

Crew Anthropometry and Spacesuit Sizing

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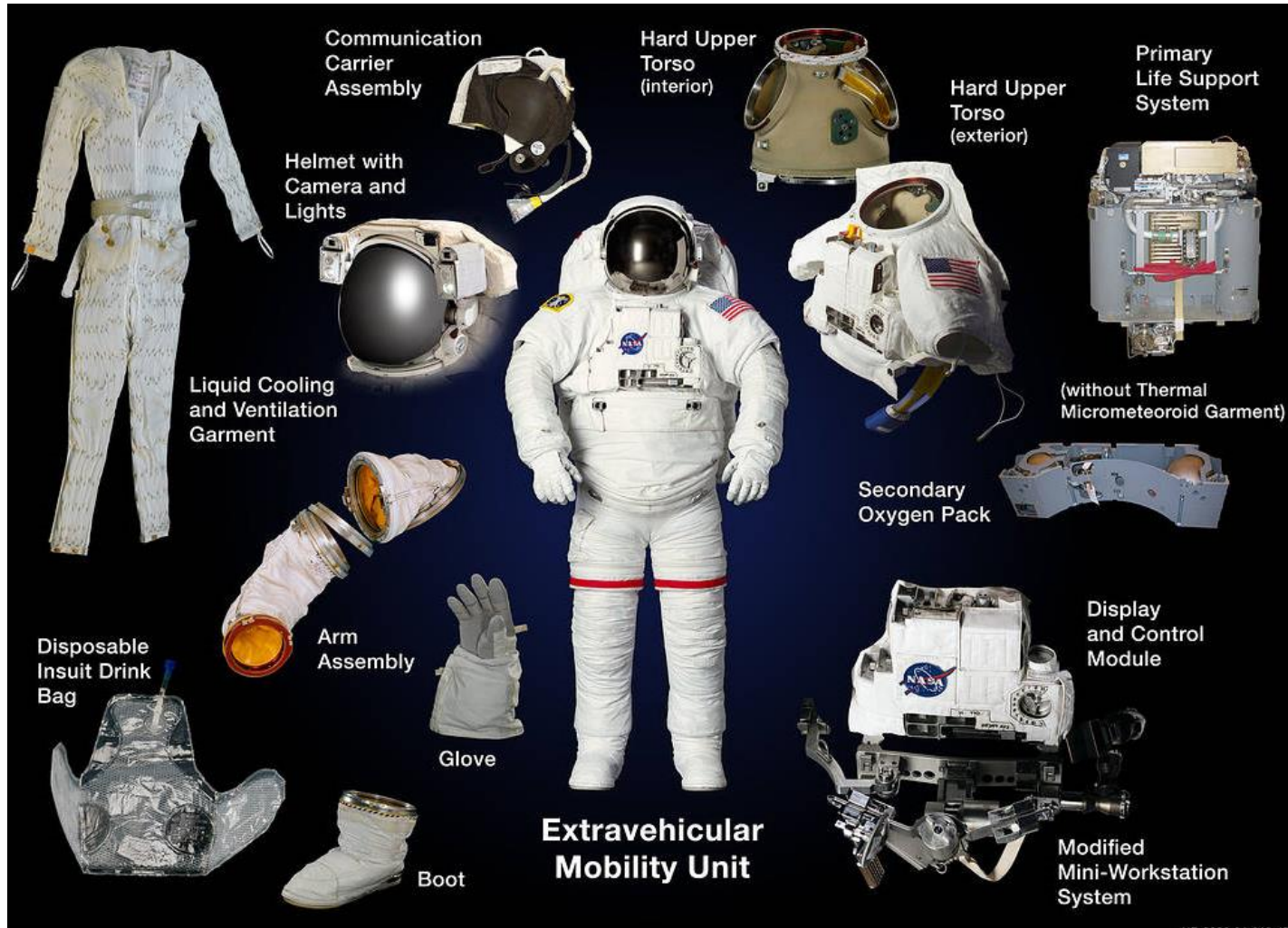
April 9, 2025



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Spacesuit: Types and Components

Extravehicular Activity (EVA) Suit



Intravehicular Activity (IVA) Suit



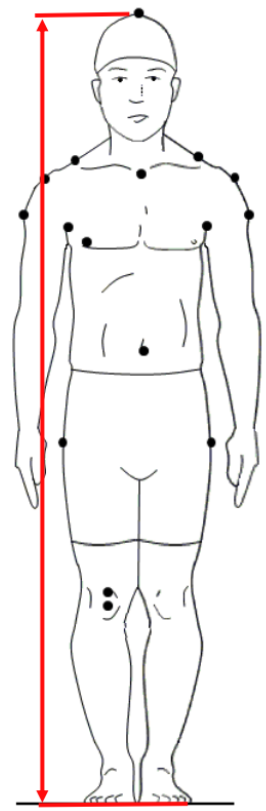
Crew Population Definition

- NASA crew population varies substantially, especially in gender, body size/shape distributions
- NASA Standards and Human System Requirements define the crew population characteristics
 - Parent database based on US Army ANSUR 1988
 - Down selected for astronaut age range (35-50 years old)
 - Growth trend estimated from NHANES and projected to year 2015

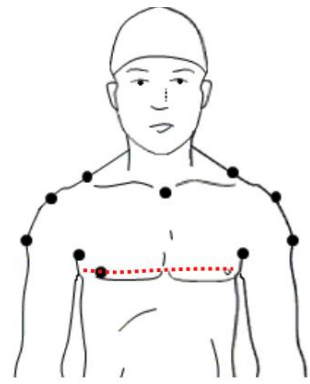


Critical Body Measurement Types

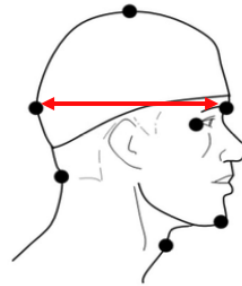
- NASA Standards and Requirements also define the types of critical body measurements
- For example, spacesuit critical measurements include, but not limited to:



