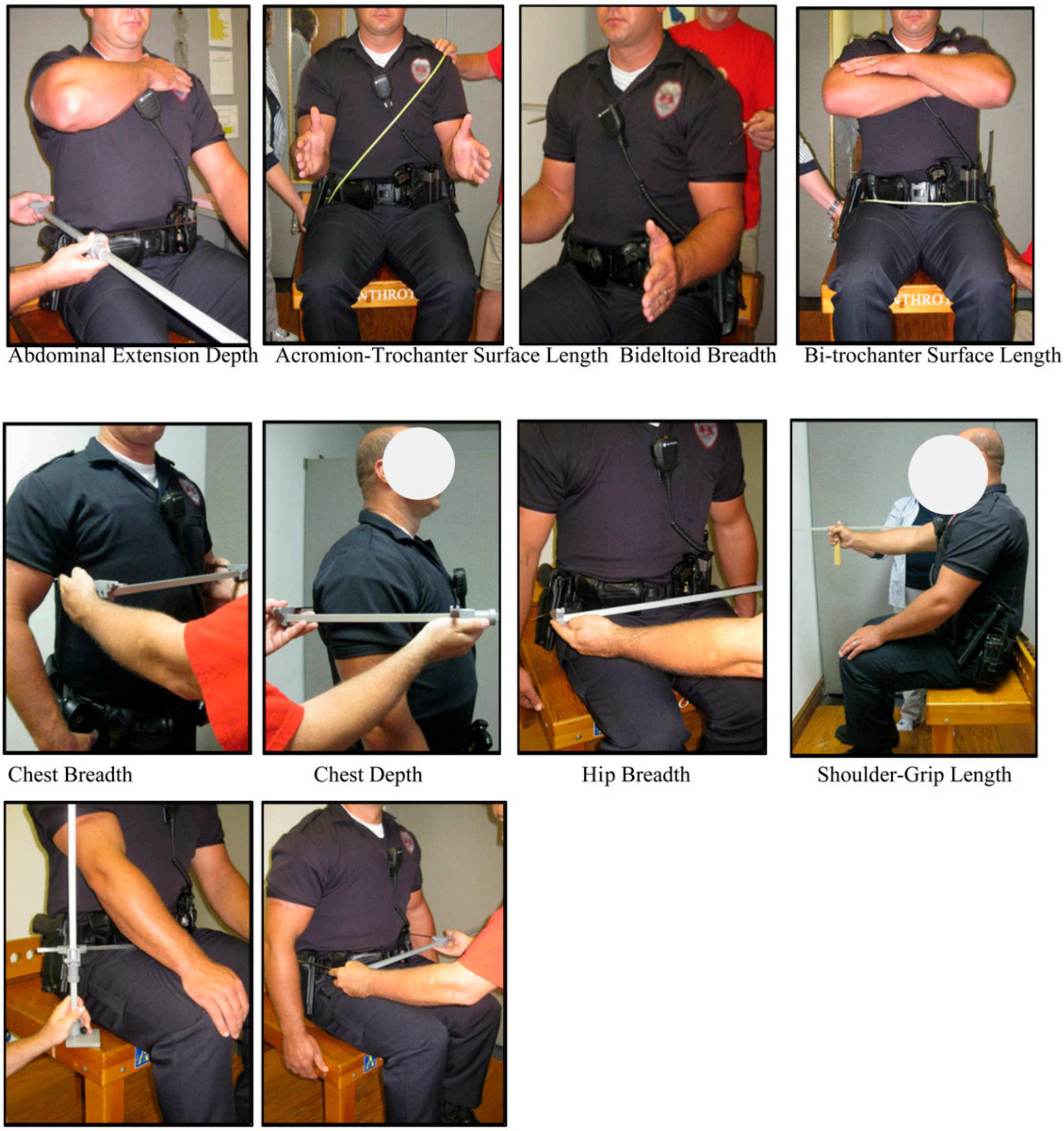

Sitting Height


Stature


Thumbtip Reach


Waist Breadth, Sitting


Waist Circumference (O)



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KEY POINTS

- This study developed a set of multivariate digital body models, which emulate approximately 95% of the current law enforcement officer (LEO) population, using a national anthropometry database of 756 male and 218 female LEOs.
- The principal component analysis-based investigation identified 15 representative body models for each gender group which represent a unique combination of body size and physique of male and female LEOs. A combination of 24 body models was suggested for cruiser workspace simulation applications.
- Three-dimensional (3D) digital body scans of the representative LEOs and their body dimensions are presented in this paper for digital LEO cruiser workspace interface simulation and evaluation.
- LEO cruiser and equipment designers and retrofitting manufacturers also can use these models and their body dimensions as the template to recruit the needed 24 subjects in lieu of random subjects to cost effectively and physically assess their LEO vehicle prototypes and verify their driver-cab interface designs.

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