HHPC2

Beyond Pass/Fail: Quantifying Risk in Space Hardware Design and Verification

Han Kim (Leidos, Inc)
Sarah Jarvis (Aegis Aerospace, Inc)
Joseph Yao (KBR, Inc)
Nate Newby (KBR Inc)

leidos AEGIS AEROSPACE KBR NASA

Approved for release (NASA STRIVES 20260001669, HHPC PubPress 1708)

NASA Requirements

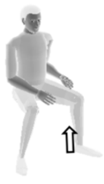
- NASA Human System Requirements define key anthropometric criteria for crew accommodation.
- These requirements ensure spacecraft, equipment, habitats, and spacesuits fit crew size, shape, reach, range of motion, and strength

Table E.2-1—Anthropometric Dimensions

Critical Dimension	Application Example	Minimal Clothing	
		Min (cm, (in))	Max (cm, (in))
Stature, Standing[3]	Maximum vertical clearance	148.6 (58.5)	194.6 (76.6)
Sitting Height[2]	Vertical seating clearance	77.7 (30.6)	101.3 (39.9)
Eye Height, Sitting[2]	Placement of panels to be within line-of-sight	66.5 (26.2)	88.9 (35.0)
Acromial Height, Sitting[2]	Top of seatback	49.5 (19.5)	68.1 (26.8)
Thigh Clearance, Sitting	Placement of objects that may be overlap (panels, control wheel, etc.)	13.0 (5.1)	20.1 (7.9)
Knee Height, Sitting	Height of panels in front of subject	45.5 (17.9)	63.5 (25.0)
Popliteal Height, Sitting	Height of seat pan	33.0 (13.0)	50.0 (19.7)
Wrist Height, Sitting (with arm to the side)	Downward reach of subject	39.6 (15.6)	54.6 (21.5)
Biacromial Breadth	Placement of restraint straps	32.3 (12.7)	44.5 (17.5)
Bideltoid Breadth	Width of seatback	37.8 (14.9)	56.1 (22.1)
Forearm-Forearm breadth	Side clearance envelope, possible seatback width	38.9 (15.3)	66.0 (26.0)
Hip Breadth, Sitting[1]	Width of seat pan	31.5 (12.4)	46.5 (18.3)
Buttock-Popliteal Length, Sitting	Length of seat pan	42.2 (16.6)	57.2 (22.5)
Buttock-Knee Length, Sitting	Placement of panels in front of subject	52.1 (20.5)	69.9 (27.5)
Foot Length, Sitting	Rudder pedal design, foot clearance	21.6 (8.5)	30.5 (12.0)
Thumb Tip Reach, Sitting	Placement of control panels, maximum reach	65.0 (25.6)	90.9 (35.8)

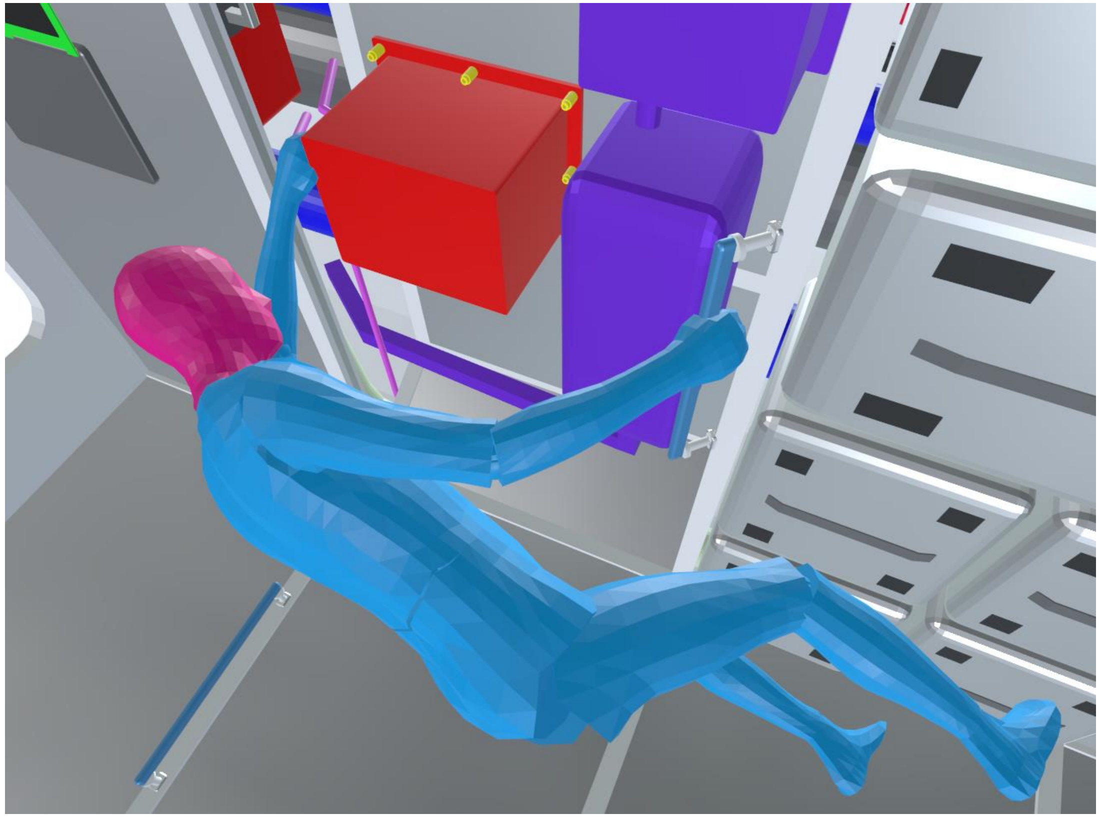
NASA STD-3001

Table E.7-1—Crew Operational Loads, Unsuited

Type of Strength			Crew Operational Loads (N, (lbf))			Withstand Crew Loads (N, (lbf))
			Crit 1 Ops	Crit 2 Ops	Other Ops	
One Handed Pulls						
Seated Horizontal Pull In[2]	Subject in a seated position pulls towards his/her body. Unilateral/Isometric measurement		111 (25)	147 (33)	276 (62)	449 (101)
Seated Vertical Pull Down[2]	Subject in a seated position pulls downwards. Unilateral/Isometric measurement		125 (28)	165 (37)	311 (70)	587 (132)
Seated Vertical Pull Up[2]	Sitting erect with feet apart, dominant hand grasping D-ring located directly to the front above the floor, pulling upward while keeping shoulder squares & other arm in lap		49 (11)	67 (15)	125 (28)	756 (170)

Requirements Verification & Waiver Process

- Requirements are defined and linked to verification methods (human subject test, analysis, inspection, demonstration)
- Verification is completed and documented to show each requirement is met.
- If a requirement is not met, a noncompliance is recorded
- A deviation or waiver is submitted with rationale, risk assessment, and mitigations
- Technical authorities and program management review and approve or reject the request
- Because many requirements are often in binary thresholds, the information available to assess waiver impact is often limited



Aims of the Work

- Propose a method that moves beyond traditional pass/fail human-system requirements toward quantifying the risk associated with non-compliance.
- Provide designers with preliminary, quantitative metrics—such as the proportion of crew affected or the probability of unsafe interactions—to supplement binary thresholds.
- Demonstrate the concept through a case study on exercise equipment volume constraints and crew movement in confined spacecraft environments.
- Explore the use of probabilistic modeling of anthropometry and movement variability as a foundation for future decision-support tools.

Case Study: Astronaut In-Vehicle Exercise Volume

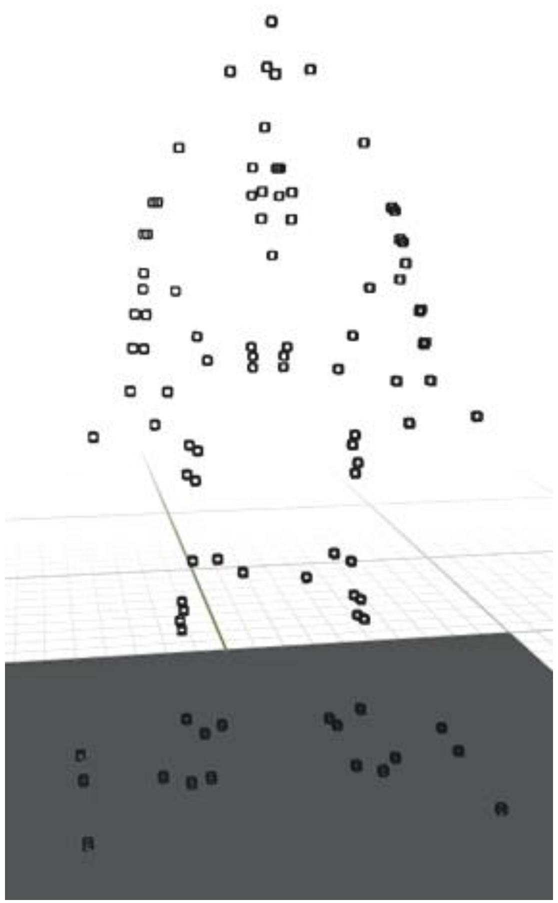
- Astronauts perform regular in-flight exercise to mitigate muscle atrophy, bone demineralization, and cardiovascular deconditioning.
- Exercise volume inside spacecraft is highly constrained due to limited habitable space and competing system needs.
- Identifying optimal exercise modalities and the minimum required exercise volume is critical for crew health and mission performance.
- Adequate exercise space affects not only exercise effectiveness but also crew safety, preventing collisions with hardware and reducing injury risk.

Quantification of Exercise Volume: Methods

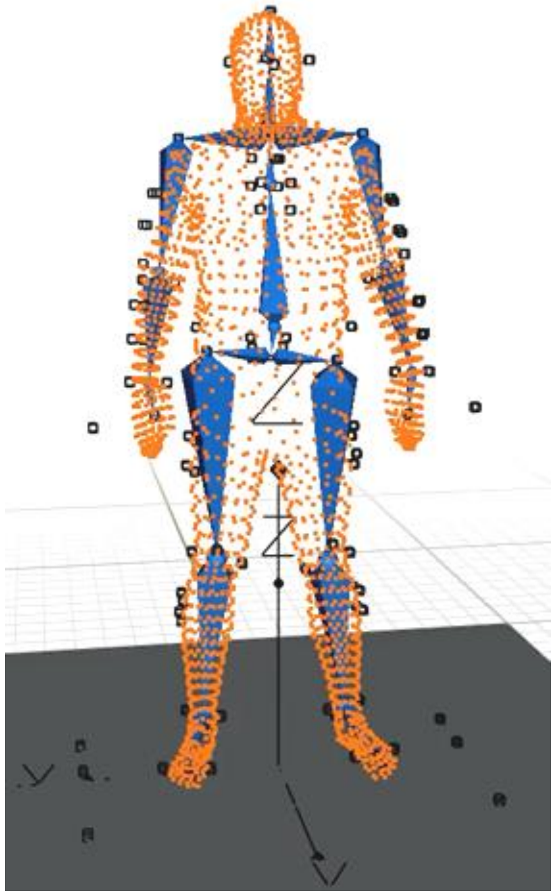
- Human subject tests performed in collaboration with NASA Exercise Physiology Laboratory
- 5 subjects (2 females and 3 males) in a range of anthropometry participated
- The subjects completed 27 exercise types selected by Exercise Physiology Laboratory for operations in the lunar surface vehicle
- Subjects performed 2-3 repetitions of each exercise for familiarization before data collection
- The subject’s motion was recorded by Vicon motion capture system

Motion Data Analysis

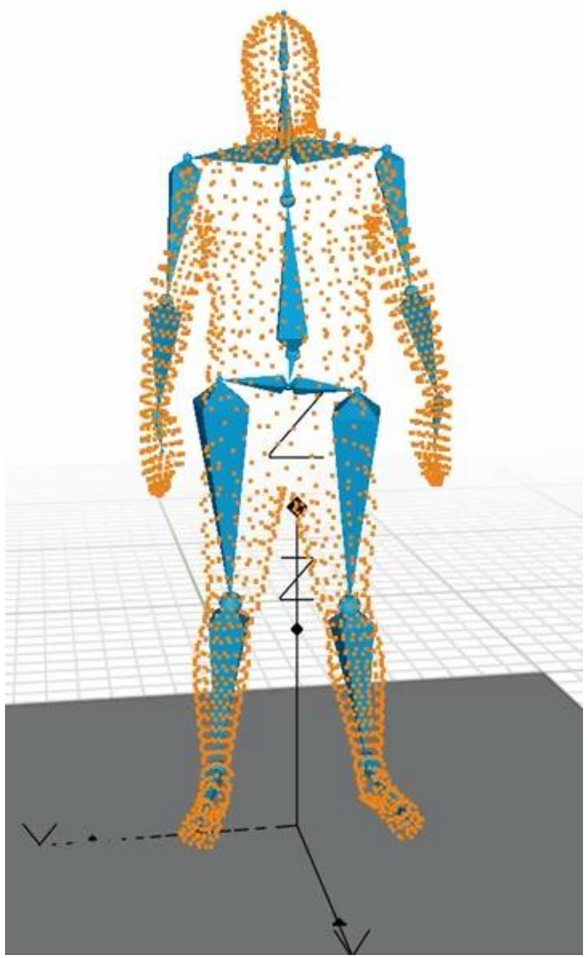
Mocap Markers



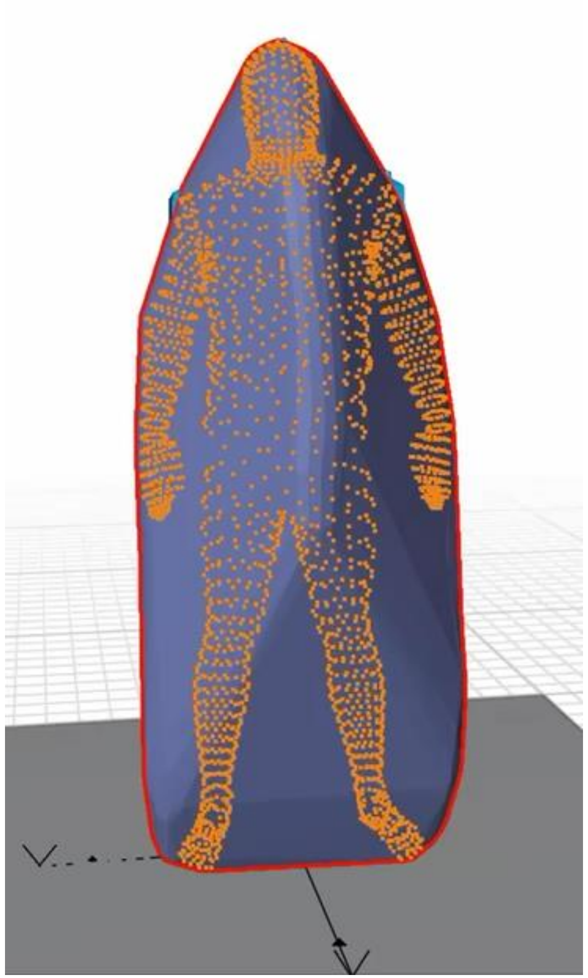
Subject 3D Body Scan Overlay



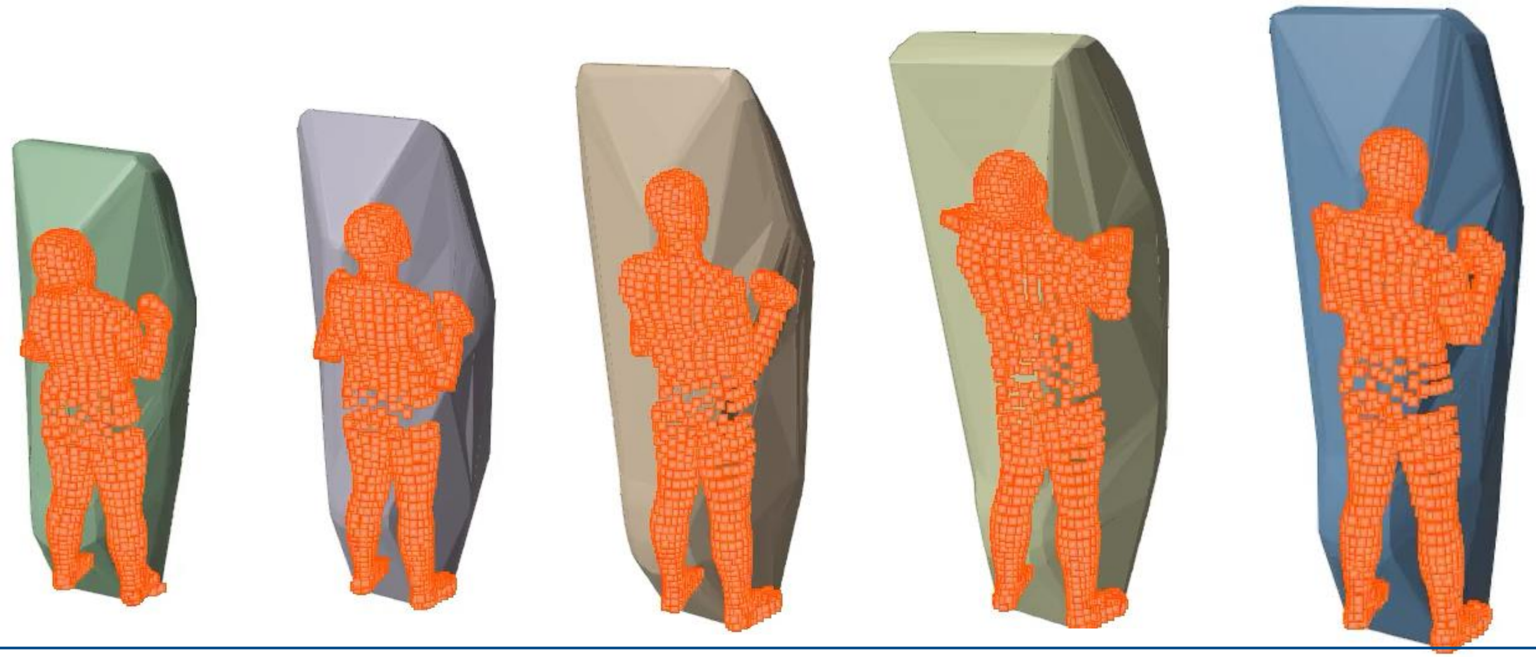
Body Surface Motion Sampling



Convex Hull Envelope Generation

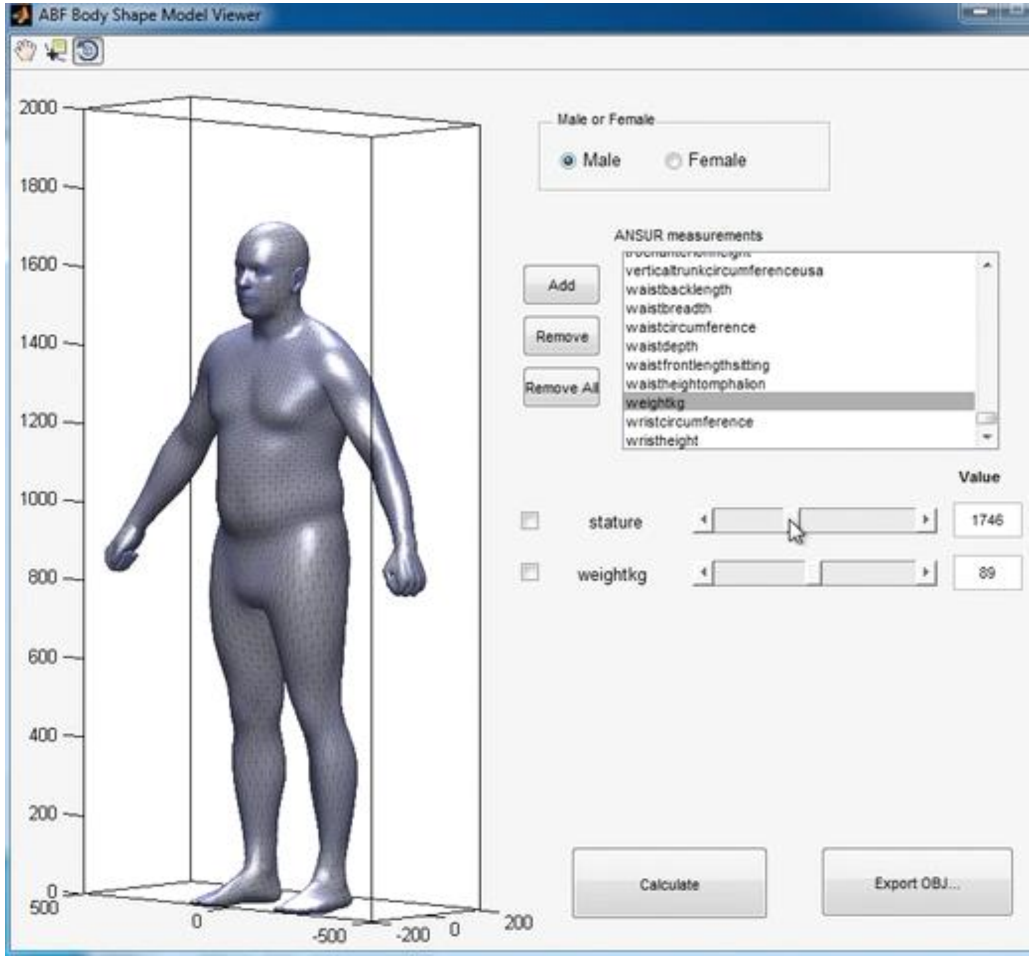


Original Motions Envelopes



	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Gender	F	F	M	M	M
Stature (percentile)	6.3	35.1	92.3	98.1	99.2
Thumb Tip Reach (percentile)	2.1	44.3	78.5	69.2	84.5
Body Weight (percentile)	15	8.8	29.5	90.9	35.6

Generation of "99th Percentile" Body



- The exercise volume needs to accommodate the largest crewmember
- Statistical body shape model generated a 99th percentile body shape
- With this method, the outcome is based on crew population, not specific individual crewmember

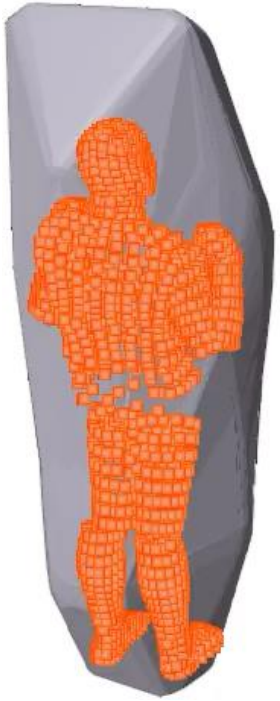
Selected Body Shape

Stature: Male 99th percentile (76.6 inches)
Thumb tip reach: Male 99th percentile (35.9 inches)
Body Weight: Male 99th percentile (242 lbs)