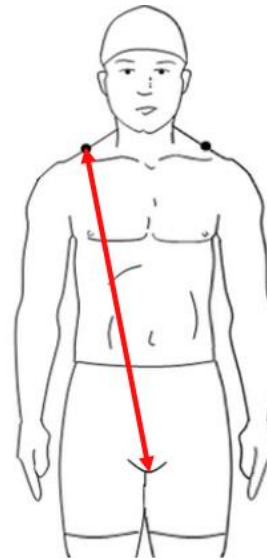
Stature



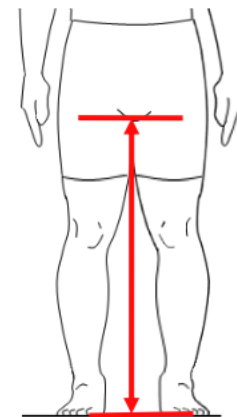
Chest Circumference



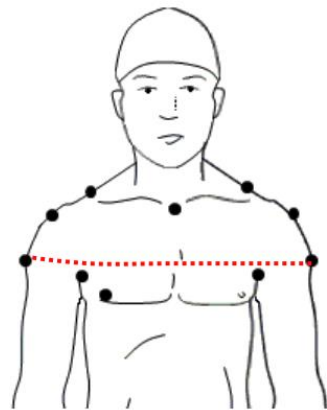
Head Length



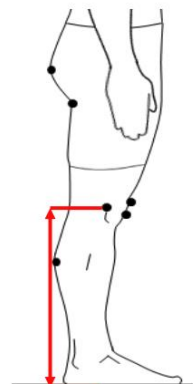
Vertical Trunk Diameter



Crotch Height

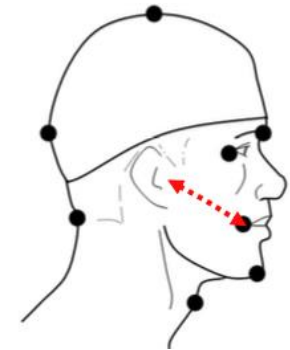


Shoulder Circumference



Knee Height

Suit Type Specific Measurements

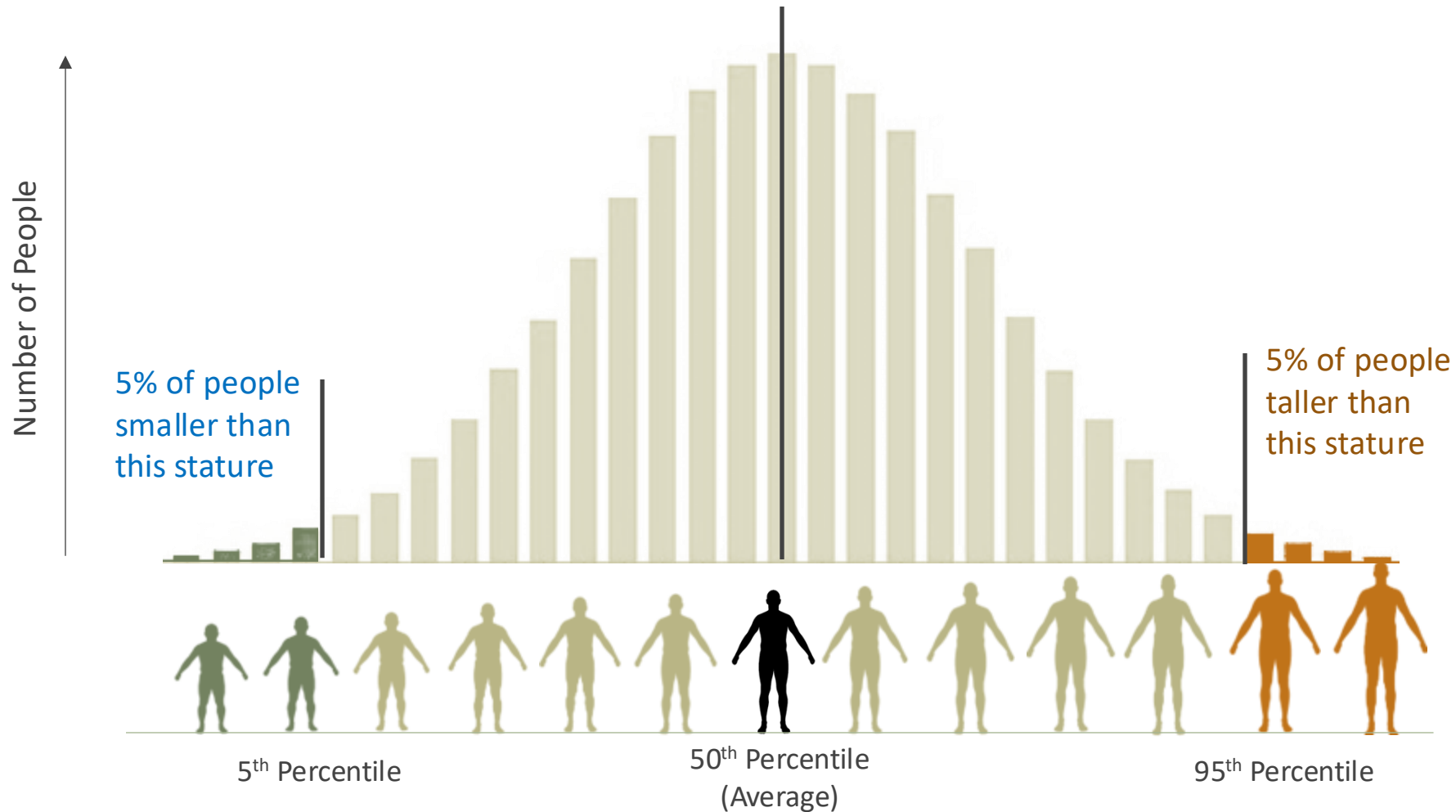


Communication Carrier Electronic Module



Critical Measurement Limits in Percentile Representation

- Requirements define the accommodation limits (smallest and largest measurements to be accommodated)
- Accommodation limits generally correspond to the prescribed percentile of the crew population, e.g., 5th-95th percentile or 1st-99th percentile stature

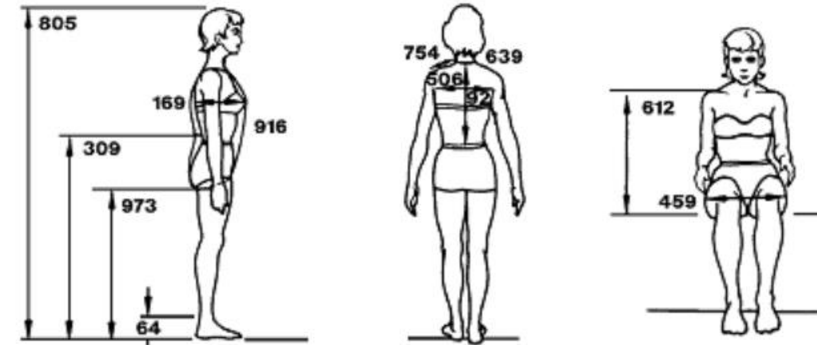


Determining Measurement Limits

- NASA spacesuit measurement limits aim to accommodate 90% of crew population
- In the past, measurement limits were defined by the range from 5th females to 95th males
- However, historical data showed some suits and hardware accommodated less than 90%

Why?

NASA-STD-3000 (1995)

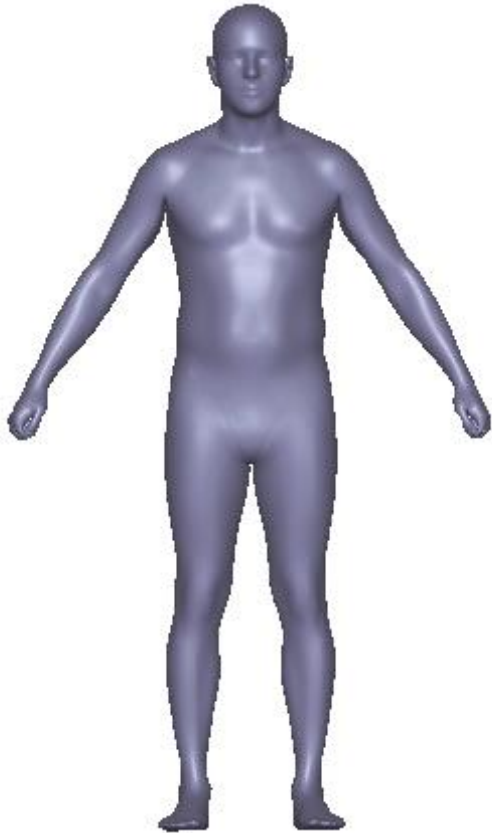


No.	Dimension	Female 5 th Percentile	Male 95 th Percentile
805	Stature	148.9 (58.6)	190.1 (74.8)
64	Ankle Height	5.2 (2.0)	15.8 (6.2)
236	Bust Depth	17.4 (6.8)	28.2 (11.1)
916	Vertical Trunk Circumference	136.9 (53.9)	182.6 (71.9)
506	Inter-Scye	32.4 (12.8)	45.4 (17.9)
639	Neck Circumference	34.5 (13.6)	41.9 (16.5)
754	Shoulder Length	11.3 (4.4)	19.0 (7.5)

Unit: cm (inches)

Multi-Variate Characteristics of Anthropometry

- Body measurements are multi-dimensional, i.e., needing more than two measurements (“multi-variate”)
- Even for persons of the identical “average” stature and body weight, all other measurements vary substantially
- The table below shows 10 sample subjects whose stature and body weight are near the 50th percentiles
- Their other measurements often exceeds 5th-95th percentile limits, sometimes as low as 1st or as high as 97th percentile



Males: 5 ft. 9 in. tall, 165 lb.



Females: 5 ft. 4 in. tall, 155 lb.

Measurement Percentiles

	Stature	Body Weight	Head Circumference	Chest Circumference	Waist Circumference	Thigh Circumference
Subject 1	Near 50 th	Near 50 th	5	70	65	68
Subject 2			84	94	64	59
Subject 3			57	76	43	23
Subject 4			77	97	24	20
Subject 5			77	57	13	33
Subject 6			91	28	54	25
Subject 7			38	60	96	9
Subject 8			14	15	26	72
Subject 9			40	33	54	25
Subject 10			17	36	1	80

Defining Limit from Multi-Variate Measurements

- Multi-variate nature of anthropometric data imposes a unique challenge in design and accommodation
- In most design problems, multiple measurements (e.g., stature and body weight) are simultaneously considered
- For example, some NASA programs intend to accommodate 90% of people in astronaut-like population
- To accommodate 90% of people, at which percentile extreme do we want to truncate each measurement?

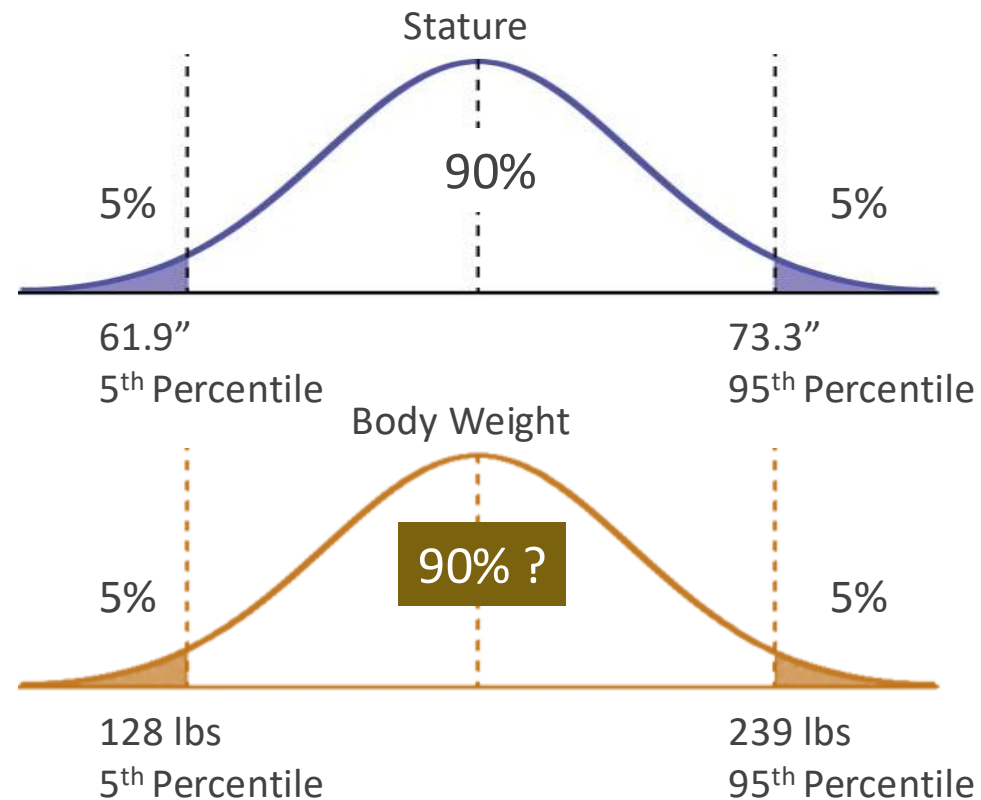
Goal: Accommodate 90% of population

Thus, suppose we truncate people at 5th & 95th percentile measurements

Step 1: Exclude people with *stature* < 5th percentile and > 95th percentile

Step 2: Exclude people with *body weight* < 5th and > 95th percentile

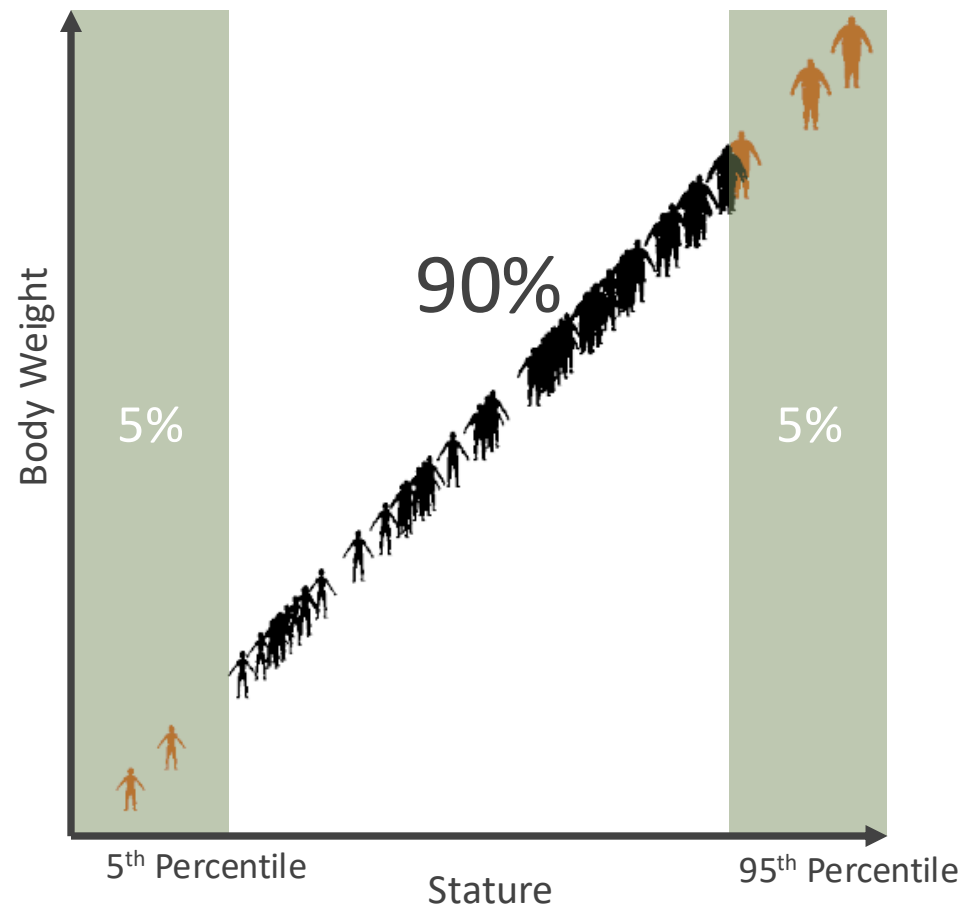
Question: How many people will be remaining after truncations? 90% or 80%?



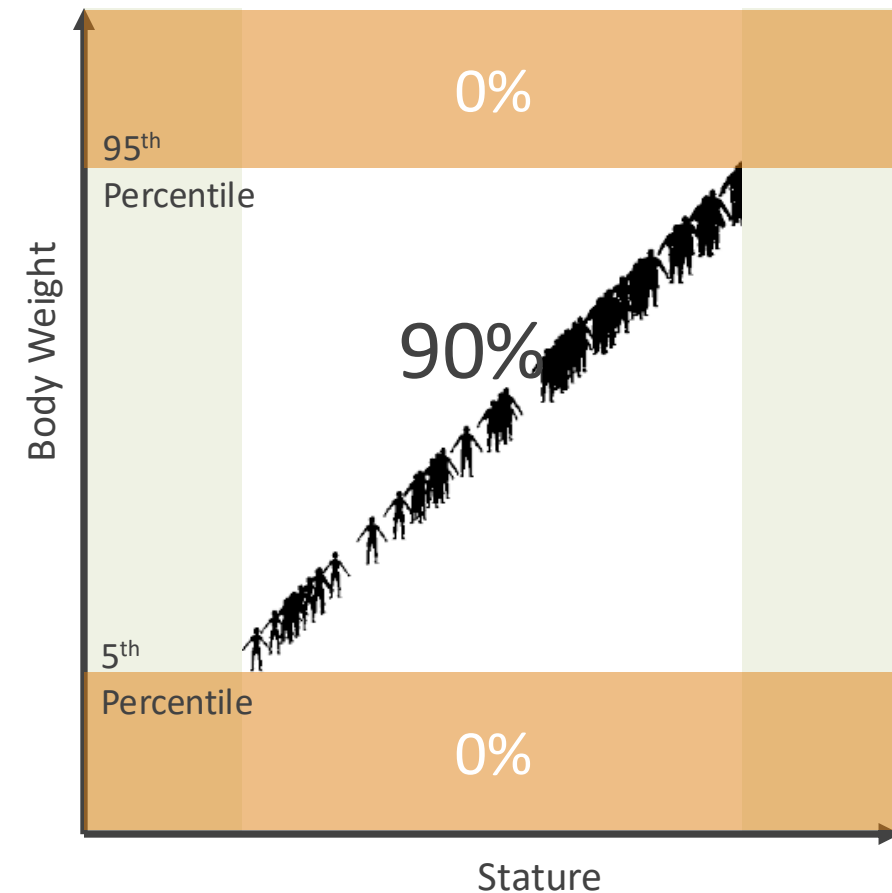
Difficulty of Multiple Measurement Truncation (*Univariate Condition*)

Hypothetical Univariate-Like Scenario: Stature and body weight perfectly covary with each other

Step 1: Truncate by stature at 5th and 95th percentiles.
90% of cases are remaining after truncation