99th Percentile Person Extrapolation

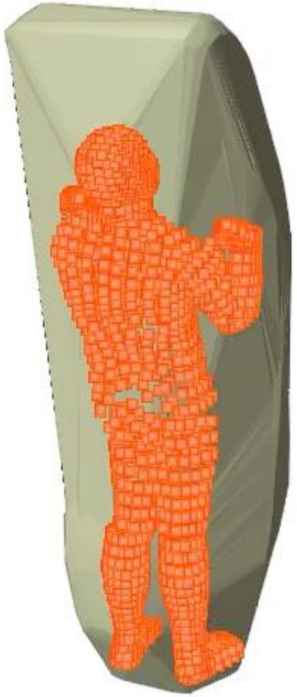
- Each subject's exercise motion was mapped to the hypothetical 99th percentile person
- Body segment lengths were scaled and extrapolated exercise volumes were re-generated

Subject 1



Subject 2

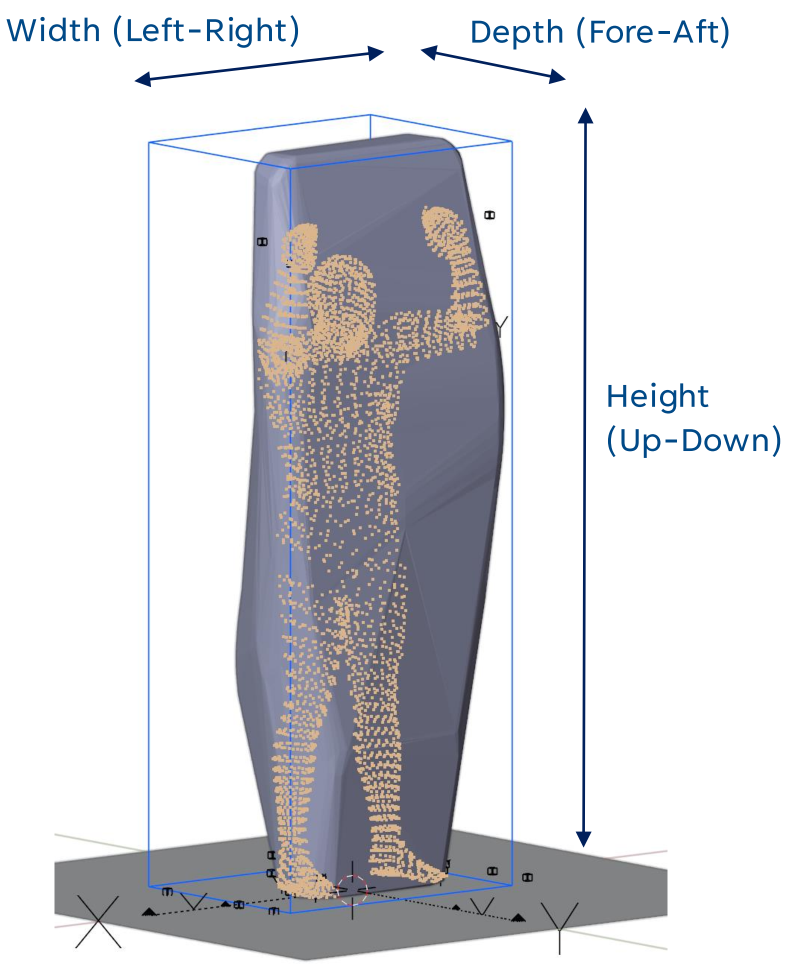
Subject 3



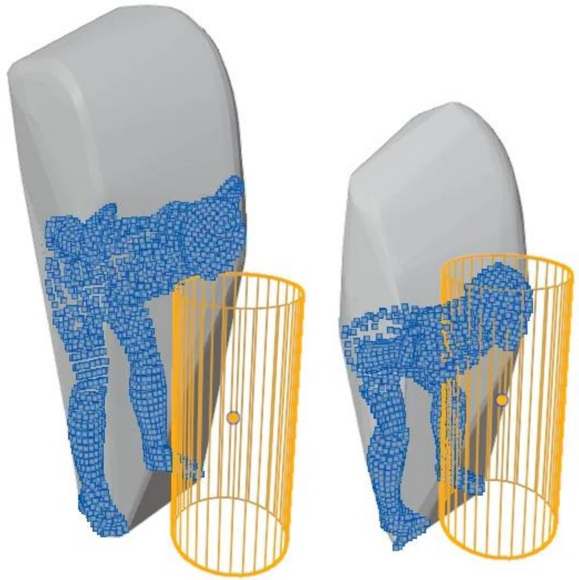
Subject 4

Subject 5

Volume Measurements by Bounding Box Representation



- Each exercise volume was measured and delivered in the bounding box dimension:
  - Width (Left-Right)
  - Depth (Fore-Aft)
  - Height (Up-Down)
- Why simplified into a box representation? Empty space created by a large person's envelope may be actually occupied for a small person

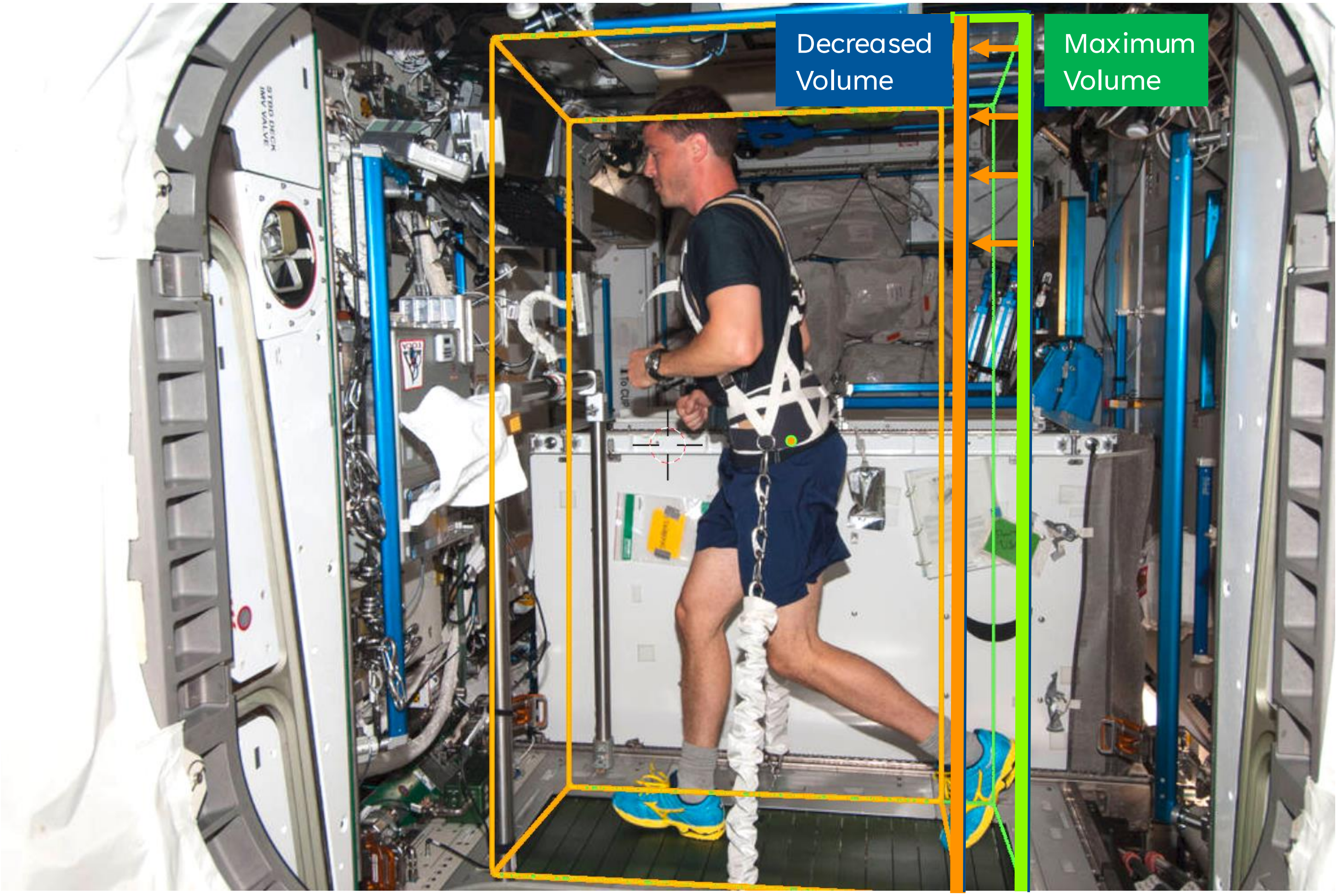


Exercise Volume: Proposed Requirement (Option A: Binary Decision Threshold)

- Exercise volume measurements represent the minimum space required for each exercise type
- If available space is smaller than these dimensions, surrounding walls or hardware may impede movement
- These measurements act as binary thresholds: the space either meets the minimum or it does not

Exercise Type	Left-Right	Fore-Aft	Up-Down
Rowing	33.3	77.9	49.5
Lat Pulldown	40.7	18.5	90.3
Squat - Bar	38.4	32.0	77.0
Shoulder Press - Bar	37.2	19.7	90.3
Deadlift - Bar	30.6	37.6	80.0
Upward Wood Chops - Handles	51.9	47.5	89.8
Kettlebell Swings - Handles	31.4	46.1	81.6
Bench Press - Bar + bench	36.3	63.6	52.2
Cycling - seat at lowest position	32.7	65.2	54.5
Treadmill Walking	30.8	47.9	77.4
Treadmill Running	32.7	49.2	79.1

Toward Option B: Requirement in Continuous Scale

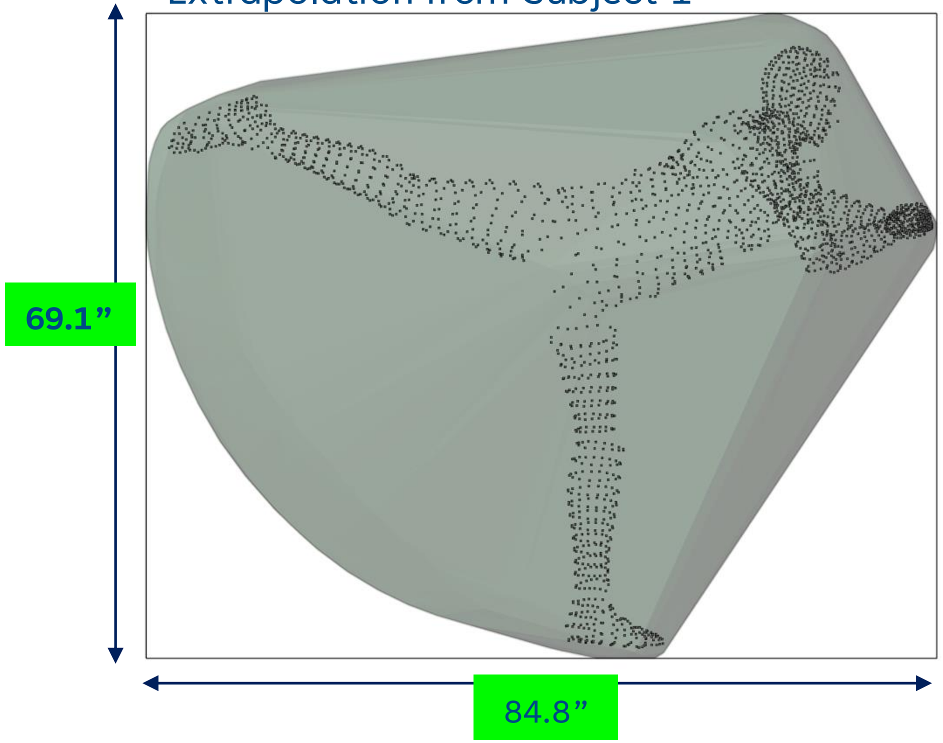


- Design constraints or waivers may require reducing exercise volume
- Binary threshold requirements provide no guidance on how much volume can be reduced
- Crew anthropometry cannot be narrowed; requirements must be based on the largest body size in crew population
- A probabilistic approach can instead define acceptable volume ranges.
- This probability function provides upper and lower bounds that reflect variability in motion patterns

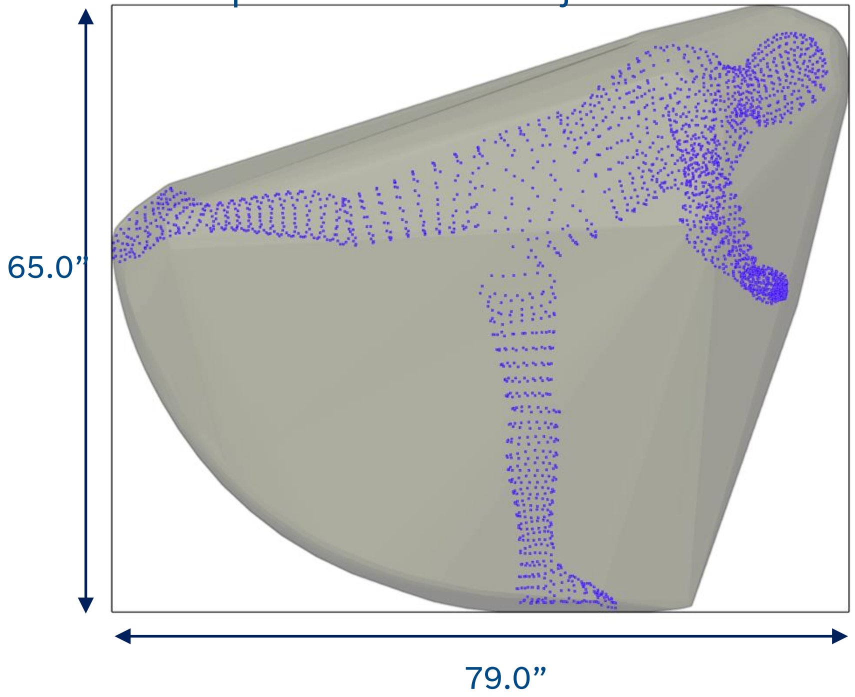
Motion Pattern and Style Variations

- Motion Volume Variations = Anthropometry + Kinematic Variations
- Although anthropometry needed to be fixed to a 99th percentile person, kinematic variations can be exploited as source of exercise volume variations
- Thus, the volume size can vary by individually different exercise techniques and motion patterns.

Extrapolation from Subject 1

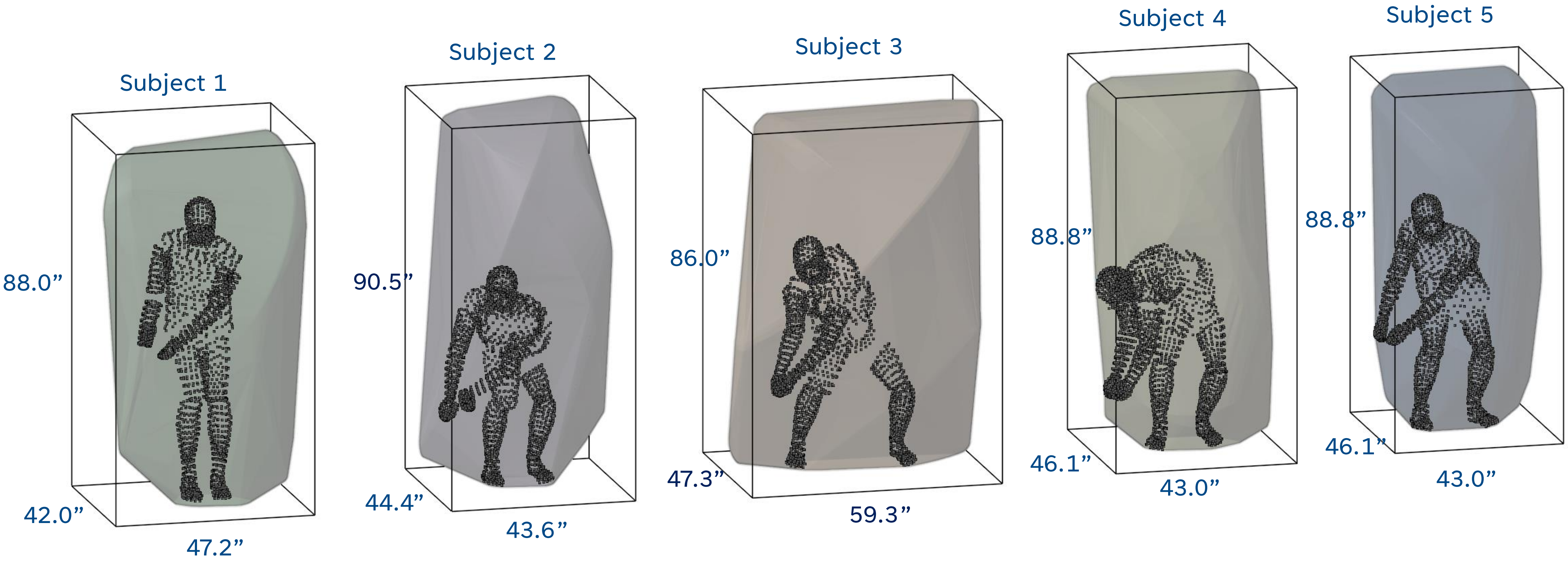


Extrapolation from Subject 4

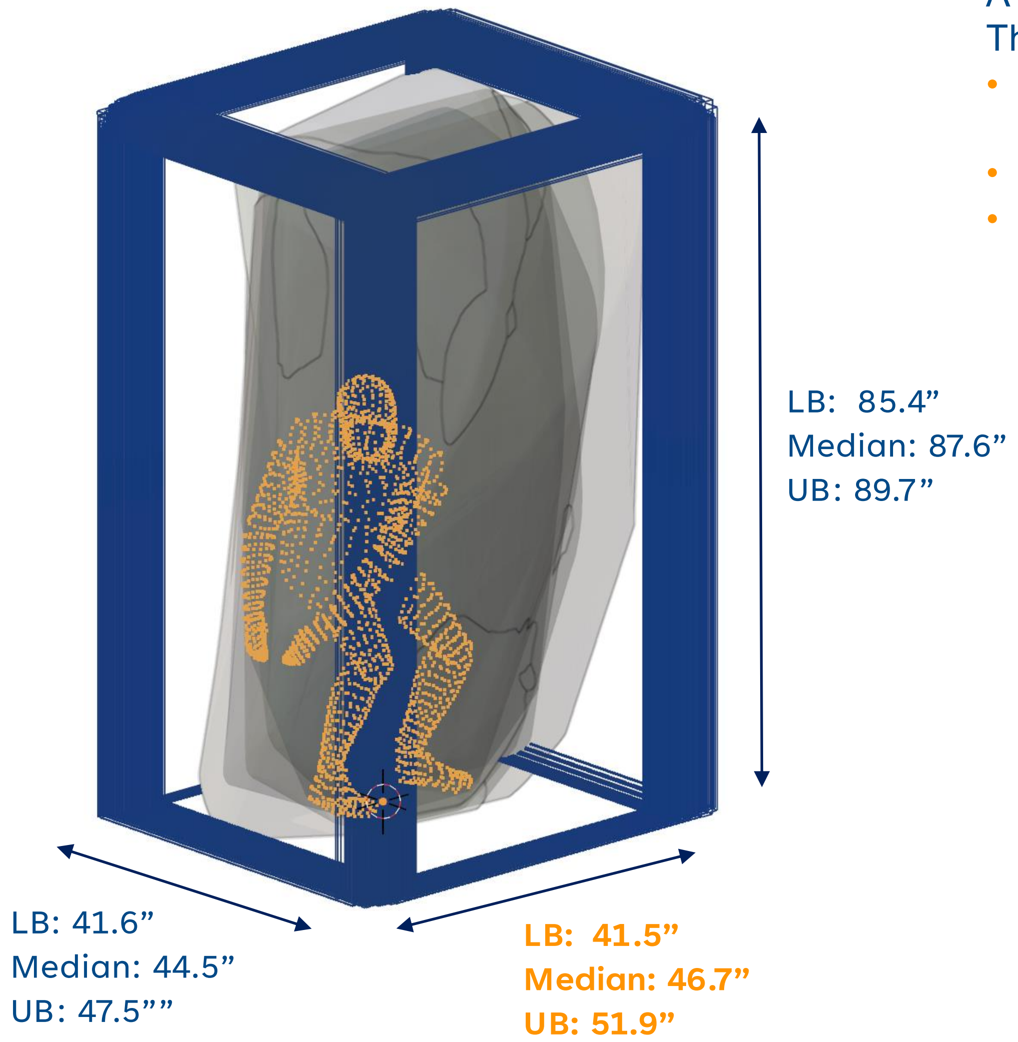


Motion Pattern and Style Variations (Cont'd)

- Sampled the volume variations across the 99th percentile extrapolated persons' exercise patterns
  - Up-down range: 86.0-90.5"
  - Fore-aft range: 42.0-47.3"
  - Left-right range: 43.0-59.3"