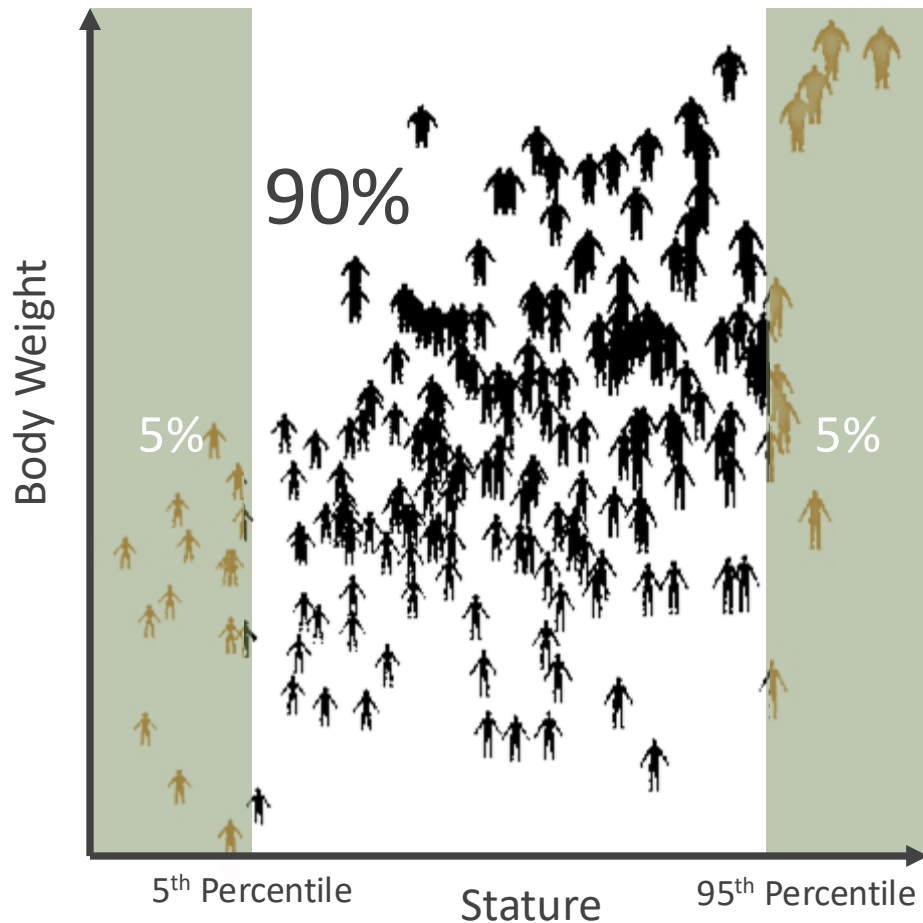
Step 2: Truncate by body weight. But no data left to be truncated. 90% of cases are still remaining.



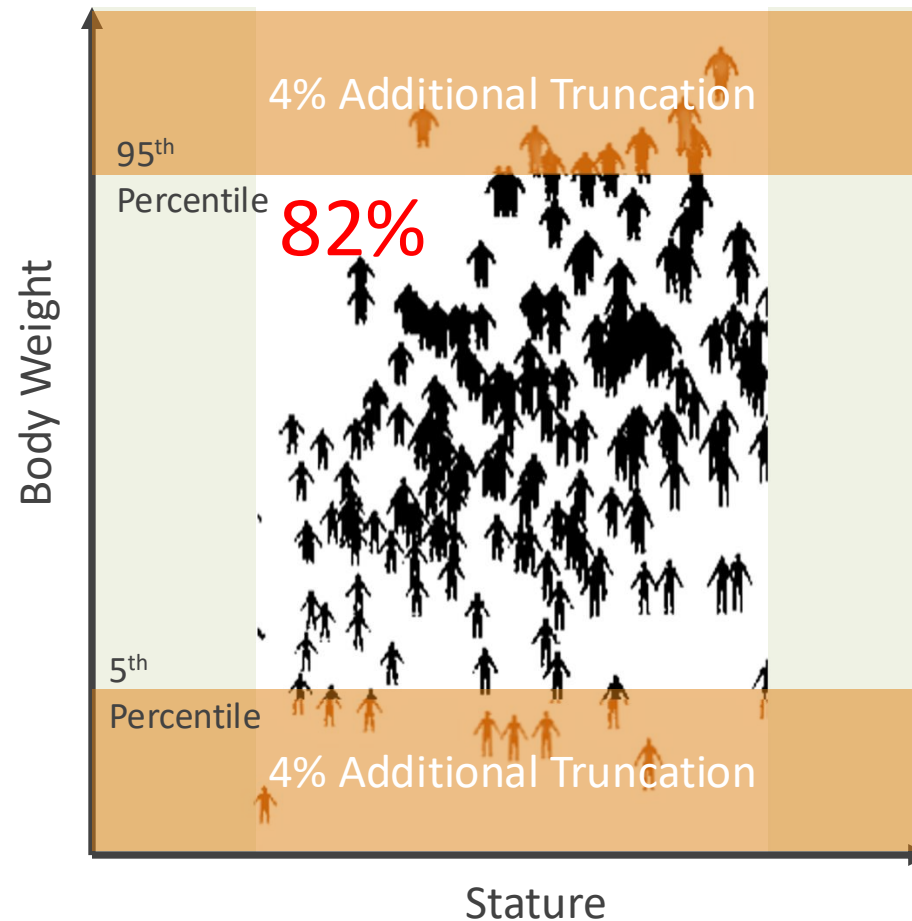
Difficulty of Multiple Measurement Truncation (*Multivariate Condition*)

Hypothetical Multivariate-Like Scenario: Stature and body weight vary with each other only in part

Step 1: Truncate by stature at 5th and 95th percentiles.
90% of people remain after truncation

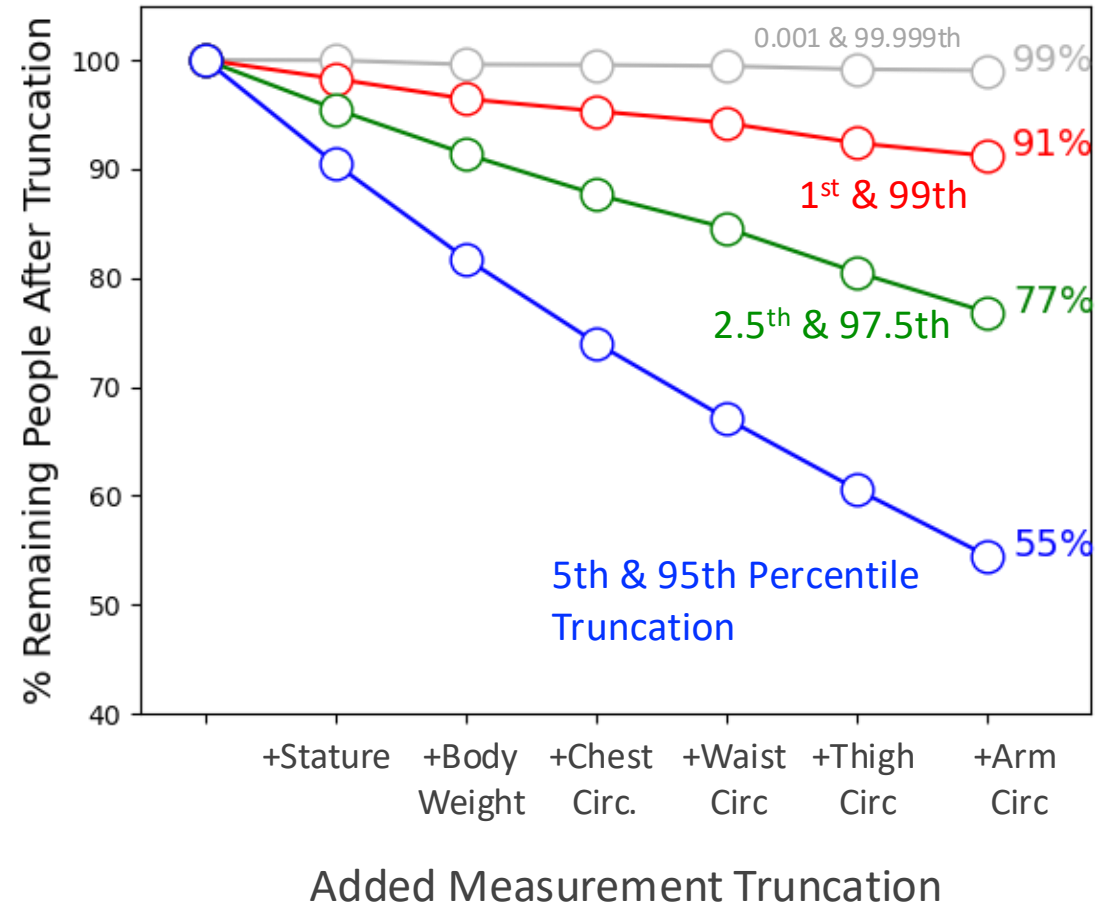


Step 2: Truncate by body weight, additional 8% cases are excluded. 82% of people remain.