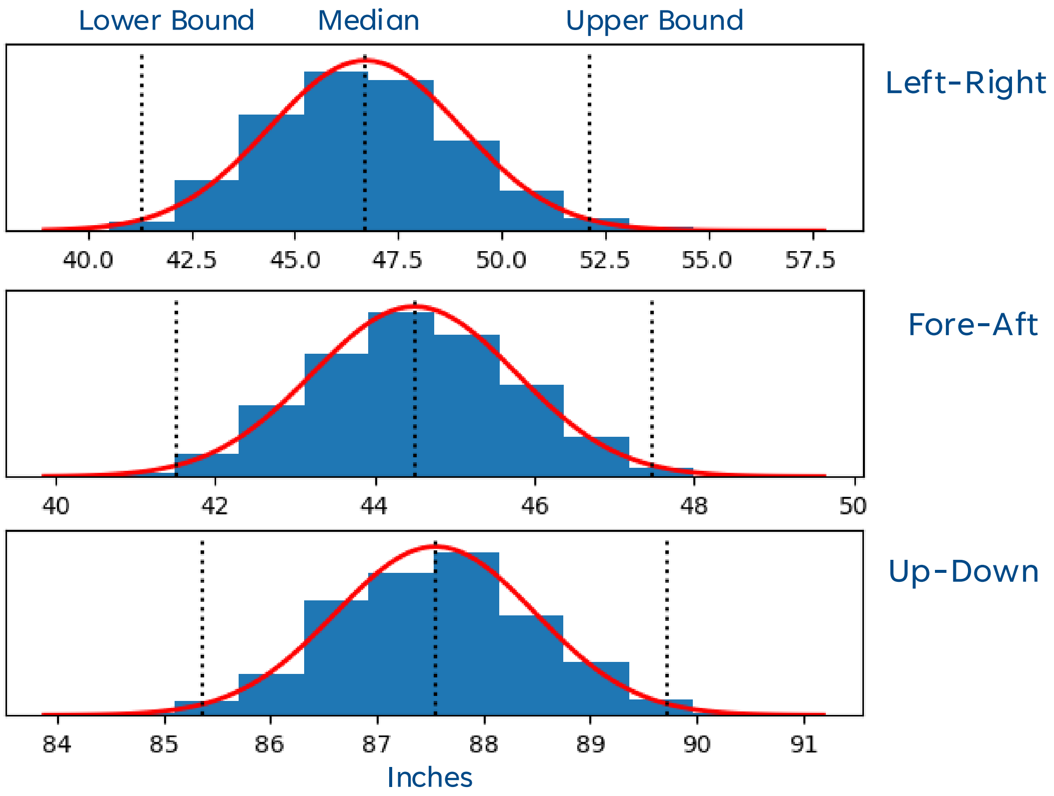


Identifying Statistical Distributions of Motion Style Variations

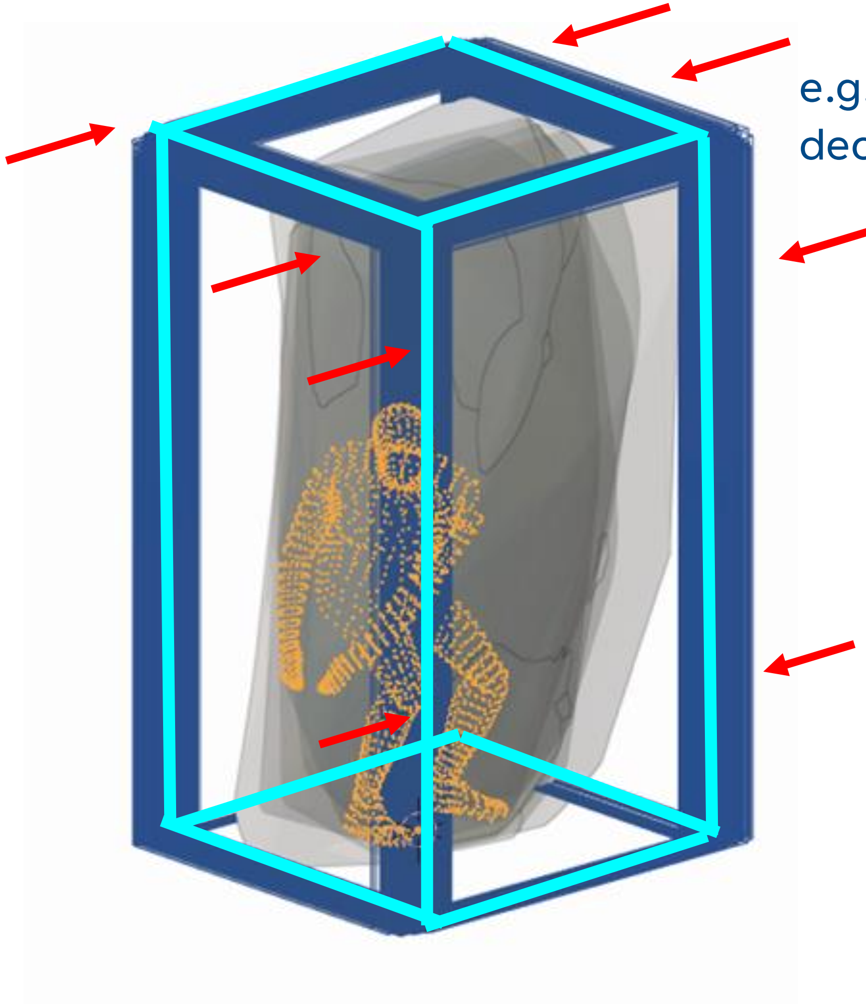


A pseudo-data distribution was estimated from data bootstrapping
The distributions indicate for left-right dimension, for example:

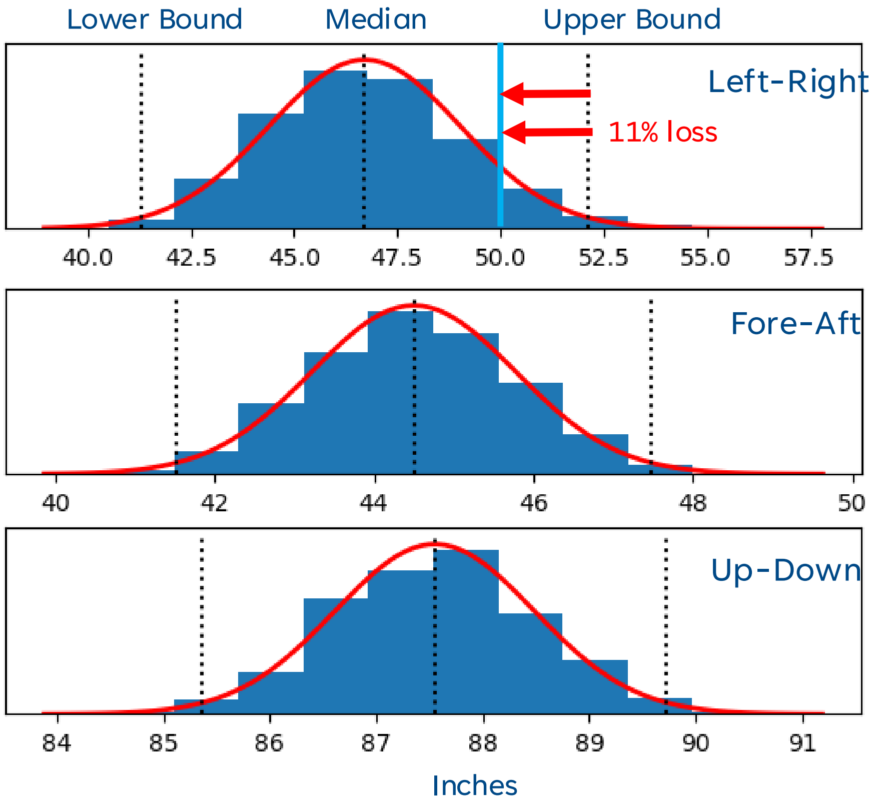
- When 51.9” (Upper Bound) was selected, 99% of motion variability shown from the tested subjects can be accommodated within the volume
- With 46.7” (Median), 50% of variability can be accommodated
- With 41.5” (Lower Bound), 1% of variability can be accommodated



Use Case: Assessing "Loss" from Decreased Exercise Volume



- Similarly, a volume reduction can be converted to the corresponding loss magnitude in motion style variations
- For example, 2.5-inch reduction in left-right dimension from the upper bound (52") can result in 11% loss. In other words, 11% of **different motion patterns** may not be accommodated



Exercise Volume: Proposed Requirement Upgrade (Option B: Lower & Upper Bounds)

Exercise Type	Left-Right		Fore-Aft		Up-Down	
	Lower Bound	Upper Bound	LB	UB	LB	UB
Rowing	30.6	33.3	66.6	77.9	44.3	49.5
Lat Pulldown	38.9	40.7	15.0	18.5	89.3	90.3
Squat - Bar	33.8	38.4	24.7	32.0	76.3	77.0
Shoulder Press - Bar	35.2	37.2	17.3	19.7	89.0	90.3
Deadlift - Bar	27.7	30.6	33.3	37.6	77.5	80.0
Upward Wood Chops - Handles	41.5	51.9	41.5	47.5	85.3	89.8
Kettlebell Swings - Handles	25.8	31.4	42.3	46.1	77.5	81.6
Bench Press - Bar + bench	34.1	36.3	57.4	63.6	45.8	52.2
Crunches - bench	26.1	33.5	58.5	69.0	26.6	38.3
Cycling - seat at lowest position	26.9	32.7	52.3	65.2	49.5	54.5
Treadmill Walking	26.8	30.8	44.1	47.9	75.6	77.4
Treadmill Running	30.4	32.7	43.5	49.2	75.3	79.1

Option A (binary threshold) provides upper bounds only

Option B (continuous scale) provides both lower and upper bounds

Unit: inches

Discussion & Conclusion

- Exercise volumes were assessed from different exercise types
  - Motion data were augmented by the subject's 3D body scan
- Estimated volumes were extrapolated for a 99th percentile person
  - Statistical body shape model was used to ensure crew population accommodation
- Motion patterns and style variations were incorporated to calculate:
  - Option A: Upper bound only (aka "worst case scenario) exercise volume
  - Option B: Upper and lower bounds, with a loss function for volume decrease
- While Option A can provide a baseline dataset, Option B can further provide a quantitatively guided approach for requirement waiver

Acknowledgement

This work was supported by NASA Human Health and Performance Contract 2 (80JSC025D0068)

With appreciation to:

NASA Exercise Physiology Laboratory

NASA Center for Design and Space Architecture

Approved for release (NASA STRIVES 20260001669, HHPC PubPress 1708)

OPTIMIZING EARCUP FIT AND SIZING FOR U.S. ARMY HEARING PROTECTION

U.S. ARMY/NASA COLLABORATIVE RESEARCH

A data-driven framework for translating ear morphology into earcup design guidance

24 MARCH 2026

Hyegjoo E. Choi-Rokas, Robin L. Carufel, Peng Li, Todd N. Garlie, K. Blake Mitchell (U.S. Army DEVCOM Soldier Center)
K. Han Kim (Leidos, Inc), Michael Schlittenhart (GeoControl Systems, Inc.) Joseph Yao, Yaritza Hernandez, Nathaniel Newby (KBR, Inc.)

RESEARCH FUNDING
U.S. Army DEVCOM Soldier Center Research Program **19-117**
U.S. Army and NASA Inter-Agency Agreement **A97EHF5M02324E9** / **F5M0097EH22E004**

THE PROBLEM

HEARING LOSS: A CRITICAL MILITARY HEALTH RISK

Hearing loss is among the most prevalent occupational health concerns in the military — affecting **~1.7% of active duty** and **~10% of National Guard and Reserve** members.

Hazardous noise from firearms, explosions, aircraft, and machinery places Soldiers at risk for permanent auditory damage, reduced situational awareness, and mission degradation.

Fewer than **35%** of Soldiers report using hearing protection 75–100% of the time during noise exposure.

WHY ONE-SIZE-FITS-ALL FAILS

DISCOMFORT

Poor fit creates pressure hotspots and device rejection during extended wear.

ACOUSTIC LEAKAGE

Inadequate seals compromise attenuation, reducing protective effectiveness.

NON-COMPLIANCE

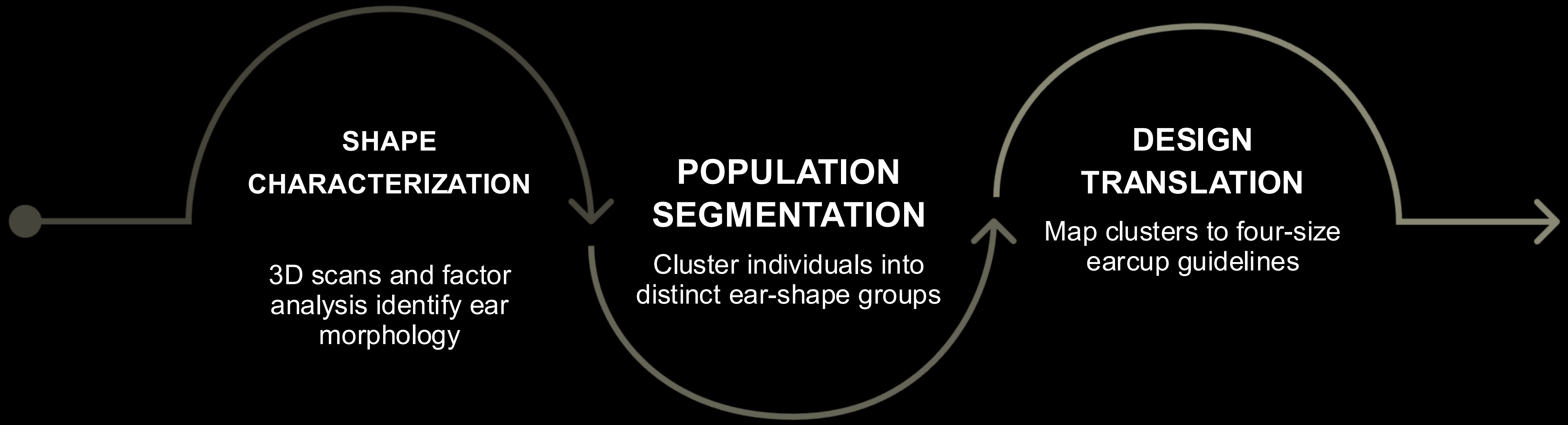
Discomfort and perceived interference with communication drive Soldiers to remove hearing protection devices (HPDs).

MORPHOLOGICAL DIVERSITY

Ear size, shape, and curvature vary significantly across the Army population.

STUDY OBJECTIVE

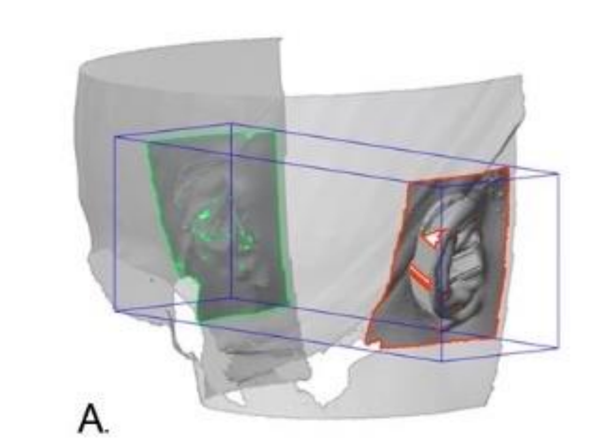
A DATA-DRIVEN FRAMEWORK FOR EARCUP DESIGN

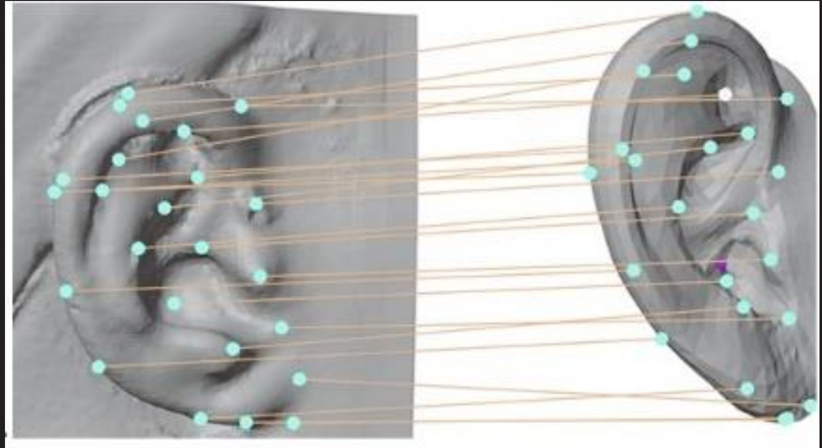


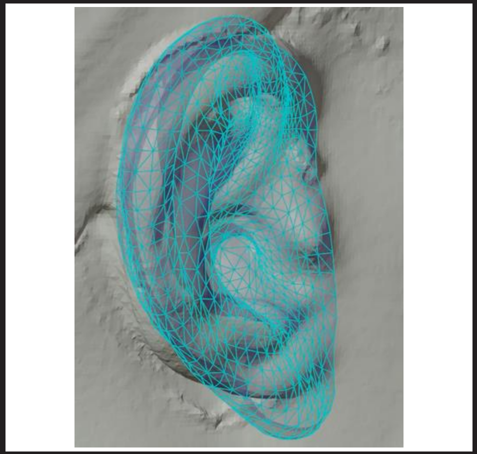
Using large-scale 3D ear scans from ANSUR II (2,910 Soldiers), this study integrates statistical shape analysis with military-relevant design considerations to develop fit and sizing recommendations for earcup-style hearing protection device (HPD).

EAR DATA DEVELOPMENT

A subset of the 2012 ANSUR II 3D head database — **1,730 males and 1,384 females** — underwent template matching to create homologous ear structures. Raw scans were cropped, aligned, and registered to a high-resolution template mesh, enabling dense point-to-point correspondence while preserving surface curvature.







15 ear dimensions were selected for analysis from a review of 35 literature sources. Dimensions related to the deep concha bowl were excluded due to scan quality limitations and design irrelevance for earcup interfaces. Measurements were extracted automatically via point-to-point correspondences from the homologically structured meshes.

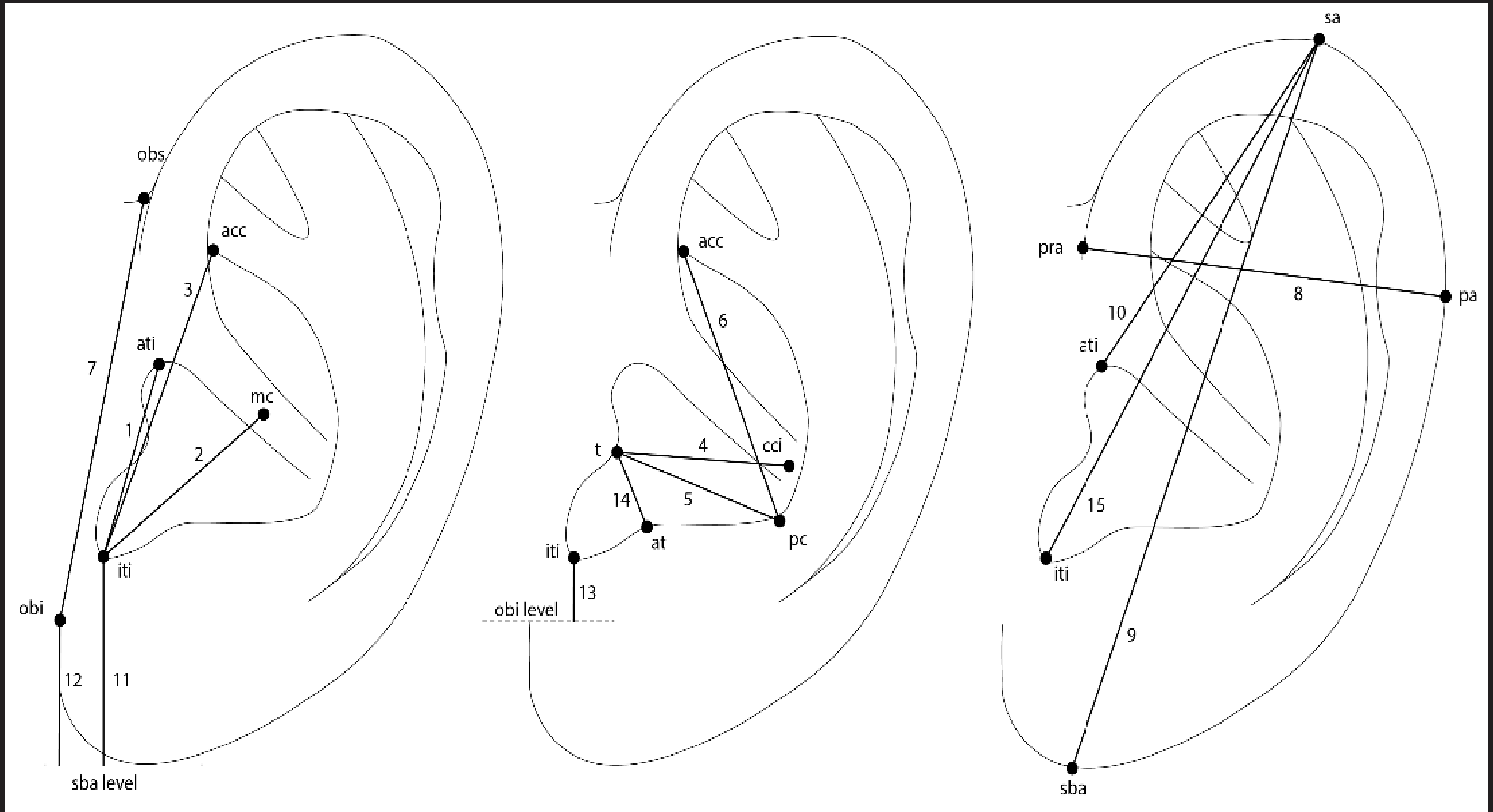
THE 15 EAR DIMENSIONS ANALYZED

LENGTH DIMENSIONS

- Ear Length (9) & Ear Cartilage Length (15)
- Upper Ear Length (10)
- Concha Length (3) & Cavum Concha Length (2)
- Tragus Length (1)
- Lobe Length (11), Attached Lobe Length (13) & Detached Lobe Length (12)
- Ear Attachment Length (7)

WIDTH DIMENSIONS

- Ear Breadth (8)
- Concha Width (5) & Cavum Concha Width (4)
- Cymba Concha Width (6)
- Intertragic Incisure Width (14)



ANALYTICAL METHOD

EXPLORATORY FACTOR ANALYSIS (EFA)

Exploratory factor analysis was carried out to uncover underlying structural relationships of the measurements

5

FACTORS EXTRACTED

Consistent across male, female, and combined datasets

77.6%

VARIANCE EXPLAINED

Combined dataset
(76.6% male alone; 77.2% female alone)

.630

Kaiser-Meyer-Olkin Test

Variables are sufficiently correlated to justify a factor analysis

FIVE MORPHOLOGICAL FACTORS OF THE EAR

FACTOR 1: EAR HEIGHT

Ear Length, Ear Breadth, Upper Ear Length, Ear Cartilage Length — overall size of the ear

FACTOR 2: CONCHAL LENGTH

Tragus Length, Cavum Concha Length, Concha Length — lengths from the intertragic incisure

FACTOR 3: LOBE/ATTACHMENT

Attached Lobe Length, Ear Attachment Length, Lobe Length — lobe and attachment region

FACTOR 4: LOWER CONCHAL WIDTH

Cavum Concha Width, Intertragic Incisure Width — widths from the tragus

FACTOR 5: UPPER CONCHAL WIDTH

Cymba Concha Width, Concha Width — upper conchal region widths

The five-factor structure was **consistent across male, female, and combined datasets**, with only minor reordering based on variance explained — confirming robustness irrespective of sex.