Simulation of Multiple Measurement Truncation

- As more different type of measurements are included for truncation, more people are excluded
- For example, if 6 measurements were considered for hardware design:
 - Truncation at 5th and 95th percentiles: 45% of people excluded, 55% retained
 - Truncation at 2.5th and 97.5th percentiles: 23% excluded, 77% retained
 - Truncation at 1st and 99th percentiles: 9% excluded and 91% retained
- In other words, if we want to accommodate 90% of population the data should be truncated at 1st and 99th percentiles, not 5th and 95th percentiles



New Crew Accommodation Requirements

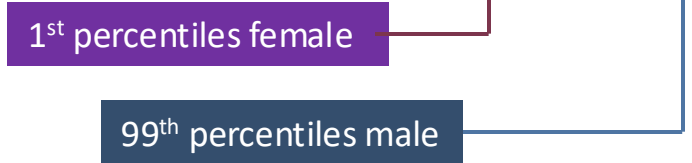
- Due to the multi-variate characteristics of anthropometry, 5th – 95th percentile limit excluded more crewmembers from accommodation than expected
- As a result, some hardware was estimated to accommodate less than 70% of crew population
- The new NASA standards enhanced the accommodation limit to **1st percentile female to 99th percentile male** to ensure 90% accommodation

NASA STD-3001 (2007)

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	59.1 (23.3)	68.8 (27.1)

1st percentiles female

99th percentiles male



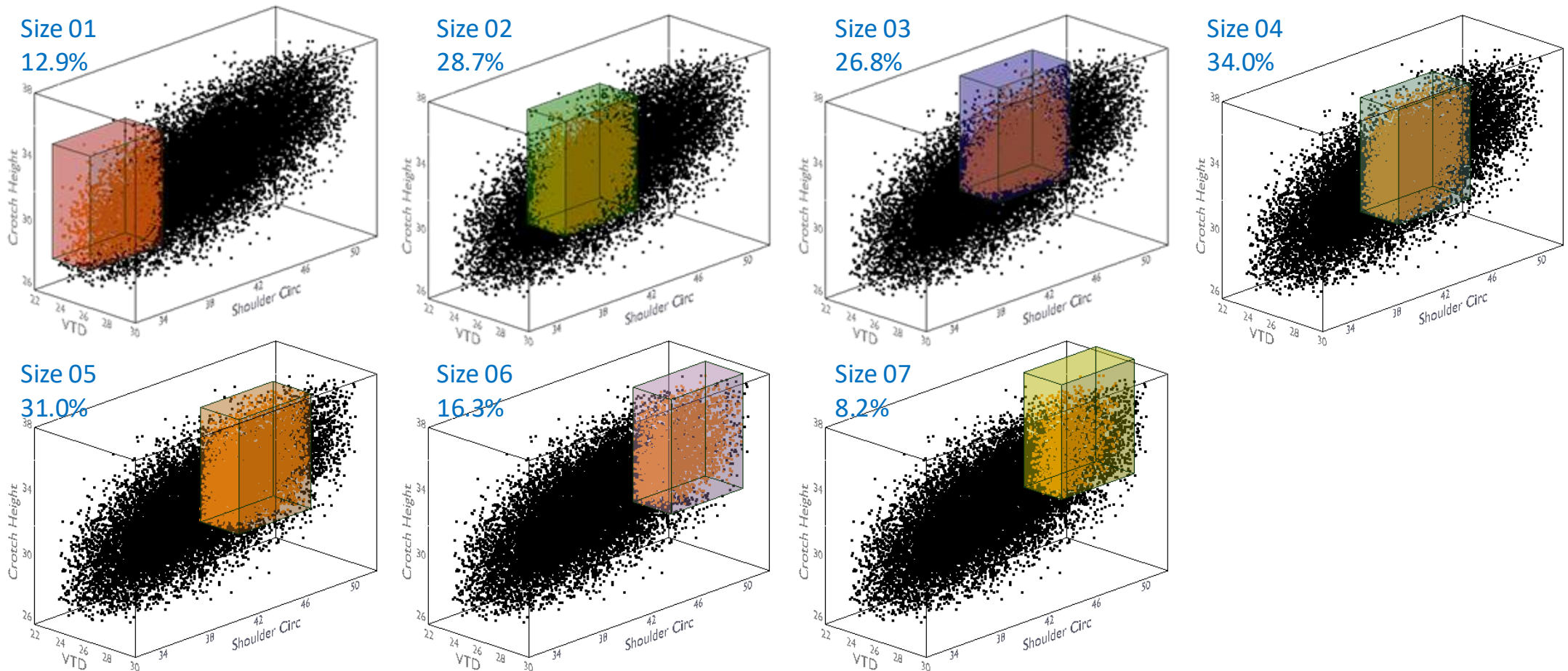
Sizing Scheme: Spacesuit Liquid Cooling and Ventilation Garment (LCVG)

- Sizing scheme defines how many sizes to be built and the body measurements each suit size aim to accommodate (e.g., small, medium, large, x-large)
- A case study demonstrates sizing scheme development, based on Liquid Cooling and Ventilation Garment (LCVG)
- LCVG is a form-fitting under-garment worn inside of the spacesuit
- LCVG functions as a microclimate conditioning system to maintain the core body temperature during EVA
- Chilled water is supplied from the portable life support system (PLSS), then circulated through 300-foot flexible tubes woven throughout the mesh



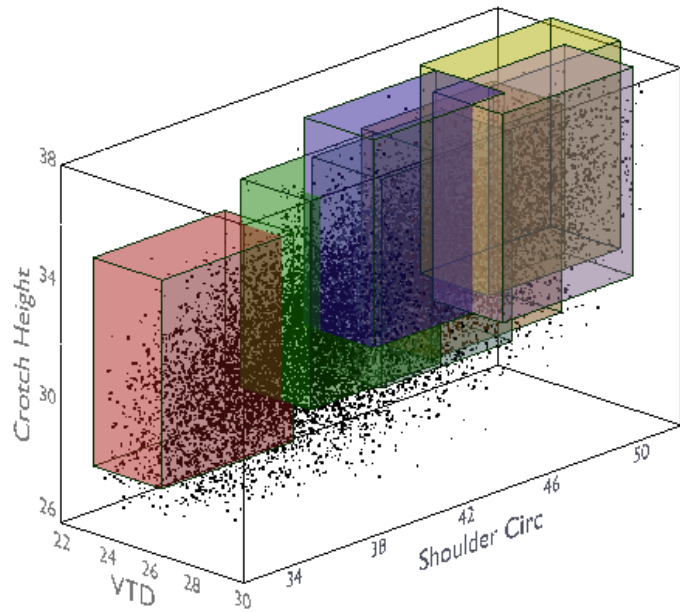
Baseline Sizing Scheme Assessment

- The existing NASA LCVG for Shuttle EMU has 7 LCVG sizes, from X-Small Long (01) to XX-large long (07)
- Accommodation rate (proportion of the dots contained in boxes) is 81.3% (each box ranges between 8.2-34.0%)
- Average Fit score across all boxes: 20.0 (each box ranges between 21.2-23.9%)
- Proportion of “good fit” cases (proportion of cases with fit score ≥ 22): 68.5%

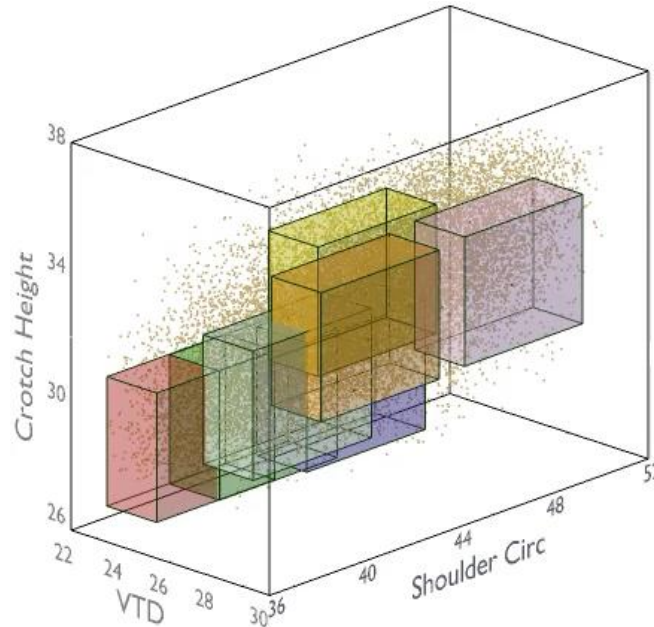


Permutation of Sizing Scheme for Maximum Accommodation

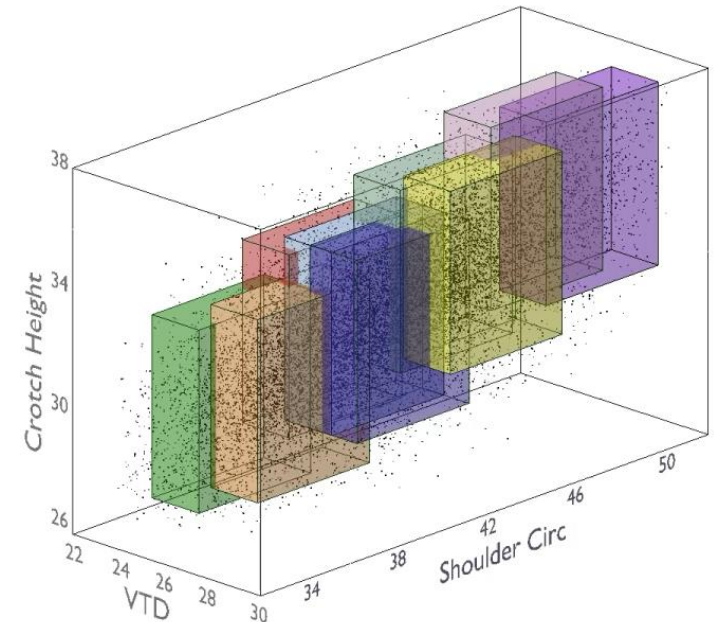
- More sizing schemes were built and tested; Accommodation performances were compared
- Across different sizing schemes, coverage range did not vary substantially, except for CrH in the baseline scheme
- However, accommodation rate and good fit proportion showed substantial improvements with new sizing schemes