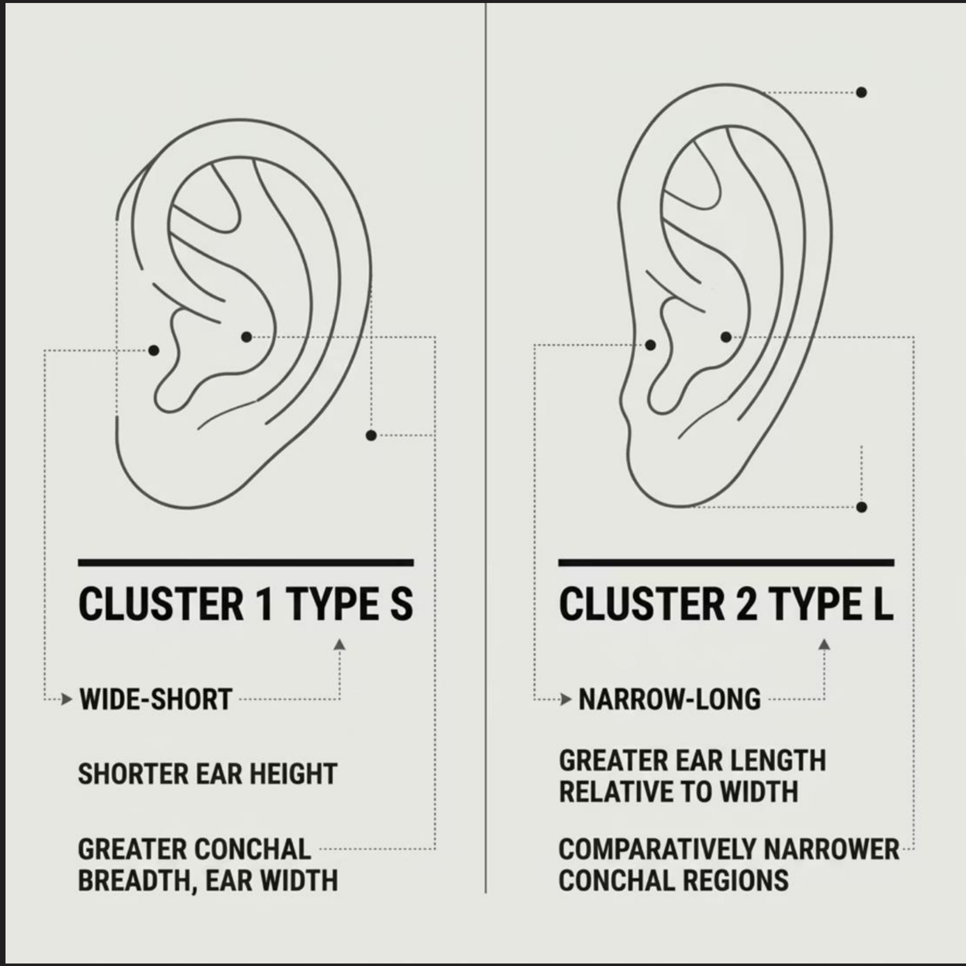
CLUSTER ANALYSIS

SEGMENTING EAR MORPHOLOGY WITH K-MEANS CLUSTERING

K-means clustering was applied to standardized factor scores. Solutions of $k = 2$, 3, and 4 clusters were evaluated using the ratio of between-cluster dispersion and within-cluster dispersion (Calinski–Harabasz index).

Although the three-cluster solution produced the highest ratio index, it primarily subdivided one cluster along secondary dimensions without introducing a distinct morphological category relevant to earcup sizing.

> The **two-cluster solution** was retained for greater parsimony and clearer morphological interpretation relevant to practical sizing.



TWO DOMINANT EAR SHAPE TYPES

TYPE S — WIDE–SHORT

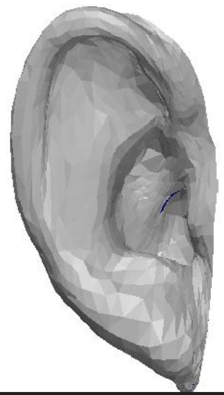
Shorter ear height with relatively greater conchal breadth and ear width. Larger Cavum Concha Width (~15–16 mm vs. 13 mm).

Female: n = 541

Male: n = 825

Female: n = 649

Male: n = 895



TYPE L — NARROW–LONG

Greater ear length relative to width, with comparatively narrower conchal regions. Larger Ear Cartilage Length (~46 mm vs. 44 mm).

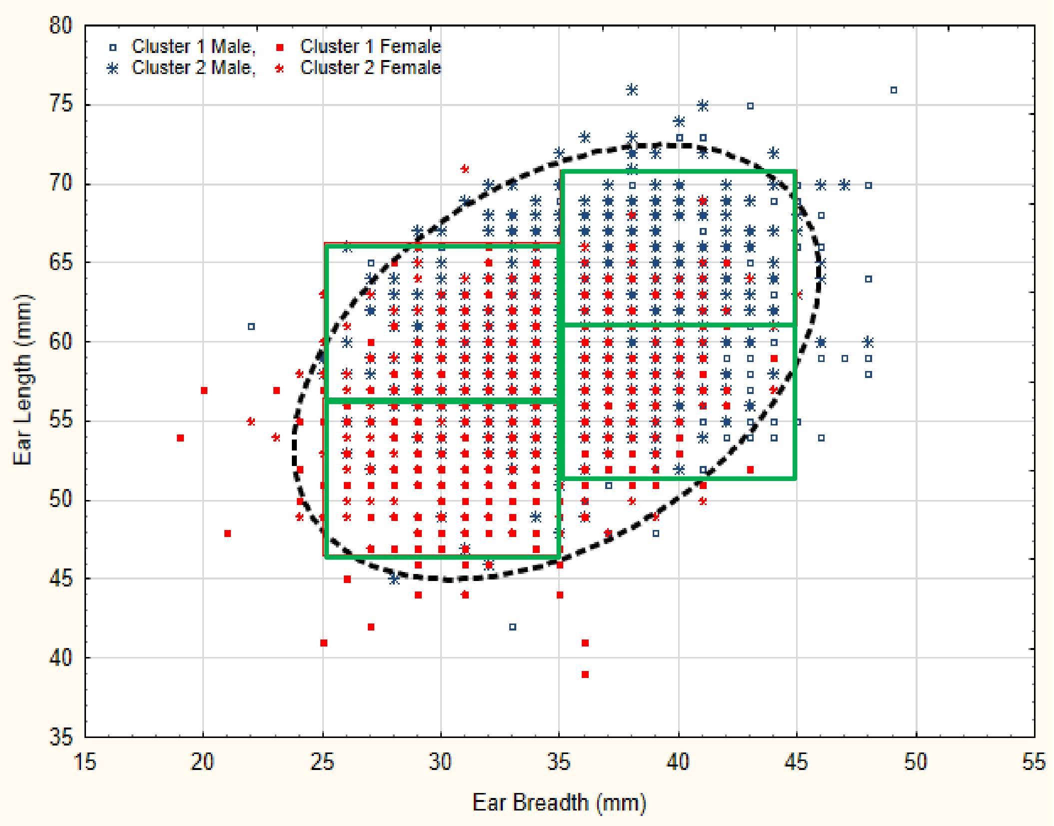
Clusters reflect **proportional differences** in length-to-width relationships — not purely absolute size. Mean differences between clusters were ≤ 2 mm, within allowable measurement error.

DEFINING THE ACCOMMODATION ENVELOPE

The joint distribution of **Ear Breadth (EB)** and **Ear Length (EL)** was modeled using a **98% bivariate tolerance ellipse** — the standard accommodation level for military equipment design.

- 98% ellipse spans **>20 mm** in Ear Breadth
- 98% ellipse spans **>25 mm** in Ear Length
- Sizing bucket dimension: **±5 mm** per size (10 mm total), aligned with Just Noticeable Difference (JND) principles

Users can perceive tactile fit differences as small as **±5 mm** (Ashdown & DeLong, 1995) — confirming this tolerance is meaningful for user experience.



DESIGN OUTPUT

A FOUR-SIZE EARCUP FRAMEWORK

The EB–EL design space was partitioned into **two breadth classes × two length classes**, yielding four sizes that collectively accommodate nearly the entire target population.

Size	Width (mm)	Length (mm)	Profile
Narrow–Short	30	51	Type L, smaller
Narrow–Long	30	61	Type L, larger
Wide–Short	40	56	Type S, smaller
Wide–Long	40	66	Type S, larger

WHY FOUR SIZES BEAT ONE

FROM SINGLE-SIZE TO MULTIPLE SIZE SCHEME

A single earcup cannot span the 20+ mm breadth and 25+ mm length range of the population. The four-size system:

- Improves **acoustic sealing** by matching cup geometry to ear shape
- Reduces **pressure hotspots** and discomfort
- Increases **compliance** through better fit and comfort
- Maintains **practical feasibility** for manufacturing

BROADER IMPLICATIONS

BEYOND HEARING PROTECTION

PPE INTEGRATION

Framework supports helmets, communication systems, and respiratory interfaces across DoD anthropometric efforts.

DIGITAL DESIGN WORKFLOWS

Size and shape data supports CAD, digital human modeling, and virtual fit assessment — reducing reliance on physical prototyping.

CONSUMER APPLICATIONS

Methodology extends to communication headsets and consumer audio devices requiring precise ear-interface fit.

LIMITATIONS

MORPHOLOGICAL CONTINUUM

Two clusters are sufficient for earcup design with generous ease allowance, but finer shape categories may be needed for tighter-fit devices.

MEASUREMENT CONSTRAINTS

Ear protrusion, cranial orientation, and headband interactions — also influencing fit — were not fully captured by template-based measurement.

JND THRESHOLD SOURCE

Tolerance ranges were based on garment fit research, not ear-specific perceptual thresholds. Direct ear-tactile validation is needed.

BILATERAL SYMMETRY ASSUMPTION

Left and right ears were treated as symmetrical; individual-level asymmetry and its impact on fit warrants further investigation.

FUTURE RESEARCH DIRECTIONS

01

FIELD VALIDATION

Evaluate real-world fit, comfort, and performance with Soldiers under operational conditions.

02

DYNAMIC FACTORS

Incorporate movement, perspiration, and prolonged wear into evaluation protocols.

03

MULTI-SYSTEM INTEGRATION

Examine interactions between earcups and helmets, eyewear, and communication systems.

04

STANDARDS ALIGNMENT

Align with ISO/TC 159/SC 3 and IEA anthropometry standards for broader applicability.

05

ADVANCED ANALYTICS

Apply nonlinear dimensionality reduction and machine learning to refine shape classification.

CONCLUSION

This study applied **template-matched 3D ear data** and **multivariate statistical modeling** to generate actionable earcup design guidance for U.S. Army Soldiers.

TWO EAR SHAPE TYPES

Type S (Wide–Short) and Type L (Narrow–Long) — defined by proportional shape, not size alone.

FOUR-SIZE SYSTEM

Narrow-Short, Narrow-Long, Wide-Short, Wide-Long — balancing coverage with manufacturing feasibility.

IMPROVED OUTCOMES

Better fit, comfort, sealing performance, and Soldier compliance compared to one-size approaches.

ACKNOWLEDGMENT

FUNDING & SUPPORT

RESEARCH FUNDING

U.S. Army DEVCOM Soldier Center Research Program **19-117**

Partially supported by U.S. Army and NASA Inter-Agency Agreement **F5M0097EH22E004**

AUTHORS

Hyegjoo E. Choi-Rokas, Robin L. Carufel, Peng Li, Todd N. Garlie, K. Han Kim, Joseph Yao, Yaritza Hernandez, Michael Schlittenhart, Nathaniel Newby, K. Blake Mitchell

U.S. Army DEVCOM Soldier Center, Natick, MA | *Leidos Inc.* | *GeoControl, Inc. KBR Inc.*

Special thanks to the Warfighters who volunteered as ANSUR II participants.

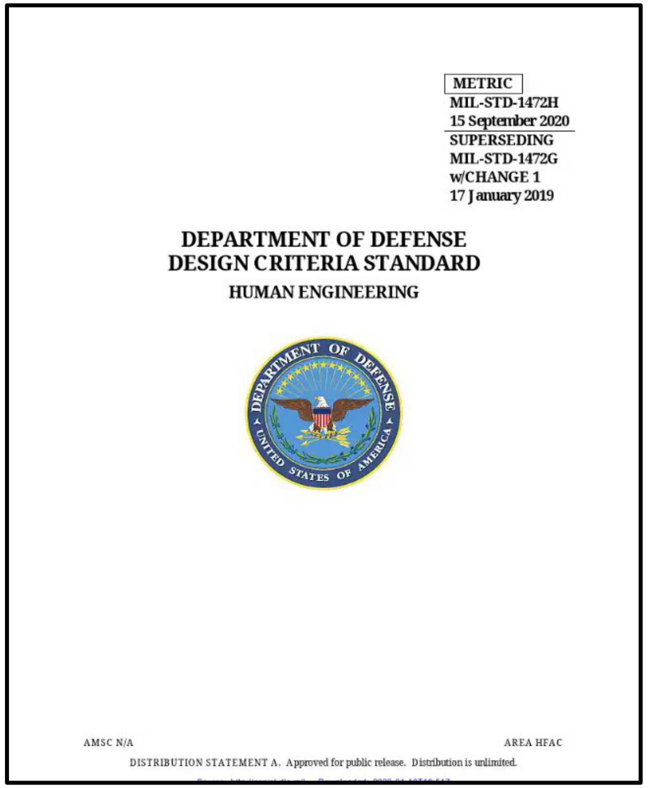
USN Aircrew Survival Vest Sizing and Fit Initiatives

24 March 2026

Lori B. Basham, CPE.
Aeromedical Research & Integration Branch
Human Systems Engineering Department (HSED)
Naval Air Warfare Center Aircraft Division (NAWCAD)
lori.l.basham2.civ@us.navy.mil

Survival Vest System (SVS) Fit & Accommodation

The SVS shall properly fit, without any degradations in mission performance or safety, the multivariate central 90% of male and the central 90% of female aircrew (T); the multivariate central 95% of male and central 95% of female aircrew (O). The multivariate accommodation shall consider the anthropometry of most importance to the system.



METRIC
MIL-STD-1472H
15 September 2020
SUPERSEDING
MIL-STD-1472G
w/CHANGE 1
17 January 2019

DEPARTMENT OF DEFENSE
DESIGN CRITERIA STANDARD
HUMAN ENGINEERING

AMSC N/A AREA HFAC

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

Multivariate Accommodation Method (MAM)

Method developed in 1992 by Air Force Research Lab (AFRL)

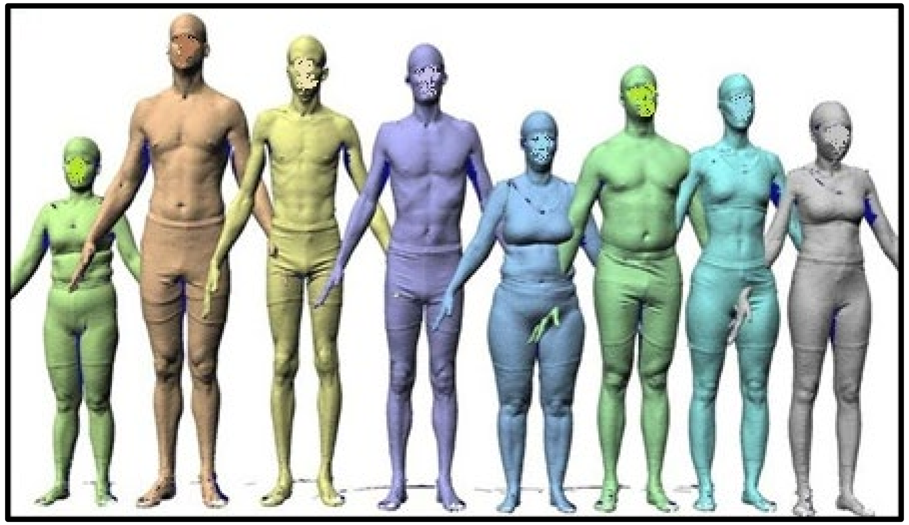
- Principal Components Analysis (PCA)
- Application relevant anthropometry considered
- Characterizes relevant combinations of body sizes and proportions for the target population
- Adopted and used in requirements specifications for DoD aircraft
- Using multivariate use case participants and modeling manikins is best practice
  - Caveat – cases used must be application appropriate

JPATS Use Cases

	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6	CASE 7
Units = inches	Small	Medium Build Short Limbs	Medium Build Long Limbs	Tall Sitting Height Short Limbs	Overall Large	Longest Limbs	Overall Small
Thumb Tip Reach	27.0	27.6	33.9	29.7	35.6	36.0	26.1
Buttock-knee Length	21.3	21.3	26.5	22.7	27.4	27.9	20.8
Knee-height Sitting	18.7	19.1	23.3	20.6	24.7	24.8	18.1
Sitting Height	32.8	35.5	34.9	38.5	40.0	38.0	31.0
Eye Height Sitting	28.0	30.7	30.2	33.4	35.0	32.9	26.8
Shoulder Height Sitting	20.6	22.7	22.6	25.2	26.9	25.0	19.5

JPATS Case 7 and 5 Participants

Example of Use Case Nearest Neighbor Participant Scans



SVS Multivariate Use Case Development

Measurements selected based on literature review, team discussions, & SME advice

Cases represent central 90% of men and 90% of women per program requirements

- MIL-STD-1472H threshold

Principal component analysis (PCA) initially run on 2012 Army Anthropometric Survey

- PCA rerun on combined USN Aircrew and Aviator databases

Three principal components (PCs) used

- Number of resulting use cases in keeping with precedent of other acquisition programs
  - SVS: (8 Cases), T-6 (7 Cases), F-35/CH-53K (8 Cases)
- Variability accounted for in line with other acquisition programs and best practices
  - SVS: (88% variability), F-35/T-6/CH-53K (89% variability)
- Accounting for more variability by adding additional PCs is not recommended
  - Exponentially increases number of use cases, not best practice
- Reducing # of PCs accounts for less variability (80.4%) and is not recommended
  - Design may not take into account long/short torso vs. top heavy/bottom heavy variability

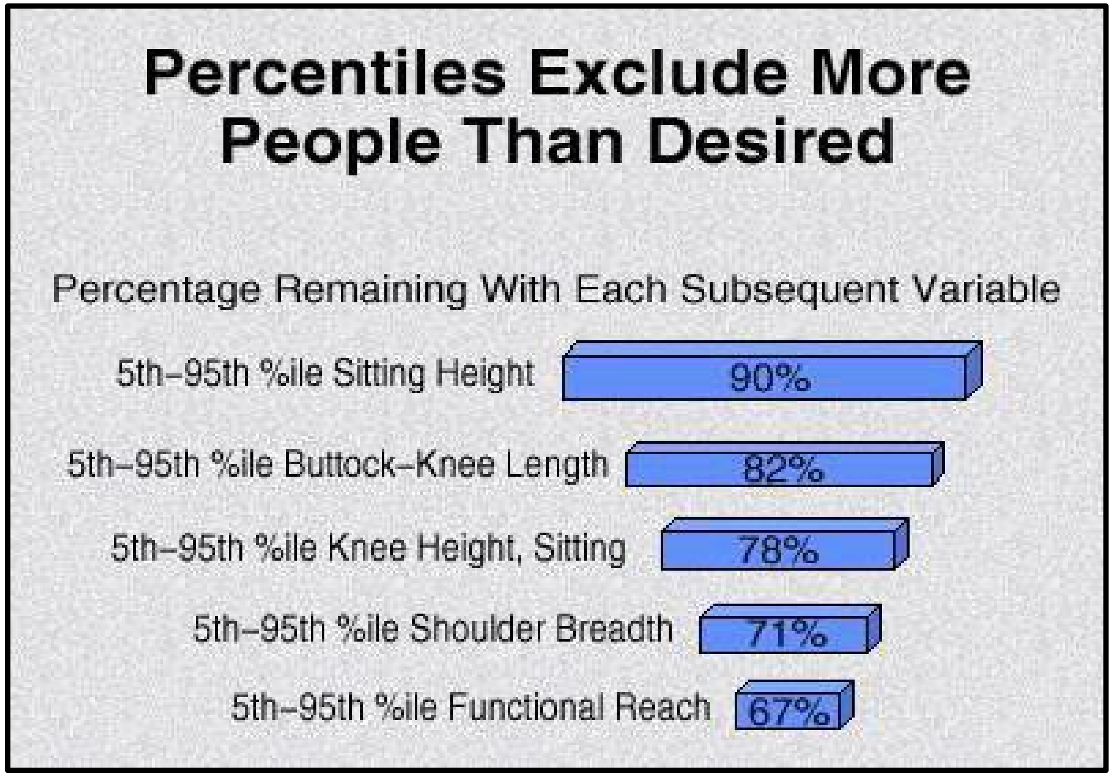
SVS Multivariate Use Case Development

Significant improvement to univariate percentile approach

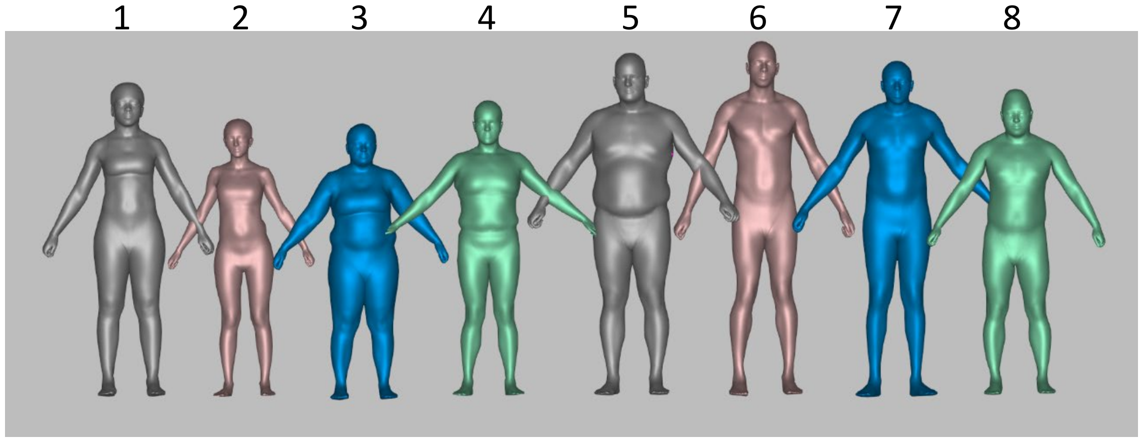
- Percentile based approach for SVS measurements yields only 54.4% female accommodation
- Percentile based approach for SVS measurements yields only 50.1% male accommodation

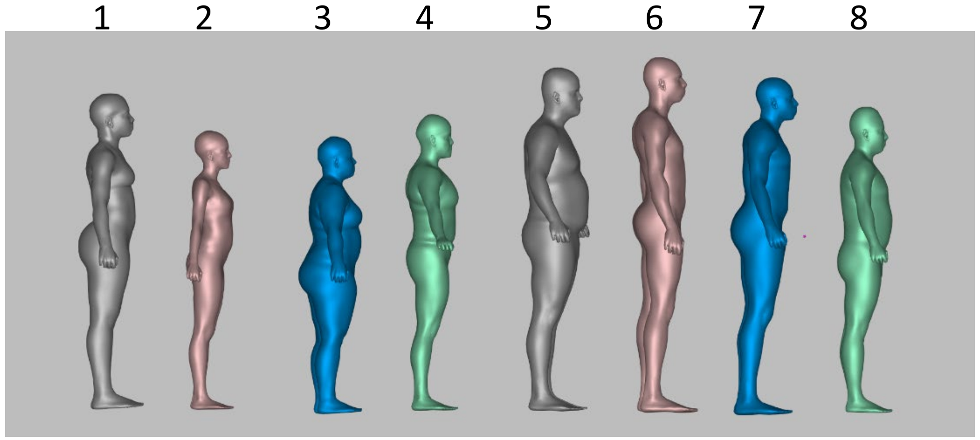
Nearest neighbor analysis

- Body scans and full anthropometry of personnel in US Army database that are best matches for SVS cases
- Comparison made to previous vest fit-check participants and Aircrew Anthropometry Study participants to support participant selection at upcoming fit-testing
- Body scans of Nearest Neighbors provided to designers for use in Gerber software



SVS Multivariate Use Cases





	Females				Males			
	1	2	3	4	5	6	7	8
	Short torso in proportion to height, larger hips/thighs	Overall small	Short and stout	Long torso in proportion to height, larger waist/chest	Overall large	Long and slim	Short torso in proportion to height, larger hips/thighs	Long torso in proportion to height, larger waist/chest
buttock circumference	42.02	33.59	42.42	38.39	47.13	38.03	41.37	38.90
cervicale height	57.56	51.77	51.09	52.34	63.13	63.97	62.57	56.90
chest circumference	35.86	30.44	39.52	38.70	49.33	39.21	41.21	42.15
thigh circumference	25.72	19.66	26.21	22.79	29.61	22.45	25.73	23.49
vertical trunk circumference	62.48	54.70	60.30	60.31	73.82	66.72	66.02	65.07
waistbacklength	16.12	14.89	15.61	17.38	20.81	20.08	18.46	19.14
waist circumference	31.88	25.31	36.61	35.91	47.07	33.90	35.69	38.37
waist front length sitting	12.94	12.33	13.21	15.03	17.31	16.32	13.76	16.76

Aid for Fit-test Participant Initial Screening – NOT FOR REQUIREMENTS DOCUMENTS								
Estimated stature	66.94	60.99	59.87	61.72	72.12	73.46	72.23	66.57
Estimated weight	157.2606	100.7244	156.2022	141.4287	271.0827	177.9876	197.3916	179.928

References

Arteau, J., Patron Gomez, H. E., & Beauregard, Y. (2018). Anthropometry and selection of full body harness: beyond stature and body mass as selection criteria.