Baseline Sizing Scheme



Baseline adjusted for maximum fit score



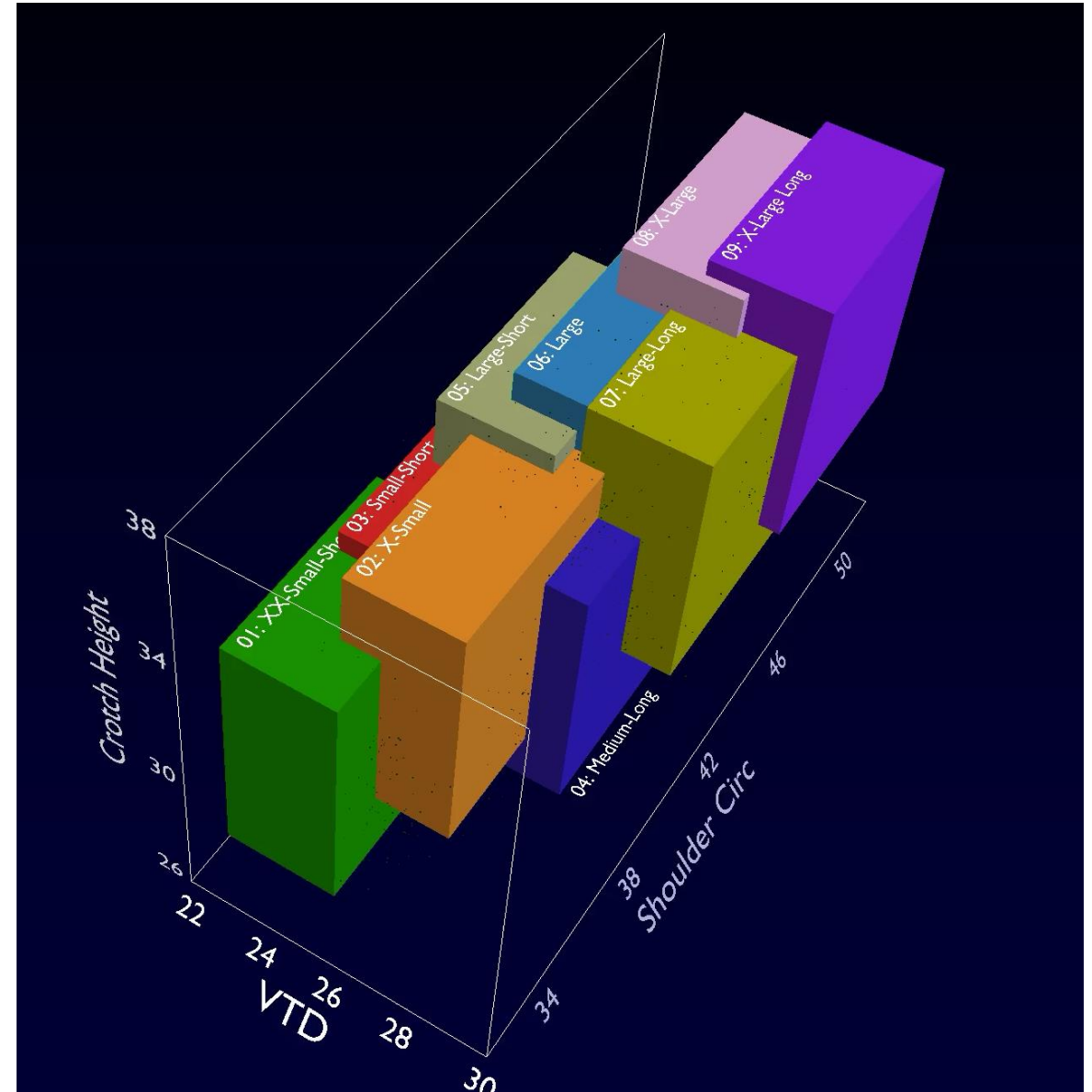
+2 Size Buckets

Accommodation Rate		81.3%	92.2%	96.9%
Good Fit Proportion		68.5%	82.7%	89.6%
Coverage Range	VTD	0.7 - 98.9	1.3 - 99.1	0.7 - 99.1
	Shoulder Circ	1.3 - 99.4	1.6 - 98.6	1.3 - 99.0
Percentiles	Crotch Height	3.5 - 99.7	0.9 - 99.4	0.9 - 99.6

Selected Sizing Scheme

- Composed of 9 size groups
- 96.9% of crew population is expected to be accommodated
- 89.6% of crew population is expected to show “good fit” (fit score ≥ 22)
- Given these metric values equal to or exceeded the 90% crew accommodation target, this 9-size system was ultimately selected by NASA for the next generation government reference design LCVG

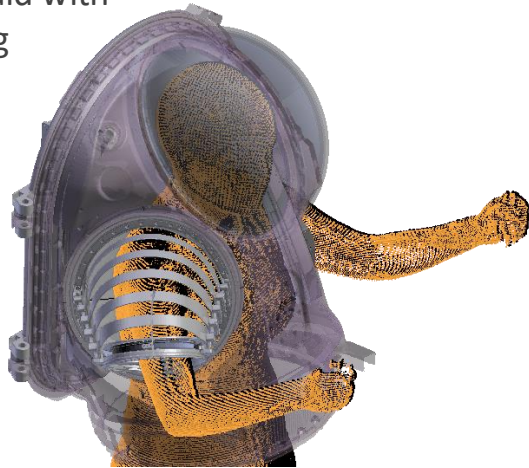
	Accommodation Rate	Average Fit Score
01 XX-Small-Short	13.5%	23.5
02 X-Small	26.8%	21.7
03 Small-Short	23.9%	24.0
04 Medium-Long	34.7%	21.3
05 Large-Short	22.8%	24.2
06 Large	34.0%	23.4
07 Large-Long	26.8%	21.3
08 X-Large	14.7%	23.4
09 X-Large-Long	13.8%	21.8



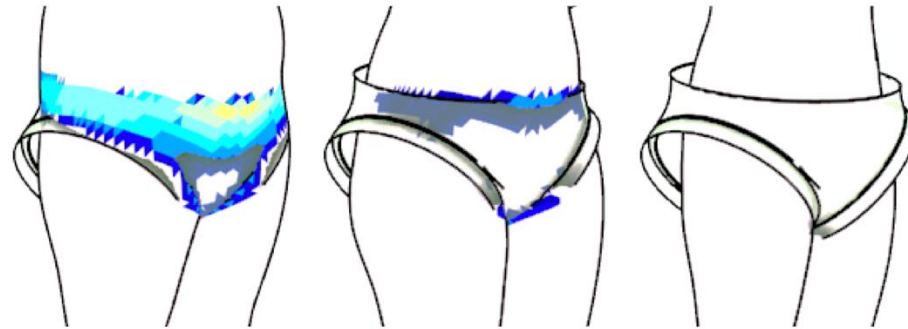
Fit Testing: (1) Virtual Method

- Once completing suit and garment design, fit should be tested for the crew population
- Virtual fit test can effectively estimate the population fit, often without physical suit or garment
- Design can be iteratively updated for optimal fit before finalization

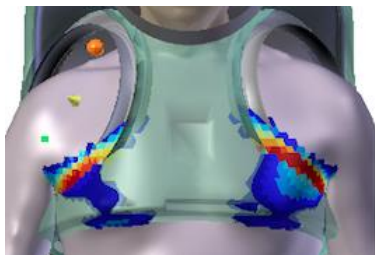
3D body scans overlaid with spacesuit 3D drawing



Suit-to-body contact pattern estimation

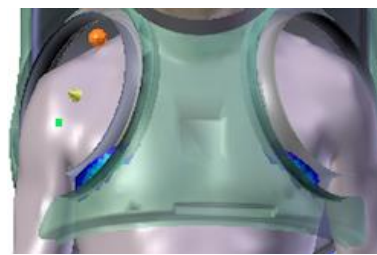
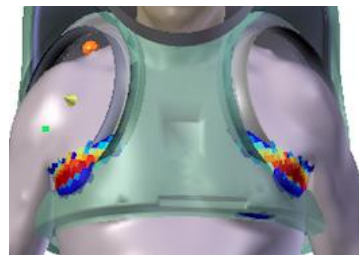


Maximum Overlap

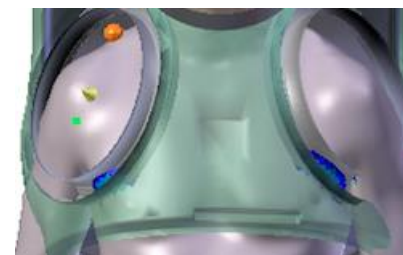


Unlikely to fit

Intermediate Overlap



Borderline fit



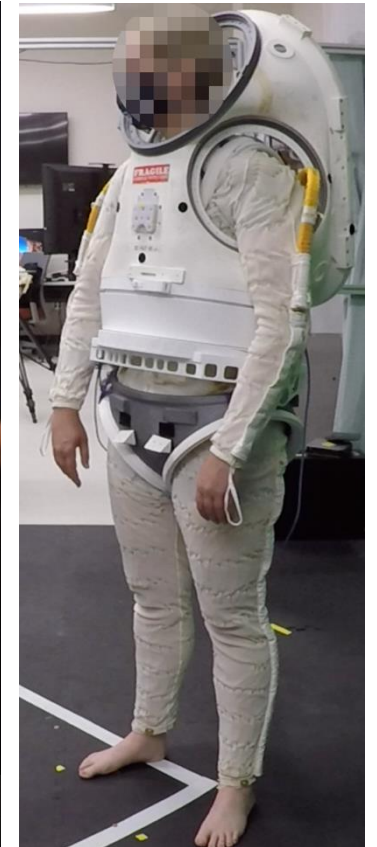
Minimum Overlap



Likely to fit

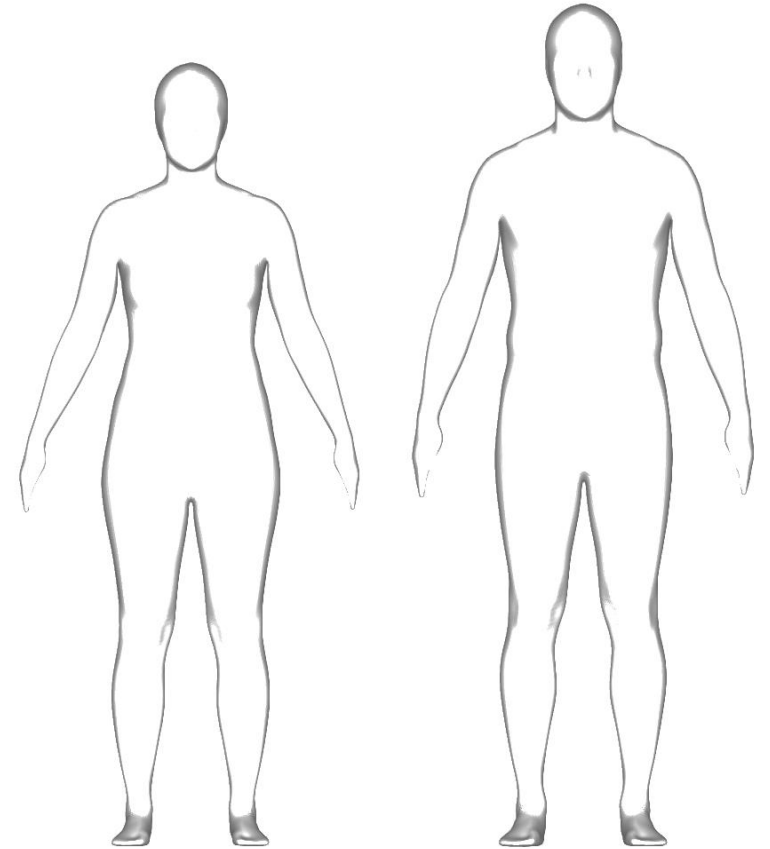
Fit Testing: (2) Physical Method

- Physical fit should be tested with human subjects
- Fit tests use either the actual suit/garment or a mockup
- Subjects perform various functional tasks while wearing a suit
- Subject feedback is collected to identify fit, mobility and other safety issues



Subject Selection for Fit Test: "Average Subjects"

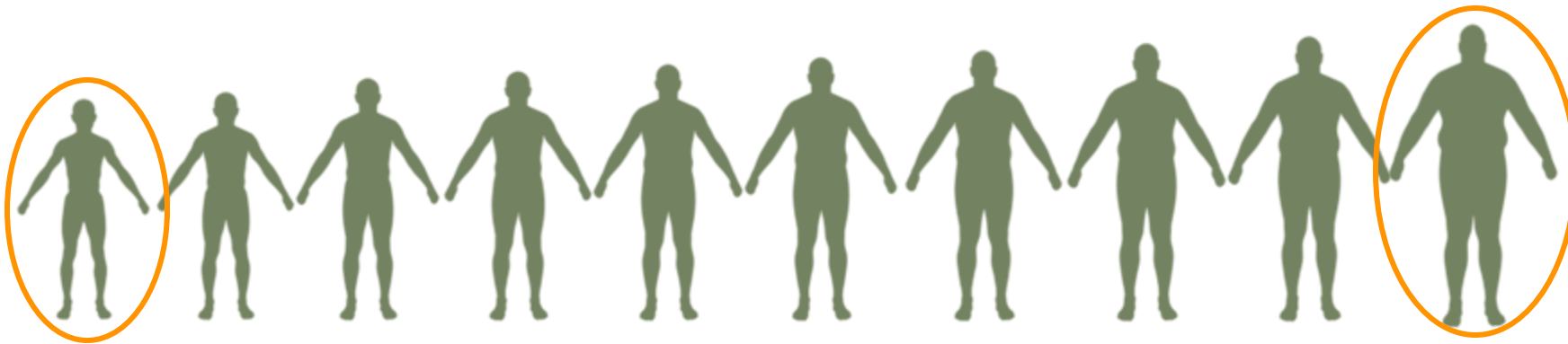
- Test subject should represent the acceptable range of crew-like population
- Without optimal test subject selection, human test results do not reveal the critical issues
- One or several subjects arbitrarily selected, are typically "average" persons
- Fast and convenient, but we need to know if the hardware can function across the range of crew population, small to large size



"Average" Body Shapes

Test Subject Selection: “Extreme Size Subjects”

- Select subjects from the extreme ends of the size spectrum (smallest and largest)
- In this way, subjects can represent the range of crew population
- In case subjects in desired body size are unavailable, select next-best person
- However, this scheme assumes body size varies in a single-dimension variable space i.e., short persons are always lightweight, tall persons are always heavy