Brisbine, B. R., Radcliffe, C. R., Jones, M. L. H., Stirling, L., & Coltman, C. E. (2022). Does the fit of personal protective equipment affect functional performance? A systematic review across occupational domains. *PLOS ONE*, *17*(11), e0278174.

Choi, H., Coate, A., Selby, M., Hudson, J., Whitehead, C., Zehner, G., & Fleming, S. (2014). *Aircrew Sizing Survey 2011:* Defense Technical Information Center.

Choi, H. J., Zehner, G. F., Hudson, J. A., & Fleming, S. M. (2009). Trends in Anthropometric Measures in U.S. Air Force Aircrew Survey Data. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *53*(10), 620–624.

da Silva, G. V., Zehner, G. F., & Hudson, J. A. (2020). Comparison of univariate and multivariate anthropometric design requirements methods for flight deck design application. *Ergonomics*, *63*(9), 1133–1149.

Department of Defense. (2020). *Department of Defense Design Criteria Standard: Human Engineering* (MIL-STD-1472H).

Department of Defense. (1998, October 30). *Joint Service Specification Guide: Cockpit/Crew Station/Cabin Handbook* (JSSG-2010-3).

Department of Defense. (1998, October 30). *Joint Service Specification Guide: Crew Systems Personal Protective Equipment Handbook* (JSSG-2010-9).

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., Corner, B. D., Carson, J. M., Venezia, J. C., Rockwell, B. M., Mucher, M., & Kristensen, S. (2015). *2012 Anthropometric survey of U.S. Army personnel: Methods and summary statistics* (Report No. NATICK/TR-15/007). Army Natick Soldier Research, Development and Engineering Center.

Hsiao, H. (2013). Anthropometric Procedures for Protective Equipment Sizing and Design. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(1), 6–35.

Hsiao, H., Bradtmiller, B., & Whitestone, J. (2003). Sizing and fit of fall-protection harnesses. *Ergonomics*, *46*(12), 1233–1258.

Hsiao, H., Friess, M., Bradtmiller, B., & Rohlf, F. J. (2009). Development of sizing structure for fall arrest harness design. *Ergonomics*, *52*(9), 1128–1143.

Hsiao, H., Kau, T.-Y., & Bradtmiller, B. (2024). A cluster-based law enforcement body armor sizing system: Concept, procedure, and design practice. *Applied Ergonomics*, *117*, 104201

Hsiao, H., Turner, N., Whisler, R., & Zwiener, J. (2012). Impact of Harness Fit on Suspension Tolerance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *54*(3), 346–357.

Hsiao, H., Whitestone, J., & Kau, T.-Y. (2007). Evaluation of Fall Arrest Harness Sizing Schemes. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *49*(3), 447–464.

Hsiao, H., Whitestone, J., Taylor, S., Godby, M., & Guan, J. (2009). Harness Sizing and Strap Length Configurations. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *51*(4), 497–518.

Hudson, J. A., Zehner, G. F., Parakkat, J., & Choi, H. J. (2006). *A Methodology for Evaluating Advanced Operator Workstation Accommodation:* Defense Technical Information Center.

Human Factors and Ergonomics Society, HFES 300 Committee. (2004). *Guidelines for using anthropometric data in product design*. Santa Monica, CA: Human Factors and Ergonomics Society.

Li, P., Corner, B., & Paquette, S. (2015). Shape analysis of female torsos based on discrete cosine transform. *International Journal of Clothing Science and Technology*, *27*(5), 677–691.

Li, P., & Mitchell, K. B. (2023). A shape classification scheme for female torso. *Applied Ergonomics*, *106*, 103904.

U.S. Department of the Navy, Office of the Chief of Naval Operations. (2025). *Anthropometric Accommodations in Naval Aircraft* (OPNAVINST 3710.37B).

Zehner, G.F., Meindl, R.S., and Hudson, J.A. (1993). *A Multivariate Anthropometric Method for Crew Stations Design.* Technical Report AL-TR-1992-0164. Wright Patterson Air Force Base, OH: Armstrong Laboratory, Air Force Systems Command

Survival Vest System (SVS) Fleet Visit
(September 2025)

	Males	Females	Both
Aircrew	56	6	62
Aviator	33	18	51
AMSO/Flight Surgeon	2	5	7
MH-53E	10	2	12
MH-60R	9	7	16
MH-60S	60	16	76
MV-22	12	4	16
Age ≤ 20	1	0	1
Age 21-25	26	5	31
Age 26-30	37	13	50
Age 31-40	24	11	35
Age ≥ 41	3	0	3
American Indian/Alaskan Native	1	1	2
Asian	2	0	2
Black	5	0	5
Hispanic	15	1	16
Pacific Islander	0	1	1
White	68	26	94
Total	91	29	120

- Sites
  - NAS Norfolk, VA
    - HSC-5, HSM-15, HSC-7, HSC-26, HSC-2, HSC-11, HSC-28
  - NAS North Island
    - HSM-78, HSM-49, VRM-50, VRM-30
- Provided participant recruitment requests in advance
- Aeromedical Safety Officer (AMSO) & Equipment Specialist (PR) feedback
- **Issues with vest and armor availability in needed sizes a common theme across squadrons**

Fleet Fit Check Anthropometry

- 26 Measurements collected
  - Armor and vest proposed sizing measurements
  - Cockpit accommodation measurements
  - Derived neck measurement from Tragion Top-of-Head
  - Info passed on from retiring product development SME
  - Literature review & SME consult
  - Multivariate use cases

- All measurers trained anthropometrists
- Participants provided soffe shorts/sports bras
- PassFit Scan collected
  - Additional predicted anthropometry

Weight
Thumbtip Reach
Stature
Cervicale Height
Chest Breadth
Thelion-Thelion Breadth
Sitting Height
Eye Height Sitting
Buttock-Knee Length
Knee Height Sitting
Biacromial Breadth
Chest Depth
Tragion Top-of-Head
Waist Front Length, Sitting
Neck Circumference
Strap Length
Shoulder Length
Chest Circumference
Chest Circumference, Underbust
Waist Circumference, Natural
Waist Circumference, Omphalion
Buttock Circumference
Thigh Circumference
Vertical Trunk Circumference
Trochanter-Crotch Circumference
Waist Back Length

Fit Check Anthropometric Variation

- Identification of “nearest neighbors” of SVS multivariate use cases
  - Prior to fit-check ran comparison against Aircrew Anthropometry Survey participants
    - Only participants who had consented to being contacted for future studies were emailed for interest/availability
  - Entered participant anthro into spreadsheet – conditional formatting quickly identified matches
- Considered univariate anthro ranges of participants for Case 2 & 5

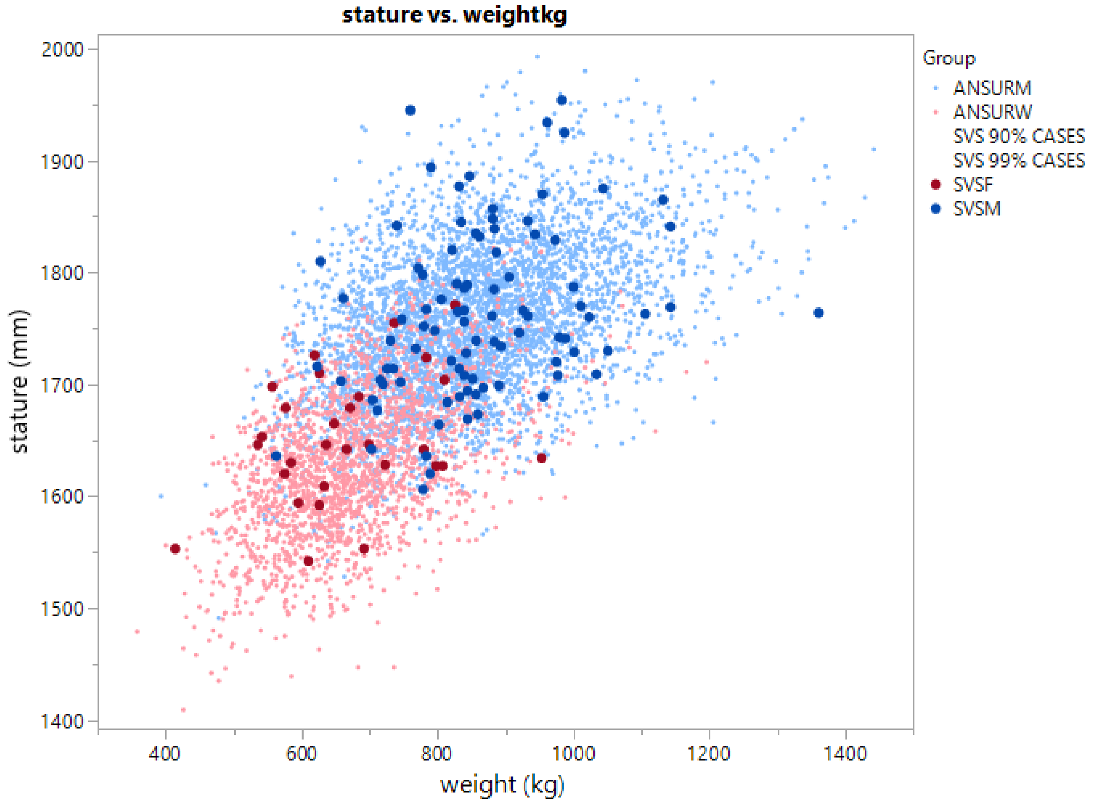
Participant “Nearest Neighbors”

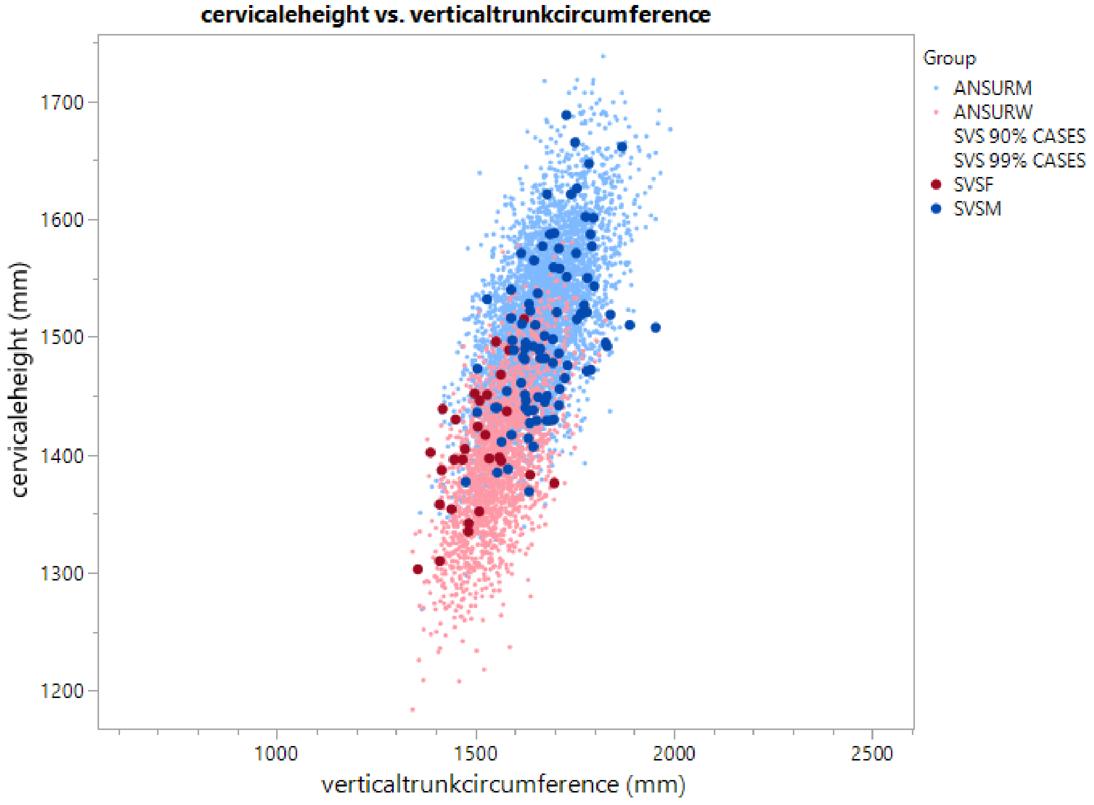
Case 1/Case 1 Partial	2, 4
Case 2/Case 2 Partial	0, 0
Case 3/Case 3 Partial	0, 3
Case 4/Case 4 Partial	1, 4
Case 5/Case 5 Partial	0, 0
Case 6/Case 6 Partial	3, 9
Case 7/Case 7 Partial	4, 9
Case 8/Case 8 Partial	2, 8

Univariate Comparison of Cases 2 and 5 with Participant Anthropometry

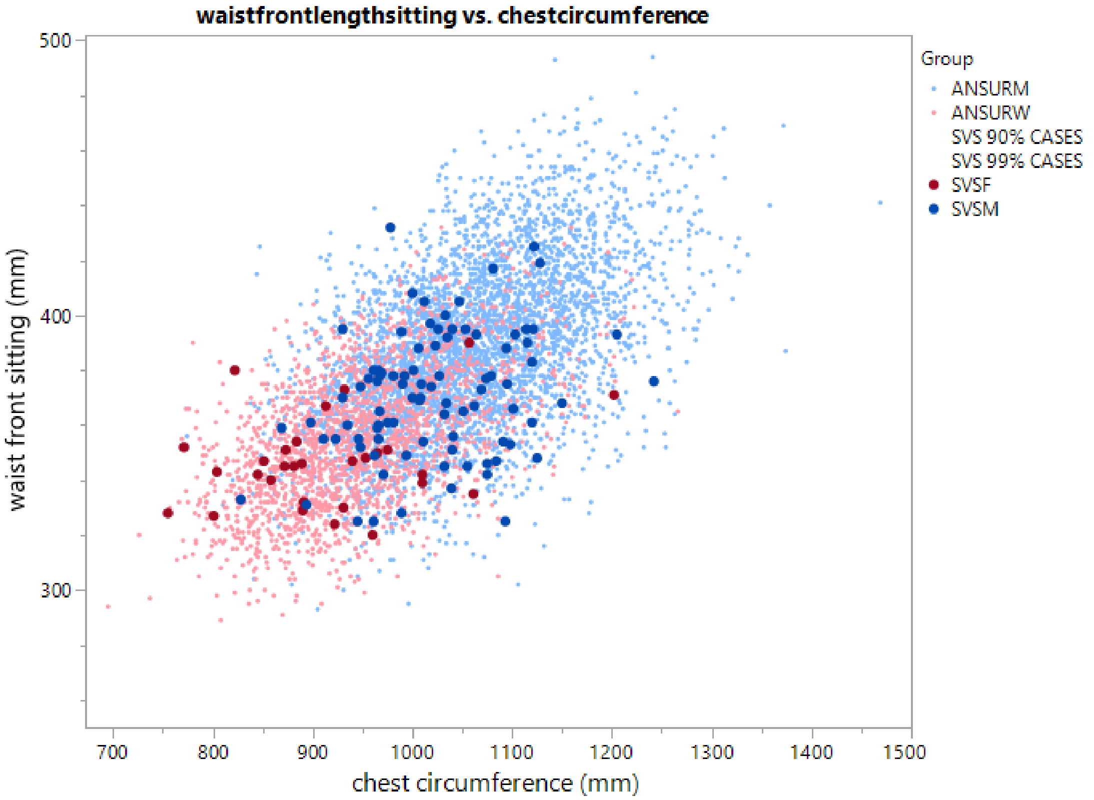
	Female Participant Minimum Measurement and Percentile	Case 2 Measurement	Case 5 Measurement	Male Participant Maximum Measurement and Percentile
Cervicale Height	51.30 (5th)	51.77	63.13	66.46 (>99th)
Buttock Circ	30.51 (<1st)	33.59	47.13	48.86 (>99th)
Waist Front Length	12.60 (7th)	12.33	17.31	17.01 (93rd)
Chest Circ	29.72 (<1st)	30.44	49.33	48.90 (98th)
Waist Circ	23.82 (<1st)	25.31	47.07	51.30 (>99th)
Thigh Circ	17.36 (<1st)	19.66	29.61	30.52 (>99th)
Vertical Trunk Circ	53.35 (<1st)	54.7	73.82	76.93 (>99th)
Waist Back Length	15.00 (4th)	14.89	20.81	20.91 (97th)

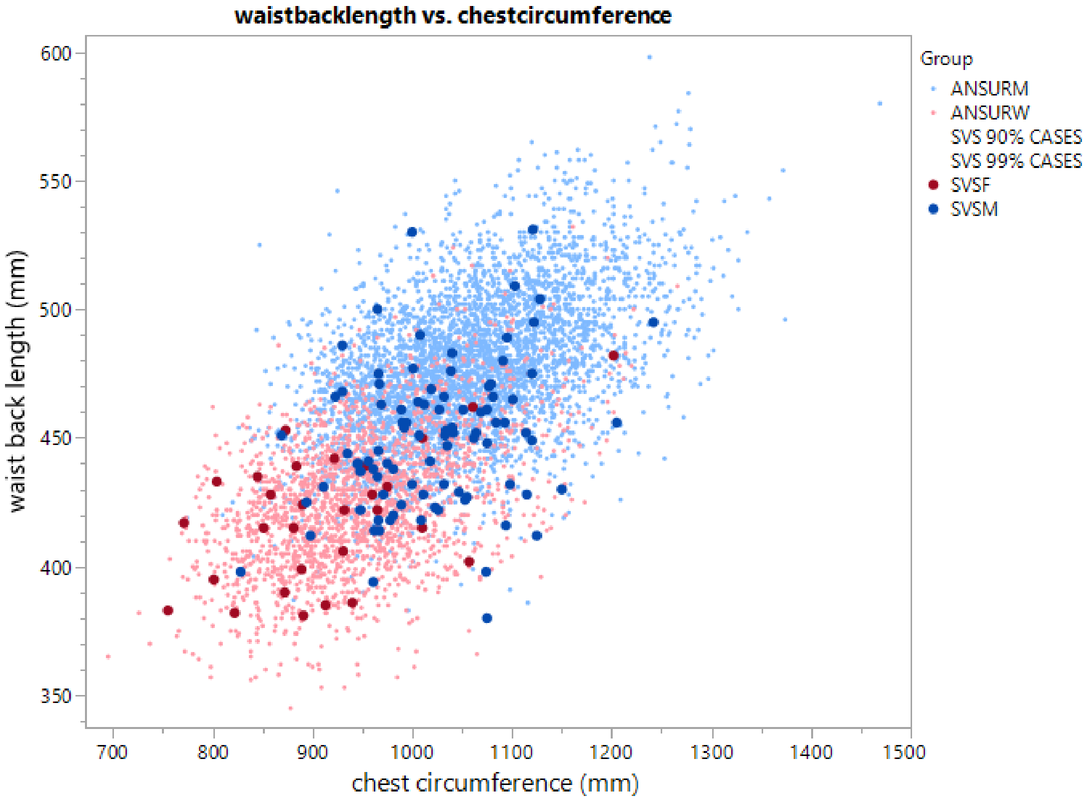
SVS Participants vs. ANSUR vs SVS Cases



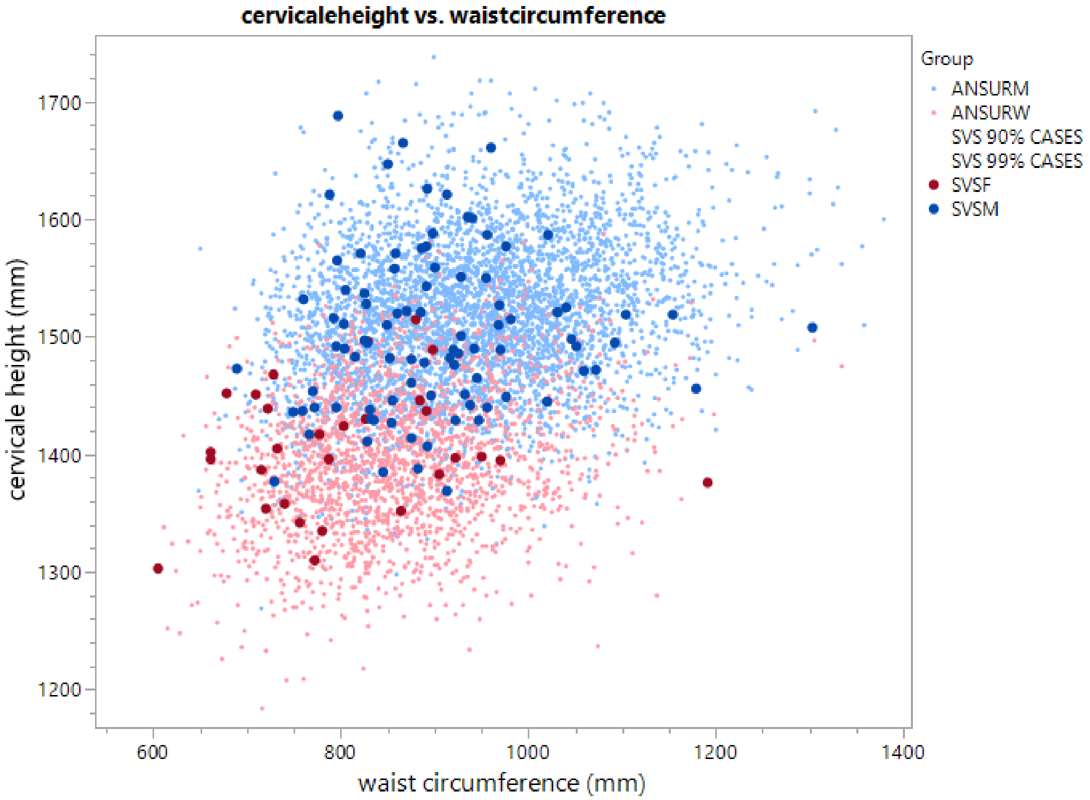


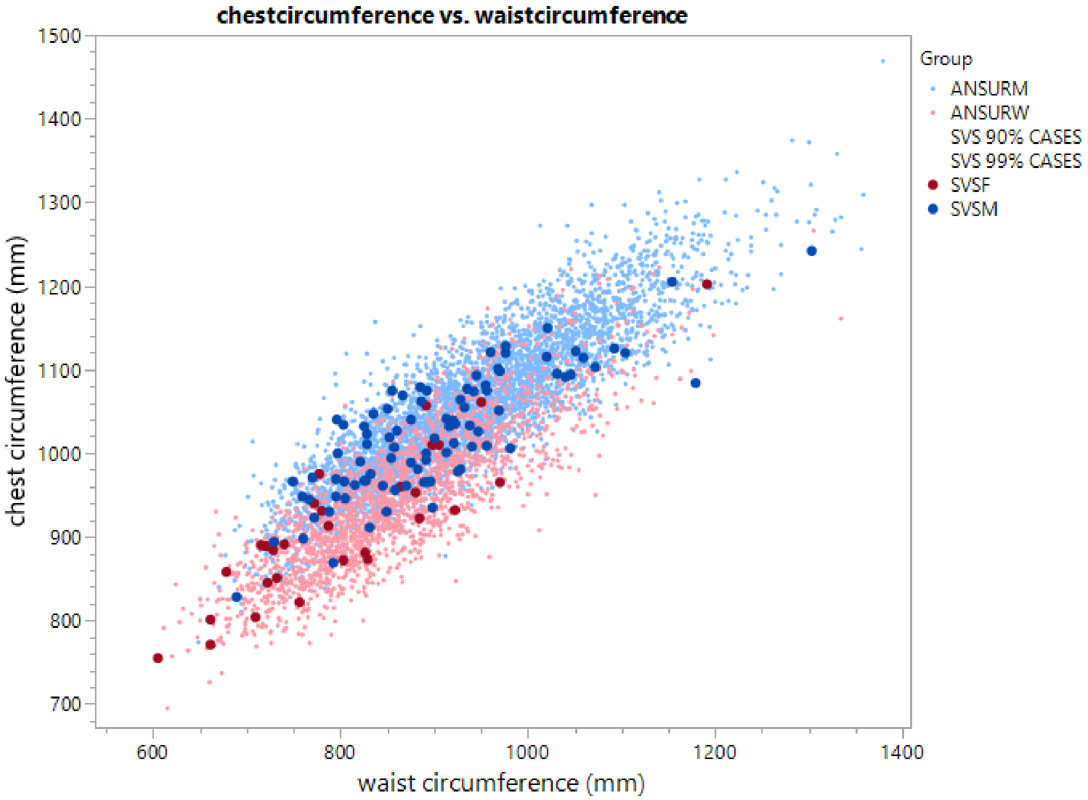
SVS Participants vs. ANSUR vs SVS Cases





SVS Participants vs. ANSUR vs SVS Cases





Fleet Fit Check Feedback Summary

FEELS GREAT

BEST PRODUCT I'VE SEEN COME THROUGH HERE EVER

GOOD RANGE OF MOTION

IS 100% BETTER

FEELS WEIGHTLESS

SLICK

COMFORTABLE

TWO THUMBS UP

MUCH BETTER THAN ALL THE OTHER VESTS I HAVE HAD

VERY SECURE

YOU GUYS CRUSHED IT

LESS BULKY VERY LIGHT

NO DISCOMFORT AT ALL

MORE COMFORTABLE THAN 33 EVEN WITH THE PLATES

FORM FITTING VERY COMFORTABLE

I COULD SIT WITH THIS FOR HOURS

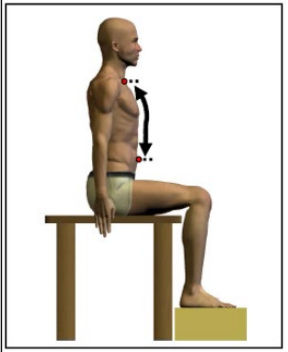
Sizing Table Evolution

- Armor size determines Front size
  - Participant best fit in XS, S, M, L, and XL plates determined
  - Participants best-fit into XS armor noted, but wore S plates and Front for fit-test
  - Participant armor fit considered minimum necessary coverage and maximum acceptable coverage
  - Other plate sizes not typically available/used
    - Making them available and integrated in SVS recommended
    - Improve/assure appropriate protection and performance (mobility, endurance)
- Other components
  - Initially used measurement range / # of planned component sizes
- Table predicted size compared to best-fit size during fit-test
  - Sizing tables and fit prediction macro updated three times
  - Shoulder sizing table would benefit from more fit-testing and/or PR feedback during flight test
    - Limited data on new size
    - Consider using strap length instead of chest circumference for sizing table

Current Sizing Tables

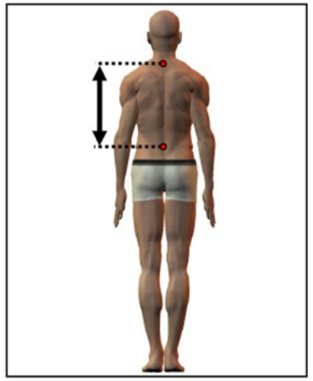
Front Size = Hard Plate Size

ESAPI/Front Plate Sizing Estimate			
	Plate dimension (in)	Thelion-Thelion (in)	Waist Front Length (in)
XS-Short	7.25x10.75	5.6-7.25	10.75-13.75
XS	7.25 x 11.5	5.6-7.25	11.5-14.5
SM-Short	8x11	6.1-8.0	11.0-14.0
SM	8.75 x 11.75	6.7-8.75	11.75-14.75
SM-Long	8x13	6.1-8.0	13.0-16.0
M	9.5 x 12.5	7.3-9.5	12.5-15.5
L	10.25 x 13.25	7.9-10.25	13.25-16.25
XL	11 x 14	8.5-11.0	14.0-17.0

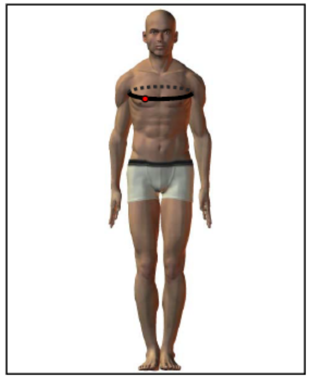


*Not all sizes are available/being used

Back Sizing Table	
	Waist-Back Length (in)
S	<16.3
M	16.3-19.5
L	>19.5



Shoulder Sizing Table	
	Chest Circumference (in)
S	<32
M	32-42
L	>42



Cummerbund

Front Size	Waist Circumference (Inches)																	
	<= 29.5	30.0	30.5	31-32.5	33.0	33.5	34 - 35.5	36.0	36.5	37 - 38.5	39.0	39.5	40 - 41.5	42.0	42.5	43 - 44.5	45.0	45.5	>= 46
XS/S	XS	XS/S	XS/S	XS/S	S	S	S	S/M	S/M	S/M	M	M	M	M/L	M/L	M/L	L	L	L
M	XS	XS	XS/S	XS/S	XS/S	S	S	S	S/M	S/M	S/M	M	M	M	M/L	M/L	M/L	L	L
L	XS	XS	XS	XS/S	XS/S	XS/S	S	S	S	S/M	S/M	S/M	M	M	M	M/L	M/L	M/L	L

SVS Tariff

- Based on USN aircrew matched database

SVS Front				
	# of Women	% of Women	# of Men	% of Men
XS	148	16.61%	64	2%
SM	543	60.94%	731	26.14%
M	165	18.52%	935	33%
L	35	3.93%	1066	38.13%
Total	891	100.00%	2796	100.00%

SVS Cummerbund				
	# of Women	% of Women	# of Men	% of Men
XS	358	40.18%	459	16%
SM	453	50.84%	1554	55.58%
M	72	8.08%	691	25%
L	8	0.90%	92	3.29%
Total	891	100.00%	2796	100.00%

SVS Shoulders				
	# of Women	% of Women	# of Men	% of Men
S	99	11.11%	1	0%
M	789	88.55%	1934	69.17%
L	3	0.34%	861	31%
Total	891	100.00%	2796	100.00%

SVS Back				
	# of Women	% of Women	# of Men	% of Men
S	243	27.27%	15	1%
M	637	71.49%	2094	74.89%
L	11	1.23%	687	25%
Total	891	100.00%	2796	100.00%

Long Duration Wear (LDW) Evaluation

- Three or more uninterrupted hours of seated work
  - Minimum duration historically applied to endurance evaluations
  - Many participants wore it longer (min 3, max 10, mean 5.3 hours)
- Additional activities at participant's discretion included
  - Driving around base
  - Lifting boxes and other items during office and lab tasks
  - MH-60 S/R simulator testing, including emergency procedures
  - Mobility testing
    - Bending, reaching, twisting,
  - MURPH workout
  - Preflight procedures in H-60 tail
  - Preflight procedures on Cargo Lab V-22
  - Running/walking

[redacted]

[redacted]

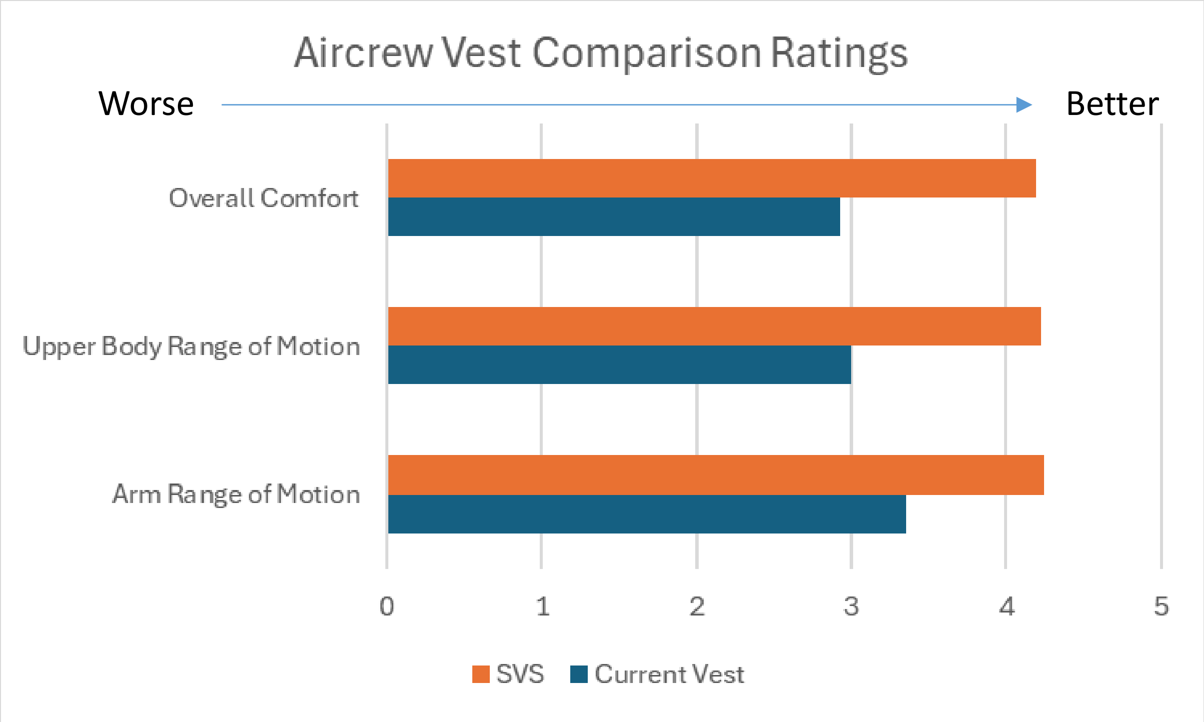
Long Duration Wear Evaluation

- 22 participants–
  - HX-21 test pilots, crew chiefs/project specialists, AMSOs, AEPs, former aircrew, design team/civilians
  - Good mix of men/women and anthropometric variation
- Modified version of USAF Modular Scalable Vest Gen II questionnaire

NAVAIR

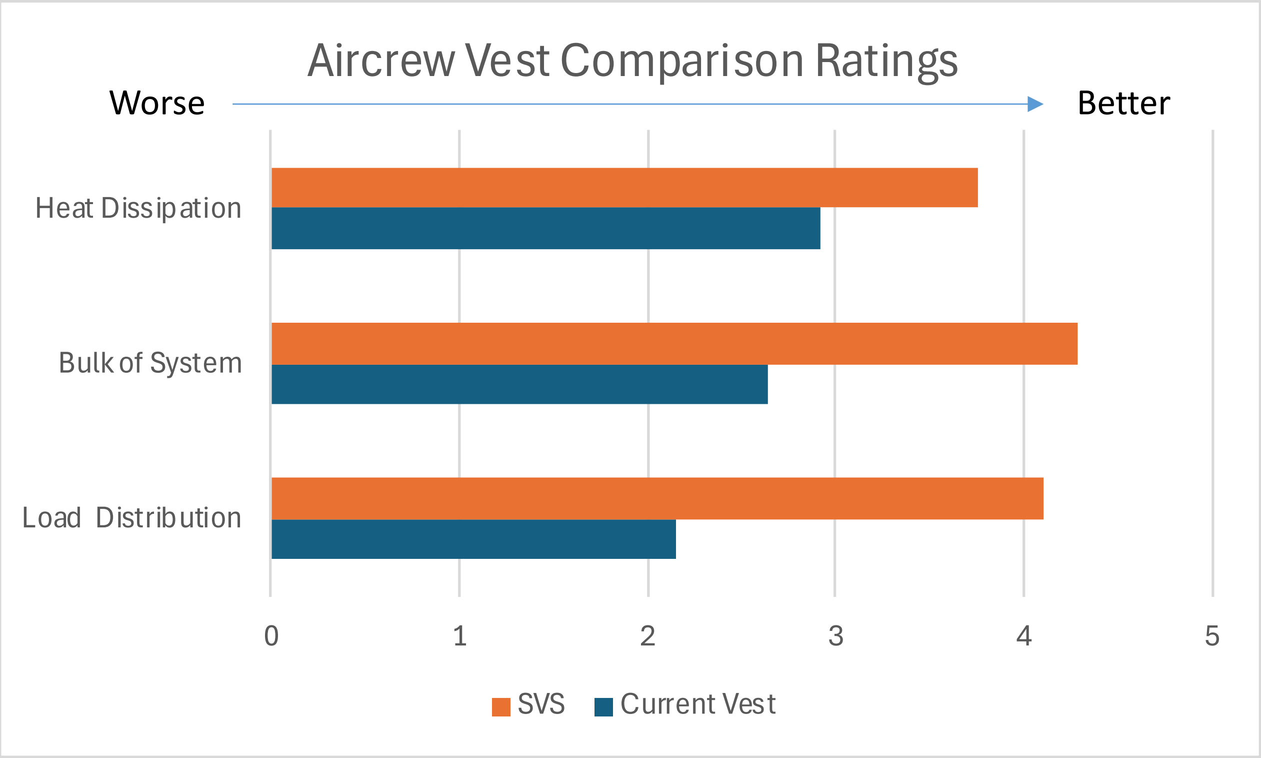
LDW Results

- For both your current vest and SVS, please rate your ability to move your arms in motions normally required while wearing a vest system (examples: reaching overhead, across the body, etc.)
- For both your current vest and SVS, please rate your ability to move your upper body in movements normally required while wearing a vest system (examples: bending at the waist, reaching, twisting, checking six, etc.)
- For both your current vest and SVS, please rate your overall comfort

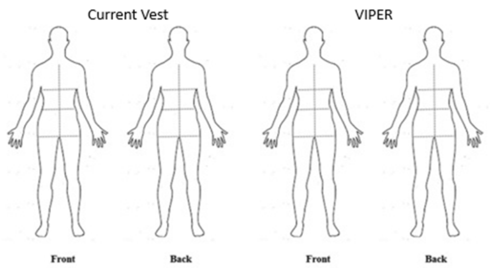


LDW Results

- For both your current vest and SVS, please rate the ability of the system to dissipate heat.
- For both your current vest and SVS, please rate the bulk of the system (distribution, quantity, retention to body, etc.)
- For both your current vest and SVS, please rate the load distribution of the vest system

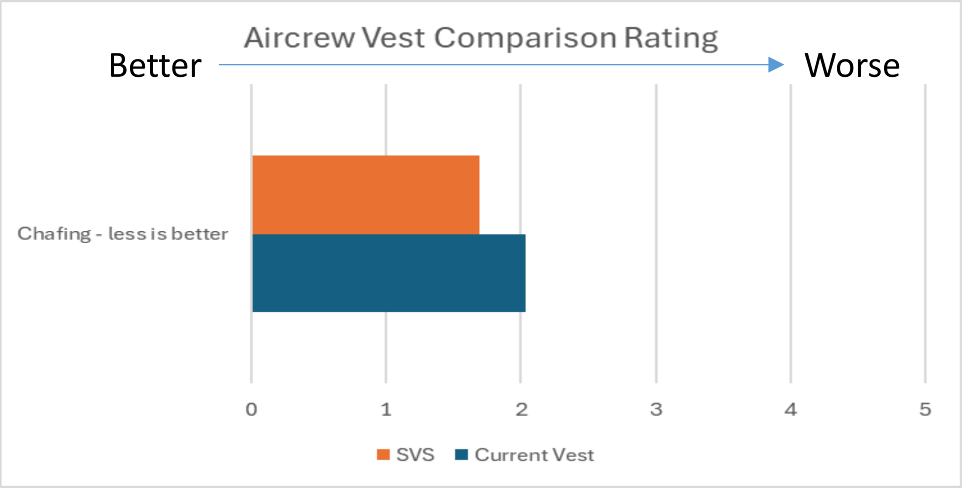


If you are experiencing uneven load distribution, please list or circle all areas you are experiencing additional pressure.

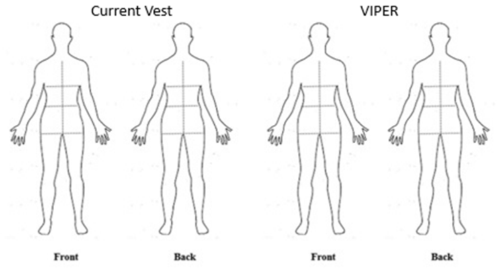


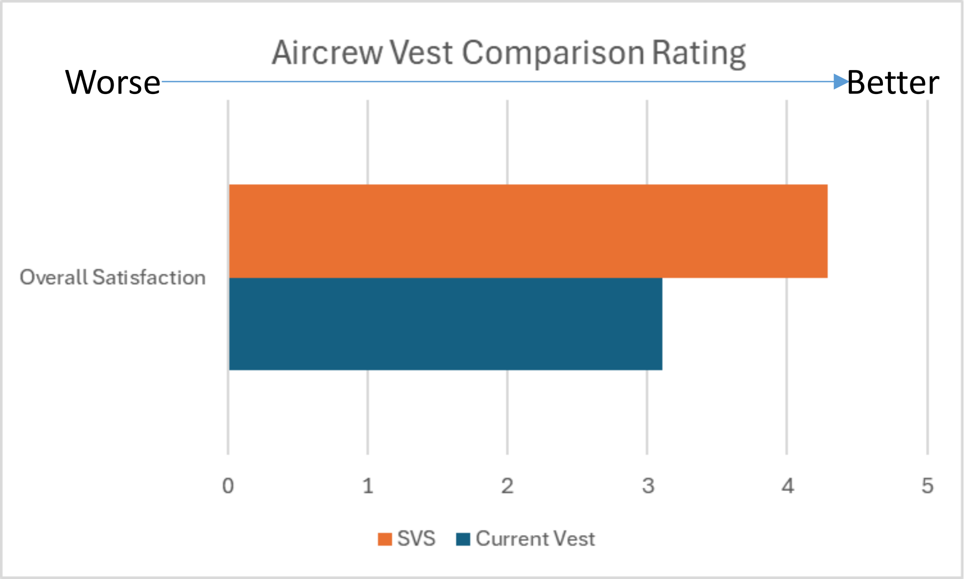
LDW Results

- For both your current vest and SVS, please rate the level of chafing/rubbing you experience while wearing this system.
- For both your current vest and SVS, please rate your overall level of satisfaction with the system



If you experience chafing/rubbing, please list or circle all affected areas:





Additional Comments From Survey

Do you have any additional comments related to SVS that you would like to share?

Thank you so much for your time and feedback!

SVS Pros

- Participants noted that sitting was particularly comfortable, with one participant having no residual effects even after 10 hours of use
- Participants noted that the bulk was significantly reduced compared to previous vests
- Improved mobility allowed participants to perform a wider range of motion
- Updated shoulder strap design (2.5) alleviated discomfort for the participants who had experienced pressure or digging from straps
- Vest integrated seamlessly with movements

SVS Cons

- 1 participant reported Hip connectors rubbed against hip bones while sitting
- 2 participants reported pressure on collarbone from where the rescue loop sat

2.5 refit of three LDW participants that experienced discomfort with shoulder strap 2.4 planned prior to CDR.

Volume and Surface Area of Vest System

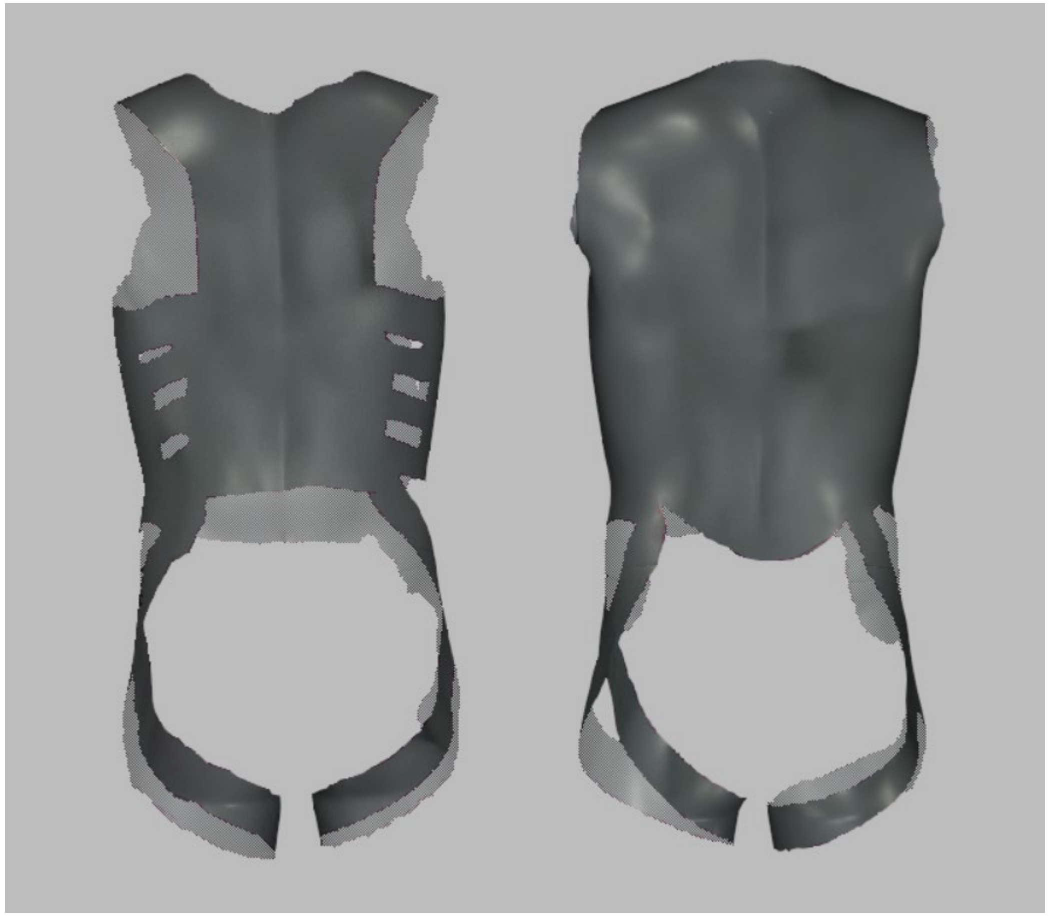
SVS (L) Aircrew Endurance Vest (R)

SVS (L) Aircrew Endurance Vest (R)

Volume and Surface Area of Vest System

Aircrew Endurance Vest (L) SVS (R)

SVS (L) Aircrew Endurance Vest (R)



Volume and Surface Area of Vest System

	AE Vest	SVS Vest
Vest Volume	0.814 ft^3	0.557 ft^3
Contact Surface Area	5.193 ft^2	4.366 ft^2

AE to SVS Reductions	Numerical	% Reduction
Vest Volume	0.257 ft^3	31.529%
Contact Surface Area	2.578 ft^2	15.929%

Next Steps

- Developmental testing (Fall 2026)
- Pull forces for cabin aircrew mobile restraint release mechanism
- Quantify shoulder borne weight of legacy vests and SVS
- Refine fit instructions for equipment specialists
- Refit LDW participants with discomfort related to shoulder straps with new version of straps

Thank You!

Acknowledgement: The authors would like to express their appreciation to all the subject matter experts and collaborators whose previous work and/or advice aided our efforts greatly.

Scan QR code for more information on our labs.

Lori Basham - lori.l.basham2.civ@us.navy.mil
Brian Corner - brian.corner@red-llc.us
Kenneth Ritchey - kenneth.j.ritchey2.civ@us.navy.mil
Katherine Tonnell – Katherine.g.tonnell.civ@us.navy.mil

Digital Design Considerations for Body Armor Fit, Size Design, and Tariffing

24 March 2026

Brian D. Corner, Ph.D.
Lori B. Basham, CPE
Aeromedical Research & Integration Branch
Human Systems Engineering Department (HSED)
Naval Air Warfare Center Aircraft Division (NAWCAD)

HUMAN SYSTEMS ENGINEERING DEPARTMENT

Digital Human Modeling and Research for Ergonomic, Anthropometric, and Medical Applications & 3D Scanning

Capability Statement

The Digital Human Modeling and Research for Ergonomic, Anthropometric, and Medical Applications & 3D Scanning (DREAMS) Laboratory is an aeromedical research facility aiding the warfighter by leveraging emerging technologies and establishing new capabilities to address Fleet priorities with a focus on physical ergonomics and 3D Scanning for program and project needs.

Core Capabilities

- **Digital Human Modeling (DHM)**

  Evaluation of anthropometric accommodation (reach, vision, clearance), ergonomic/biomechanic analysis for musculoskeletal (MSK) injury risk reduction and improved endurance, protective clothing and equipment fit, size design, and tariffing.

- **3D Scanning and Motion Capture**

  Digital scanning of aircraft (interior or exterior), aircraft parts, test coupons, workstations/seating, personnel (bodies, heads, hands, feet, postures), facilities, and more.

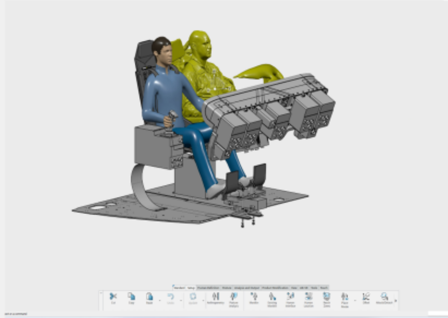
- **Technical & Research Expertise**

  Certified and highly experienced subject matter experts with a history of success in conducting research and transitioning benefits to program offices and the Fleet.

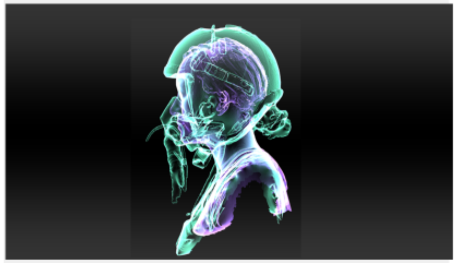
- **Collaborations**

  Affordable and efficient Fleet support through partnerships that include US Army CCDC, AFLCMC/WNU, USMC MERS, NAMRU-D, NCTRF, ONR, NASA, CFD Research, Humanetics, Dassault, and many academic collaborators.

Artec Leo 3D Scanner



Delmia DHM with Pilot Manikin Twin and Scan



3D Scan Overlay of Pilot With/Without Mask

Work Products

- Anthropometric and 3D scan databases, summary statistics
- Reviews of contractor provided DHM analysis
- DHM application evaluations (commercial or SBIR developed)
- Creation of multivariate use cases for requirements specifications and corresponding DHM manikin families for anthropometric and MSK injury risk modeling efforts.
- RDT&E aligned to Fleet capability gaps

Lab Manager: Kenneth Ritchey
Kenneth.j.ritchey2.civ@us.navy.mil

Branch Head: Sam Trepp
Samuel.g.trepp.civ@us.navy.mil

HUMAN SYSTEMS ENGINEERING DEPARTMENT

Applied Physical Ergonomics Lab

Capability Statement

The Applied Physical Ergonomics (APE) Lab provides platform/product program and direct Fleet support to optimize aviator, aircrew and troop/passenger safety, health, endurance, and performance across the physical ergonomics domain. APE is the only Navy facility with Aircrew Interoperability Deputy Tech Warrant Holder designation.

Core Capabilities

- **Aircrew Interoperability Tech Authority**

  Develop and report USN/USMC anthropometric restriction codes (ARCs) for all aircraft; updates to the ARCs to reflect changes in seating, cockpit layout, or pilot flight equipment.

- **Accommodation Evaluations & Fit Events**

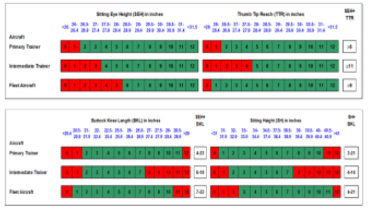
  Define, determine, measure and assess system performance in relation to anthropometric compatibility and user accommodation, providing compliance assessments and certifications for acquisition decisions and airworthiness.

- **Expertise Across Physical Ergonomics Domain**

  Anthropometry, strength/force, musculoskeletal (MSK) injury risk reduction and mitigation, endurance, body composition, range of motion/mobility, sizing/fit.

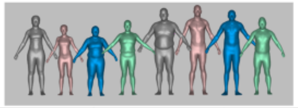
- **Fleet & External Customer Support**

  Respond to accommodation related requests from Aeromedical Safety Officers and other Fleet stakeholders; provide support to foreign military sales (FMS) customers, aircraft manufacturers, and other military services.



Anthropometric Restriction Codes

Cockpit & Cabin Accommodation Evaluations



	Females				Males			
	1	2	3	4	5	6	7	8
	Short torso in proportion to height, larger hips/thighs	Overall small	Short and stout	Long torso in proportion to height, larger waist/chest	Overall large	Long and slim	Short torso in proportion to height, larger hips/thighs	Long torso in proportion to height, larger waist/chest
buttock circumference	42.02	33.59	42.42	38.39	47.13	38.03	41.37	38.90
cervicale height	57.56	51.77	51.09	52.34	63.13	63.97	62.57	56.90
chest circumference	35.86	30.44	39.52	38.70	49.33	39.21	41.21	42.15
thigh circumference	25.72	19.66	26.21	22.79	29.61	22.45	25.73	23.49
vertical trunk circumference	62.48	54.70	60.30	60.31	73.82	66.72	66.02	65.07
waistbacklength	16.12	14.89	15.61	17.38	20.81	20.08	18.46	19.14
waist circumference	31.88	25.31	36.61	35.91	47.07	33.90	35.69	38.37
waist front length sitting	12.94	12.33	13.21	15.03	17.31	16.32	13.76	16.76

Multivariate Use Cases

Work Products

- Input to aircraft design requirements including development of anthropometric use cases; source selection support
- Requirements verification
- Cockpit accommodation evaluations and Anthropometric Restriction Codes (ARCs)
- Aircraft and ground workstation design evaluations
- Equipment fit-testing/mapping; endurance evaluations
- Technical reports
- Updates to NAVAIRINST 3710.9X & Manual 3710.1

Lab Manager: Lori Basham
lori.l.basham2.civ@us.navy.mil

Branch Head: Sam Trepp
samuel.g.trepp.civ@us.navy.mil

What Constitutes Good Body Armor Fit & Accommodation?

- In the context of this presentation:
  - Provides ≥ minimum required coverage/protection
  - Does not compromise mobility & performance
  - Does not cause pain or injury
  - Accounts for shape variation
  - Balance between survivability, endurance, and physiological burden
  - Interoperability with clothing and other protective equipment

Contributing Issues to Poor Body Armor Fit & Accommodation

1. Design Issues

   Inadequate Sizing
2. Incorrect Tariffing
3. Procurement Decisions
4. Supply Chain Issues
5. Fitting Issues After Fielding

Contributing Issues to Poor Body Armor Fit & Accommodation

- Insufficient requirements and/or requirements verification
- Design trades
- Population differences not considered
  - Not enough awareness of population variation
  - Data gaps
- Univariate anthropometric approach
- Wrong measurements considered
- Dynamic fit not considered
- Duration of wear not considered
- Ineffective sizing tables
  - Inadequate testing when developing sizing tables
    - Few, if any, opportunities to update sizing tables following fielding
  - Sizing table anthropometry issues
    - Univariate vs. bivariate vs. multivariate
    - Measurements in sizing table may not be best predictors of good fit

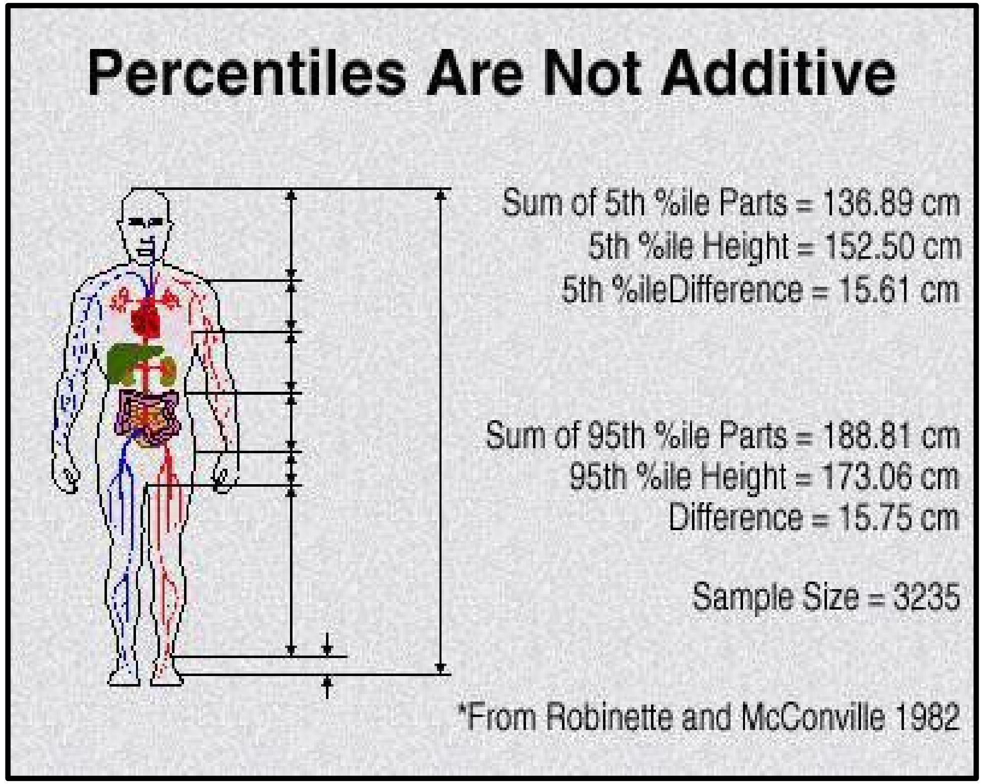
Design Issues

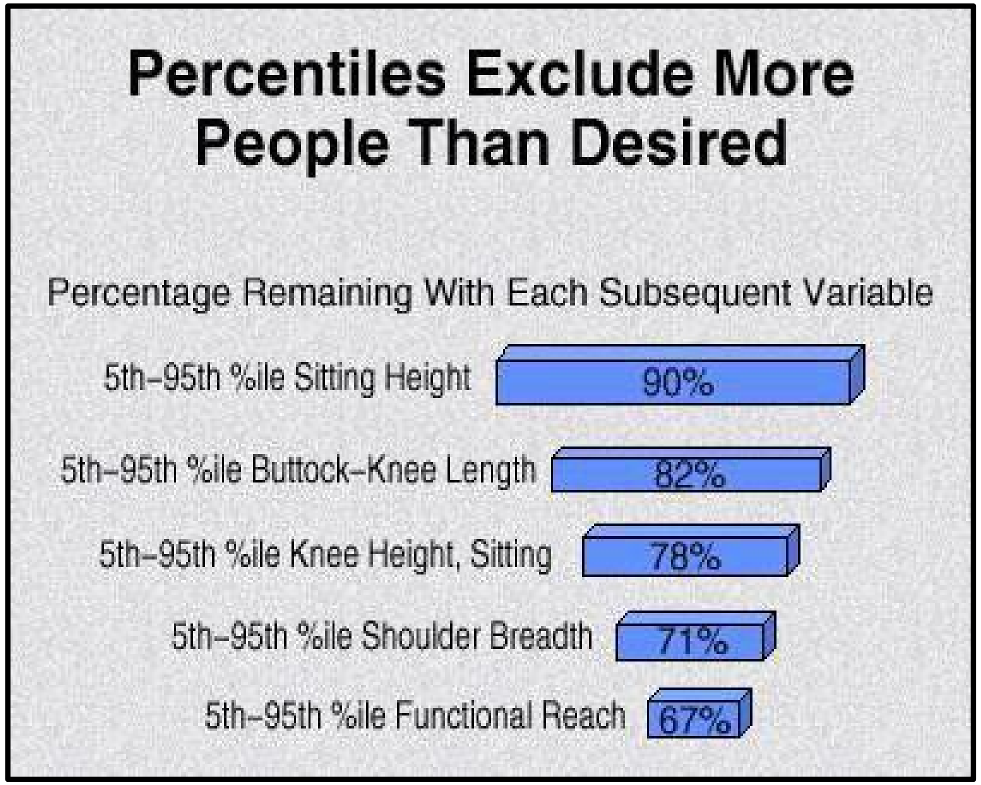
&

Inadequate Sizing

Anthropometry – Percentiles Problem

- Multiple percentiles do a bad job of describing people yet continue to remain in use
- A series of univariate analysis ≠ multivariate analysis



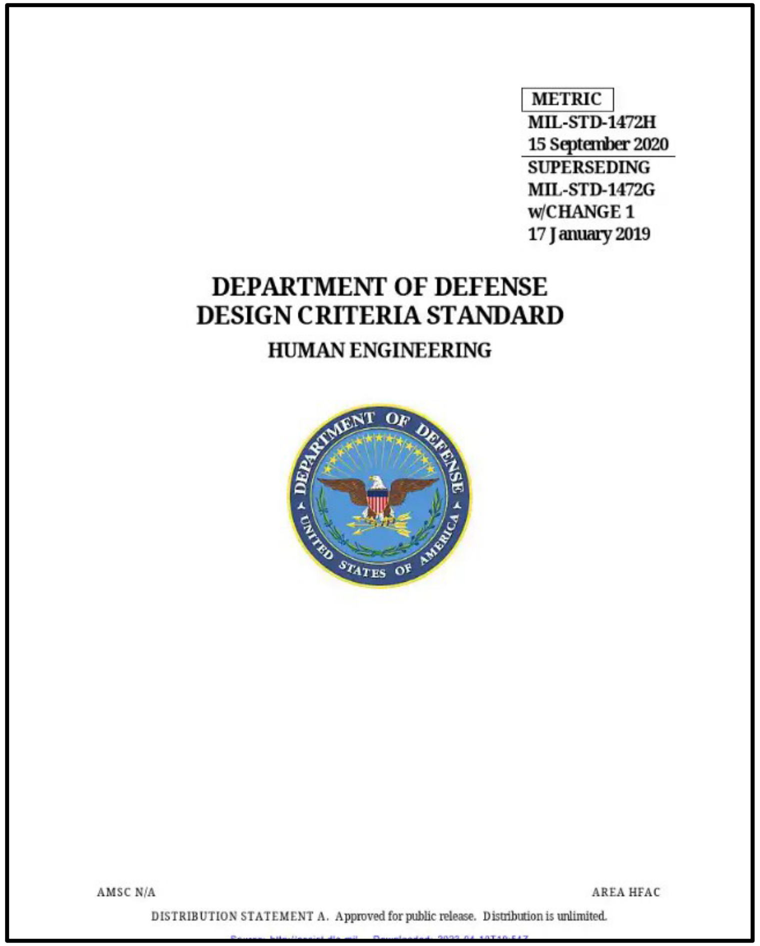


See Moroney & Smith (1972) Empirical reduction in potential user population as a result of imposed multivariate anthropometric limits. NAMRL-1164, Naval Aerospace Medical Research Laboratory, Pensacola, FL.

MIL-STD-1472H
Populations Not Percentiles

Regular populations. The population(s) to be accommodated, including operators, maintainers, and support personnel, shall include both genders of applicable **military, non- military, and foreign military personnel**.

Unless otherwise specified, the design of DoD systems, equipment, and facilities shall accommodate the **multivariate** central 90 percent (95 percent preferred) of **suitably clothed and equipped males** of the target user population and the multivariate central 90 percent (95 percent preferred) of the **suitably clothed and equipped females** of the target user population **using dimensions applicable to the tasks**.


METRIC
MIL-STD-1472H
15 September 2020
SUPERSEDING
MIL-STD-1472G
w/CHANGE 1
17 January 2019

DEPARTMENT OF DEFENSE
DESIGN CRITERIA STANDARD
HUMAN ENGINEERING

AMSC N/A AREA HFAC

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

Multivariate Accommodation Method (MAM)

- Method developed in 1992 by Air Force Research Lab (AFRL)
  - Principal Components Analysis (PCA)
  - Characterizes relevant combinations of body sizes and proportions for the target population
  - Initially adopted and used in requirements specifications for DoD aircraft

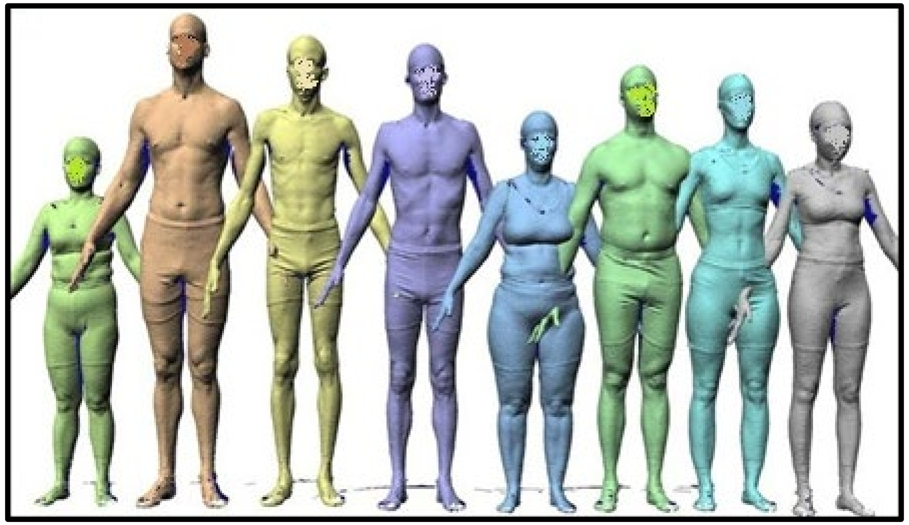
- Important considerations
  - Intended population
    - Pilots, Troops, Rescue Swimmers, etc.
    - Which service?
  - Intended application
    - Cockpit accommodation, troop seating, anti-exposure suit, armor

JPATS Use Cases

Units = inches	CASE 1 Small	CASE 2 Medium Build Short Limbs	CASE 3 Medium Build Long Limbs	CASE 4 Tall Sitting Height Short Limbs	CASE 5 Overall Large	CASE 6 Longest Limbs	CASE 7 Overall Small
Thumb Tip Reach	27.0	27.6	33.9	29.7	35.6	36.0	26.1
Buttock-knee Length	21.3	21.3	26.5	22.7	27.4	27.9	20.8
Knee-height Sitting	18.7	19.1	23.3	20.6	24.7	24.8	18.1
Sitting Height	32.8	35.5	34.9	38.5	40.0	38.0	31.0
Eye Height Sitting	28.0	30.7	30.2	33.4	35.0	32.9	26.8
Shoulder Height Sitting	20.6	22.7	22.6	25.2	26.9	25.0	19.5

JPATS Case 7 and 5 Participants

Example of Use Case Nearest Neighbor Participant Scans



Current Hard Plate Sizes and Accommodation

- 2012 Army anthropometric data run through armor sizing tables
  - Three plates in the current system
  - Front length & chest width (bithelion)

	# of ANSUR Women	% of ANSUR Women	# of Disaccom ANSUR Women	% of Disaccom ANSUR Women
XS-Short	2	0.10%	0	0.00%
XS	318	16.00%	0	0.00%
SM-Short	0	0.00%	0	0.00%
SM	1134	57.10%	13	0.70%
SM-Long	152	7.70%	26	1.30%
M	233	11.70%	0	0.00%
L	93	4.70%	11	0.60%
XL	3	0.20%	9	0.50%
			13*	0.70%
Total ANSUR women in database = 1986				
*Very large width vs. length discrepancy				

	# of ANSUR Men	% of ANSUR men	# of Disaccom ANSUR men	% of Disaccom ANSUR men
XS-Short	0	0%	0	0%
XS	123	3%	0	0%
SM-Short	0	0%	0	0%
SM	669	16.40%	20	0.50%
SM-Long	826	20.20%	26	0.50%
M	1020	25%	0	0%
L	394	9.70%	215	5.30%
XL	34	0.80%	453	11.10%
			302*	7.40%
Total ANSUR men in database = 4082				
*Potentially not protected by any current plate lengths				

Sizes Fleet/PRs reported being available and in use

Future Hard Plate Sizing?

- US Army CCDC developed body armor sizing recommendations for appropriate fit & accommodation of their population.

The distribution of 1" below Suprasternale to midway between the 10th rib and Iliocristale against maximum coverage Chest Breadth (75% for female & 79% for male).

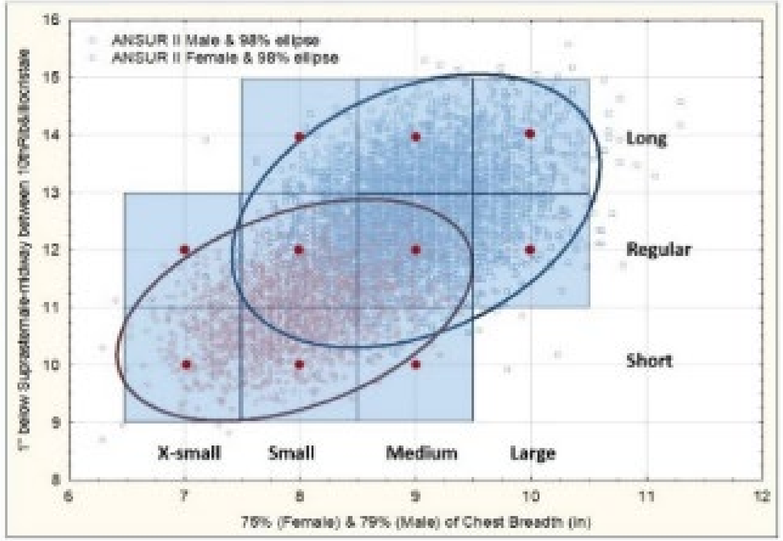


Table 2. Size tariff of front plate for male and female U.S. Army personnel.

Percentage (%)		X-small	Small	Medium	Large	Total
Short	*Female*	14.90	33.18	4.58	--	52.67
	Male	0.07	1.10	1.15	--	2.32
Regular	*Female*	4.68	30.56	11.33	0.35	46.92
	Male	0.20	14.97	38.66	9.58	63.41
Long	*Female*	--	0.00	0.15	0.00	0.15
	Male	--	3.80	21.36	8.15	33.34
Total	*Female*	19.59	63.75	16.06	0.35	99.80
	Male	0.27	19.87	61.17	17.76	99.07

Table 3. Specification of the family of armor plates.

	Plate Size (in)									
Width	*X-Small (7")*		*Small (8")*			*Medium (9")*			*Large (10")*	
Length	*Short*	*Regular*	*Short*	*Regular*	*Long*	*Short*	*Regular*	*Long*	*Regular*	*Long*
Front	10"	12"	10"	12"	14"	10"	12"	14"	12"	14"
Back	12"	14"	12"	14"	16"	12"	14"	16.5"	14.5"	16.5"
Side Plate	6"x 6"		7"x 6"		7"x 8"	8"x 6"		8"x 8"	9"x 8"	

Choi-Rokas, H., Garlie, T., Mitchell, K. (2022). Theoretical Framework for the Sizing of Body Armor Plates to Optimize Fit. http://doi.org/10.54941/ahfe1001898

Contributing Issues to Poor Body Armor Fit & Accommodation

- Wrong population considered
  - Outdated demographic & anthropometric databases
- Loss of sizing table fidelity- Is the size in stock?
- Using outdated tariffing/procurement figures
- Incorrect tariffing has serious consequences
  - Safety and Readiness (especially for shortages of critical safety items)
  - Costs of purchasing wrong sizes in quantity

Incorrect Tariffing

Contributing Issues to Poor Body Armor Fit & Accommodation

- SME tariffing recommendations may be traded
  - Only subset of sizes may be procured
    - Cost, schedule, lack of understanding about impact of cutting available sizes
- Not all sizes may be available for purchase

Procurement Decisions

- Having great design, sizing, and tariffing will not matter if the sizes needed are not made available to the Warfighter when they need them.
- Cumulative logistics may force size compromises
  - Sacrificed protection and performance
  - Affects related equipment (vests/carriers)

Supply Chain Issues

Contributing Issues to Poor Body Armor Fit & Accommodation

- Necessary sizes not available
  - Equipment specialists forced to issue what they have
- Sizing table inadequacies
  - Issue what really fits or what table says should fit?
- Poor fit criteria and instructions
- Equipment specialist proficiency

Fit Issues After Fielding

Contributing Issues to Poor Body Armor Fit & Accommodation

Design Issues

Inadequate Sizing

Incorrect Tariffing

Procurement Decisions

Supply Chain Issues

Fitting Issues After Fielding

The cumulative effect

Degradation in Warfighter Protection & Performance

Standardized Measurement & Evaluation

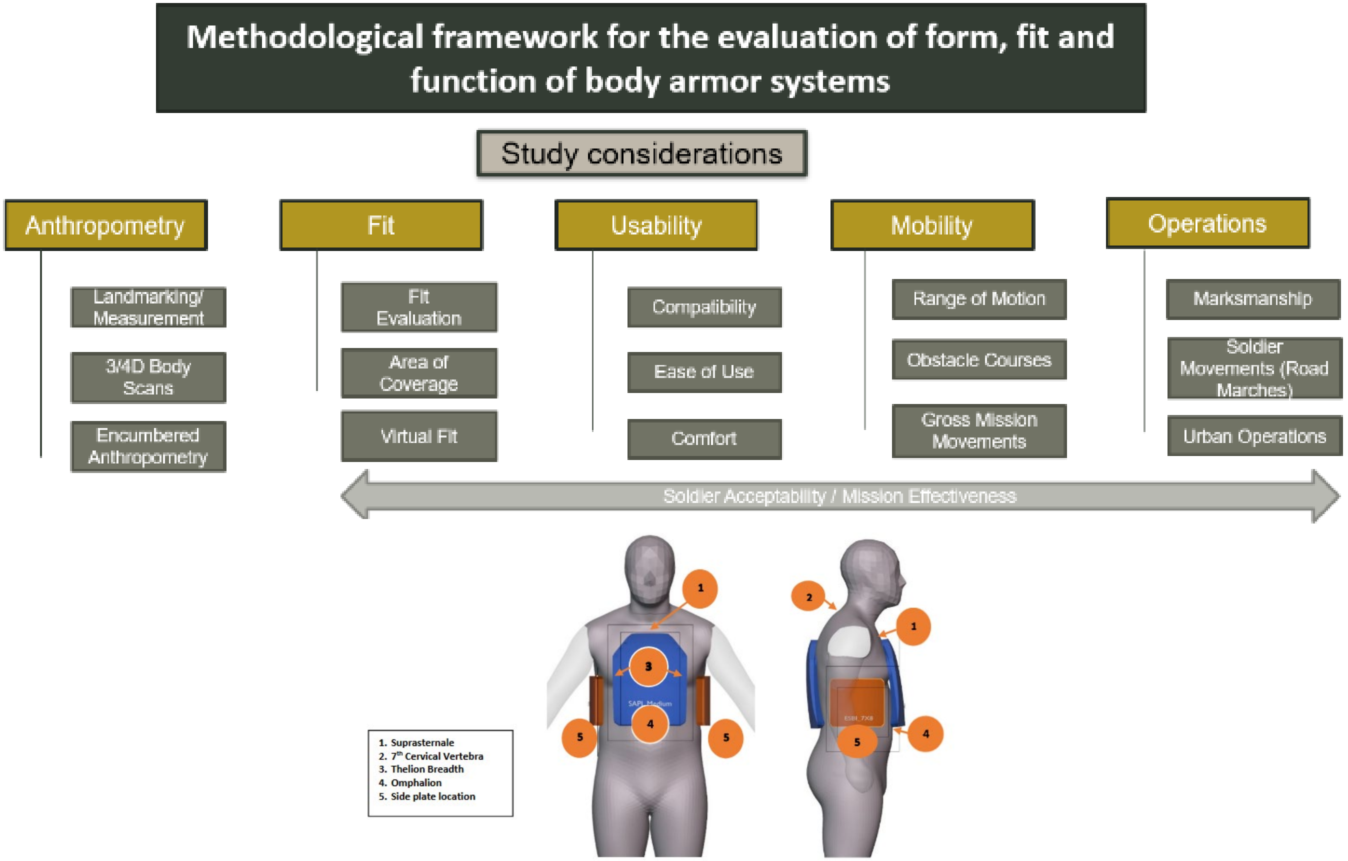
Formalizing Fit Assessment

Contributions

- Standardized anthropometric procedures
- Structured form-fit-function evaluation framework
- ASTM measurement & fitting protocol

Outcome

- Repeatable evaluation methods
- Improved acquisition testing consistency
- Scalable training guidance



Garlie, T. N., Choi-Rokas, H., Hennessy, E., & Mitchell, K. B. (2024). A Methodological Framework for the Evaluation of Form, Fit, and Function of Body Armor Systems. https://apps.dtic.mil/sti/trecms/pdf/AD1230728.pdf
ASTM International. (2025). Standard Practice for Body Armor Wearer Measurement and Fitting of Armor, E3003-25. Published August 2025. https://DOI:10.1520/E3003-25

Include Mobility & Performance Measures that Consider Pose

Misfit Degrades Operational Capability

Evidence

•Reduced shoulder/trunk range of motion

•Increased bulk

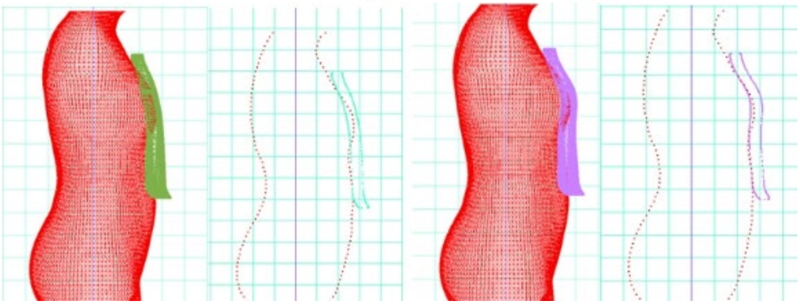
•Reduced anatomical coverage

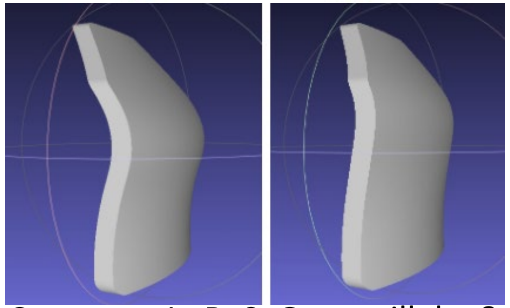
Operational Risk

•Mobility interference

•Weapon handling limitations

•Vehicle ingress/egress degradation





Choi, H. J., Garlie, T. N., & Mitchell, K. B. (2019). Effects of Body Armor Fit on Encumbered Anthropometry Relative to Bulk and Coverage. In R. S. Goonetilleke & W. Karwowski (Eds.), *Advances in Physical Ergonomics & Human Factors* (Vol. 789, pp. 260–272). Springer International Publishing. https://doi.org/10.1007/978-3-319-94484-5_28

Choi, H. J., Mitchell, K. B., Garlie, T. N., & DeSimone, L. (2019). Effects of Body Armor Fit on Warfighter Mobility as Measured by Range of Motion (ROM). In R. S. Goonetilleke & W. Karwowski (Eds.), *Advances in Physical Ergonomics & Human Factors* (Vol. 789, pp. 16–28). Springer International Publishing. https://doi.org/10.1007/978-3-319-94484-5_2

Choi-Rokas, H., Garlie, T., & Blake Mitchell, K. (2022). *Theoretical Framework for the Sizing of Body Armor Plates to Optimize Fit*. 13th International Conference on Applied Human Factors and Ergonomics (AHFE 2022). https://doi.org/10.54941/ahfe1001898

Li, P., Choi-Rokas, H., Mitchell, B., Tashjian, A., & Hurley, M. (2023). *An iterative and anthropometrically driven approach to body armor plate design for females*. 14th International Conference on Applied Human Factors and Ergonomics (AHFE 2023). https://doi.org/10.54941/ahfe1003349

Quantify Sex-Based Fit Disparities

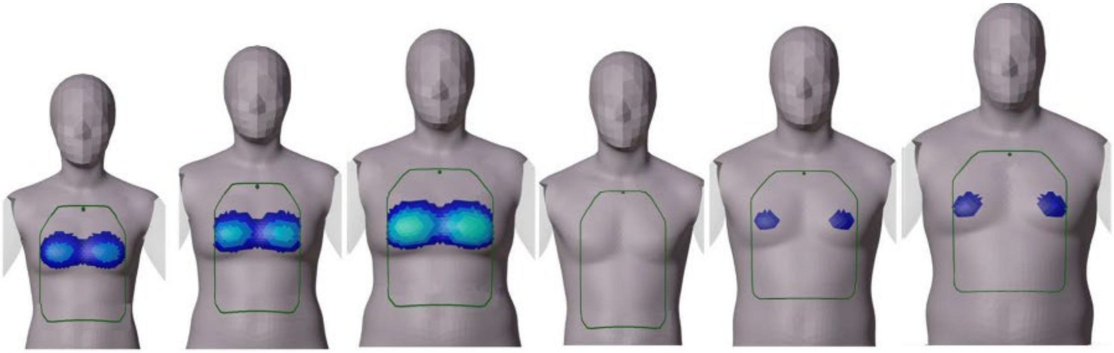
Female Soldiers Experience Greater Contact & Restriction

Key Findings

- 25× greater body-to-plate contact volume (females)
- 6.5× greater contact depth
- Length is strongest predictor of fit problems

Implication

- Current sizing disproportionately affects women
- Vertical dimensioning requires redesign



	Females			Males		
Stature	152.2	162.8	170.2 cm	164.4	175.5	186.9 cm
Chest Circumference	81.0	94.5	108.5 cm	91.4	105.9	120.4 cm
Contact Area	196.4	197.4	303.4 cm^2	0.0	43.0	66.8 cm^2
Contact Volume	45.7	47.2	100.9 cm^3	0.0	2.0	4.6 cm^3
Max. Contact Depth	1.7	1.7	2.3 cm	0.0	0.4	0.6 cm
Fitting Plate Size	FP-C	FP-F	FP-G	FP-F	FP-G	FP-H

Kim, K. H., Green, W. J., Hernandez, Y., Rajulu, S. L., Choi-Rokas, H. E., Li, P., Garlie, T. N., & Mitchell, K. B. (2024). Virtual fit assessment of U.S. army body armor using NASA spacesuit techniques. *Applied Ergonomics*, *120*, 104339. https://doi.org/10.1016/j.apergo.2024.104339

Brisbine, B. R., Molloy, R. H., Carstairs, G. L., & Coltman, C. E. (2026). Soldiers experience fit issues, musculoskeletal pain, and equipment and mobility interference with military body armour. *Applied Ergonomics*, *130*, 104645. https://doi.org/10.1016/j.apergo.2025.104645

Transition to Digital & Predictive Methods

From Physical Prototypes to Virtual Fit Modeling

Advances

•Derived virtual overlay method

•3D deformation measurement

•Finite-element torso simulation

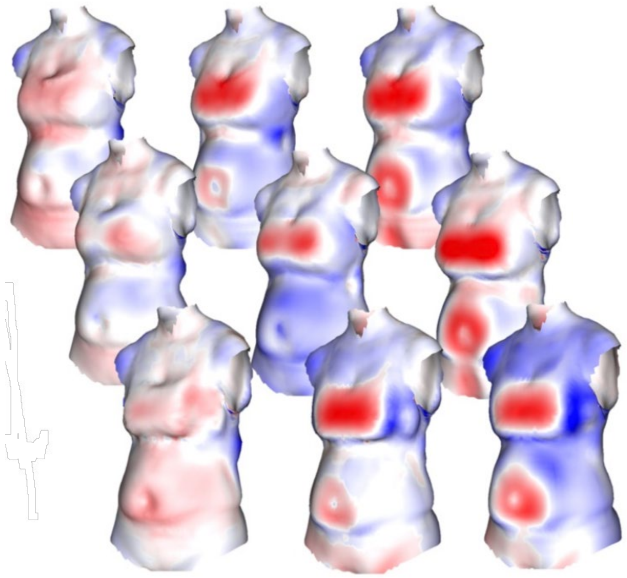
•Physics-based contact prediction

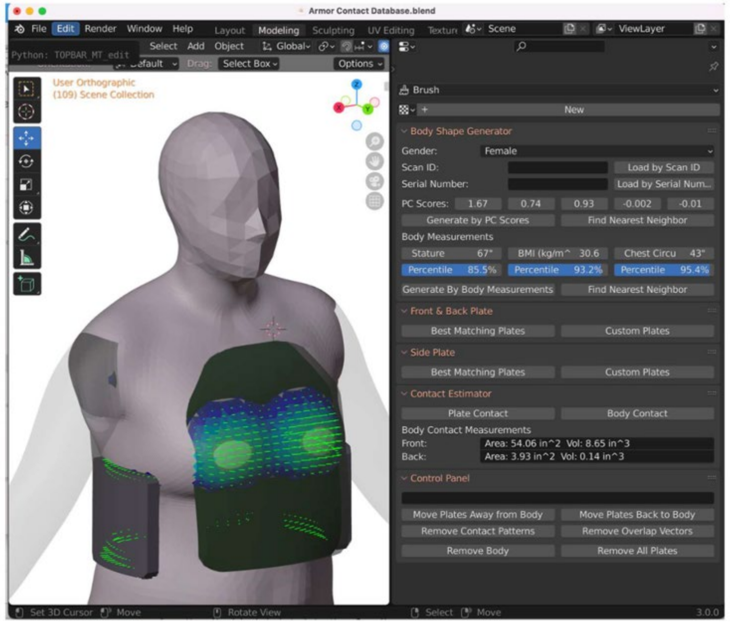
Impact

•Predict plate fit without field trials

•Accelerates design cycles

•Enables digital twin capability





Jones, M. L. H., Park, B.-K. D., Ebert, S. M., Boyle, K. J., Hu, J., & Reed, M. P. (2023). *Female Body Armor Fit: Measurement Methods, Software Tools, and Finite-Element Simulation*. https://dx.doi.org/10.7302/25150

Kim, K. H., Green, W. J., Hernandez, Y., Rajulu, S. L., Choi-Rokas, H. E., Li, P., Garlie, T. N., & Mitchell, K. B. (2024). Virtual fit assessment of U.S. army body armor using NASA spacesuit techniques. *Applied Ergonomics*, *120*, 104339. https://doi.org/10.1016/j.apergo.2024.104339

Choi, H. J., Garlie, T. N., Tashjian, A., & Li, P. (2020). Effects of Body Armor Fit on Area of 3D Surface Coverage. In M. Di Nicolantonio, E. Rossi, & T. Alexander (Eds.), *Advances in Additive Manufacturing, Modeling Systems and 3D Prototyping* (Vol. 975, pp. 571–583). Springer International Publishing. https://doi.org/10.1007/978-3-030-20216-3_53

Strategic Takeaways

- Move from Percentiles → Multivariate Shape Modeling
- Incorporate Female-Specific Morphology
- Treat Fit as Performance + Health Variable
- Implement Virtual & Simulation-Based Design
- Standardize Evaluation Across Programs

Thank You!

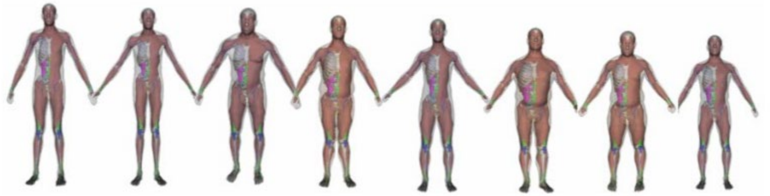
Lori Basham: lori.l.basham2.civ@us.navy.mil

Brian Corner: brian.corner@red.llc.us

Current DREAMS Lab Digital Design Related Initiatives

- Delmia DHM ergonomics tools evaluation project
  - Quantify MSK injury risk associated with aircrew posture, tasking, and protective equipment.
- Consider existing and emerging modeling applications for development of in-house clothing and protective equipment modeling capabilities.
  - Gerber AccuMark
  - CLO 3D
  - Innovision Integrated Digital Engineering Environment for Personal Protective Equipment Development (IDEEP) and Integrated Digital Environment for Airman Fit and Accommodation (IDEA)
  - CFDRC Anthropometry Model Generator (AMG)
  - Others?
- Support ongoing development of PassFit System
  - CRADA with University of Michigan Transportation Research Institute (UMTRI)
- Pursue development of aircrew specific parametric shape models
- Pursue development of aircraft specific accommodation models
- Seat Specific Posture Modeling (SSPM) project

Delmia manikin twin & 3D Scan of CH-53K Pilot



CFDRC AMG

UMTRI PassFit