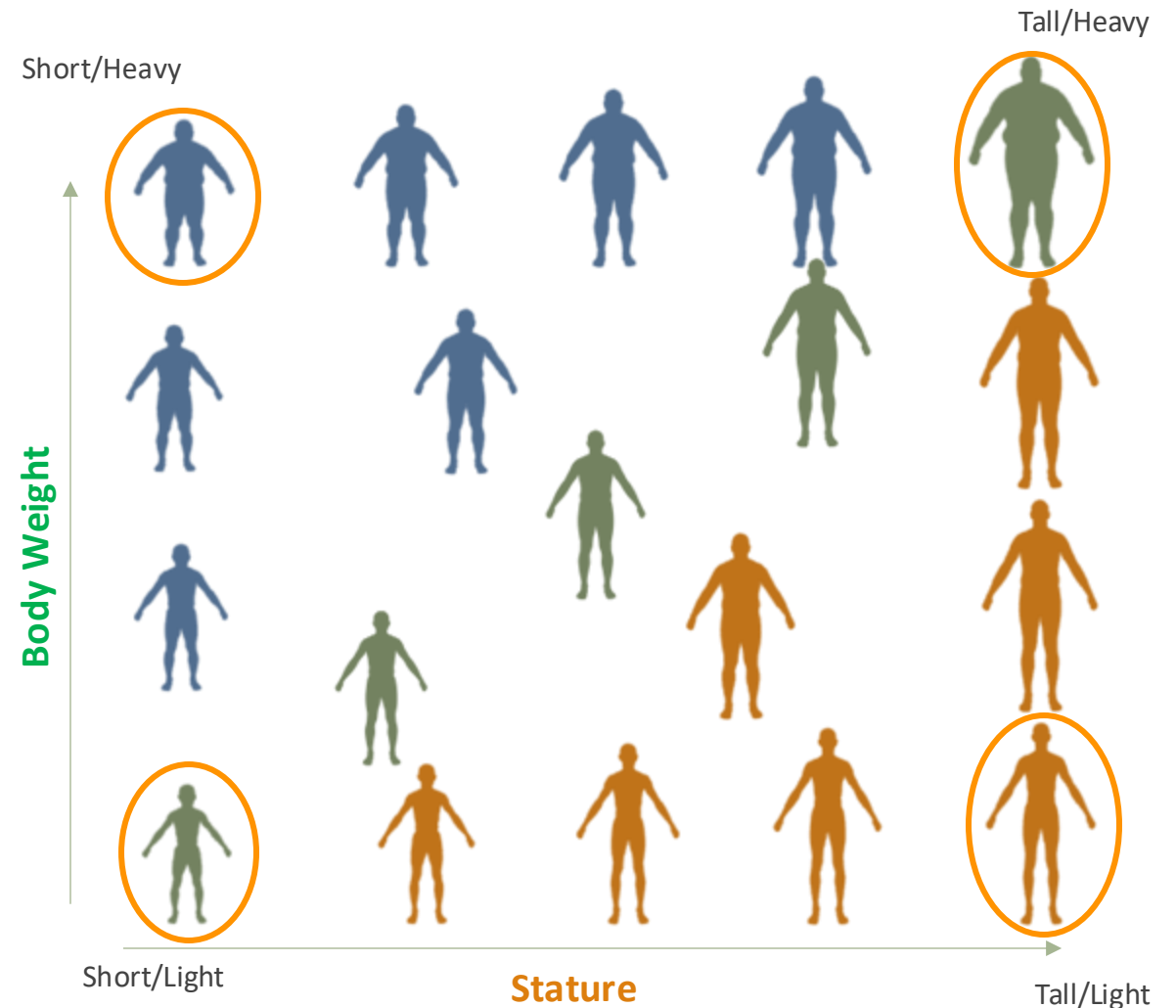


Short & lightweight
58" 95 lbs
EVA-RD-001 Minimum

Tall & heavy
77" 243 lbs
EVA-RD-001 Maximum

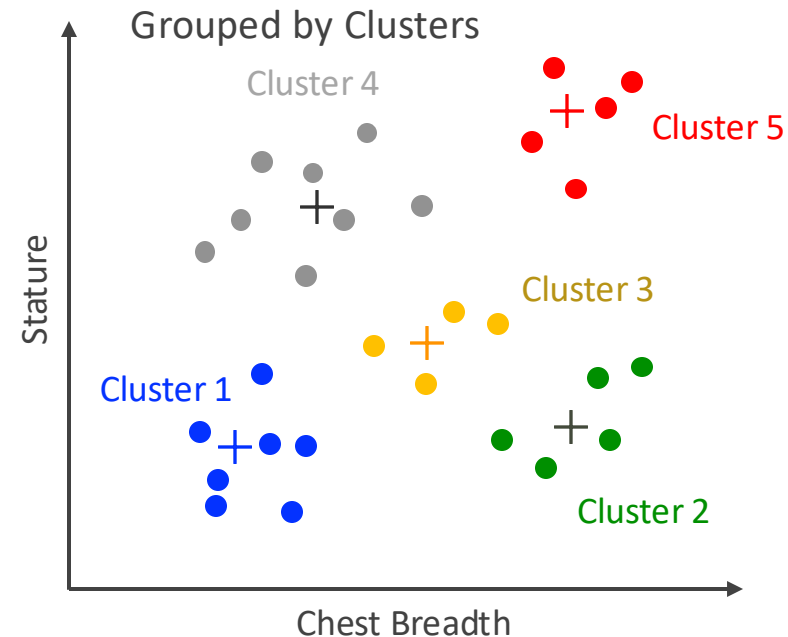
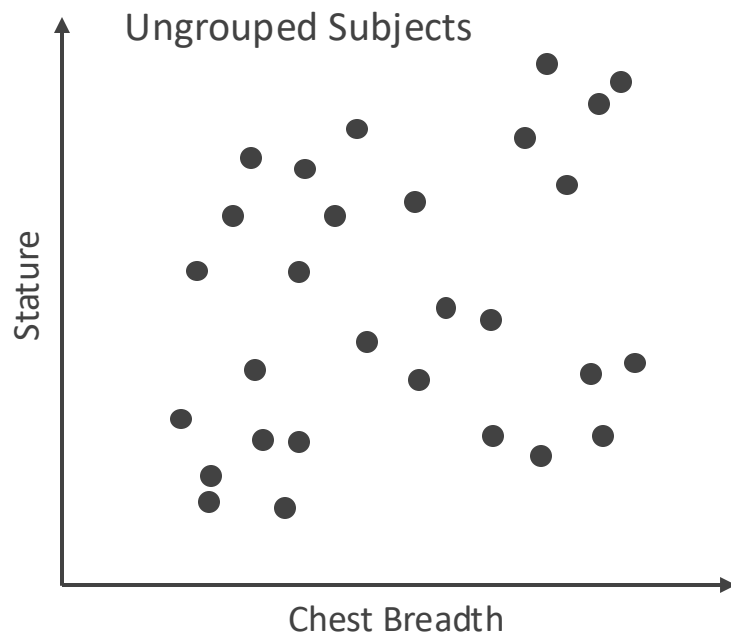
Test Subject Selection from Multi-Variate Measurements

- Body shapes vary in (at least) a two-dimensional variable space (e.g., stature and body weight)
- In this case, we need at least 2 variables x 2 extreme ends each = 4 subjects to be selected
- The required number of test subjects increases with the number of measurements
In such cases, a dimensional reduction technique should be used (e.g., principal component analysis)



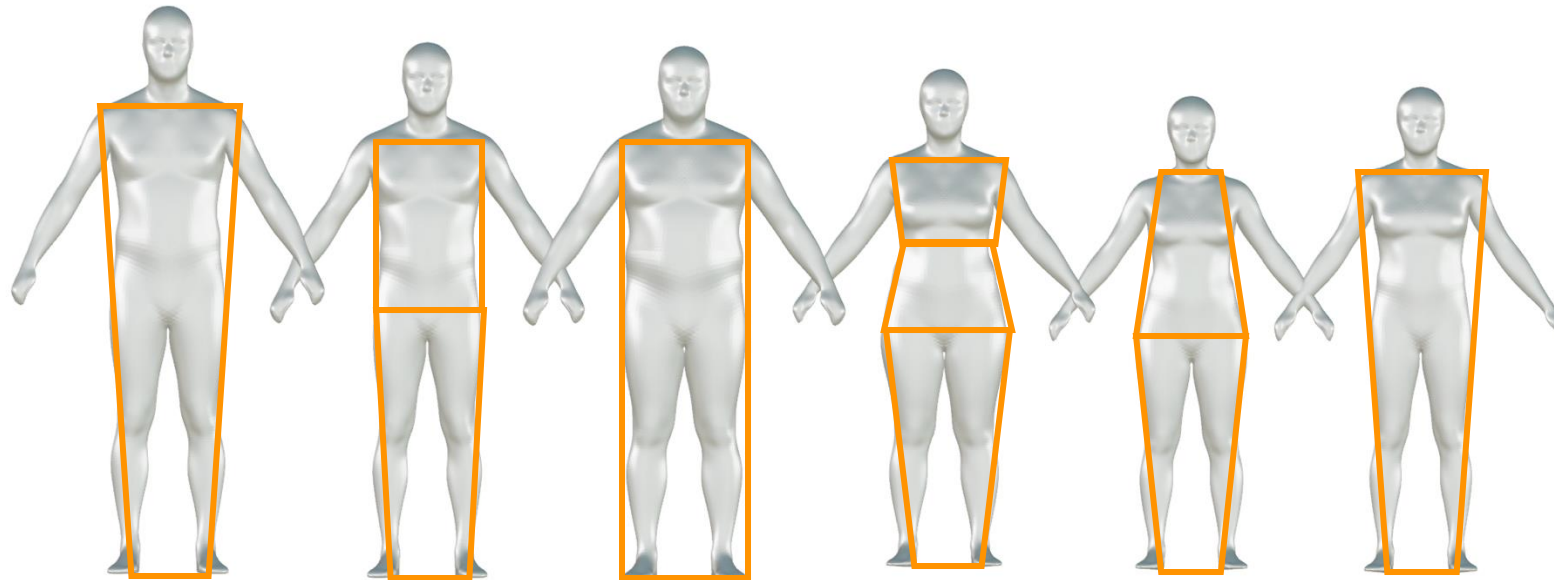
Test Subject Grouping

- In reality, however, human test subjects at the extreme anthropometry ends are not easily available
- Also, subjects “inside” the extreme bounds still provide valuable fit information
- Without a strategic method, thus, subject sampling can be substantially biased or skewed
- One of the useful techniques is to group the available subjects, and sample subjects from each cluster
- A clustering analysis (e.g., k-means clustering) forms groups by measurement similarity; For each subject, the “best matching” cluster is identified by the distance to the cluster centroids



Phenotypes: Emergent Body Shape Patterns from Clustering

- Cluster analysis produces different “phenotypes”, namely emergent patterns in body shape variations (e.g., inverse triangle, square, pear, hourglass)
- Testing with each of the clusters can optimize subject selection while covering the body shape varieties



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Stature	Blue	Blue	Blue	Red	Red	Red
Chest Breadth	Blue	Blue	Blue	Blue	Red	Red
Hip Breadth	Blue	Red	Blue	Blue	Blue	Red

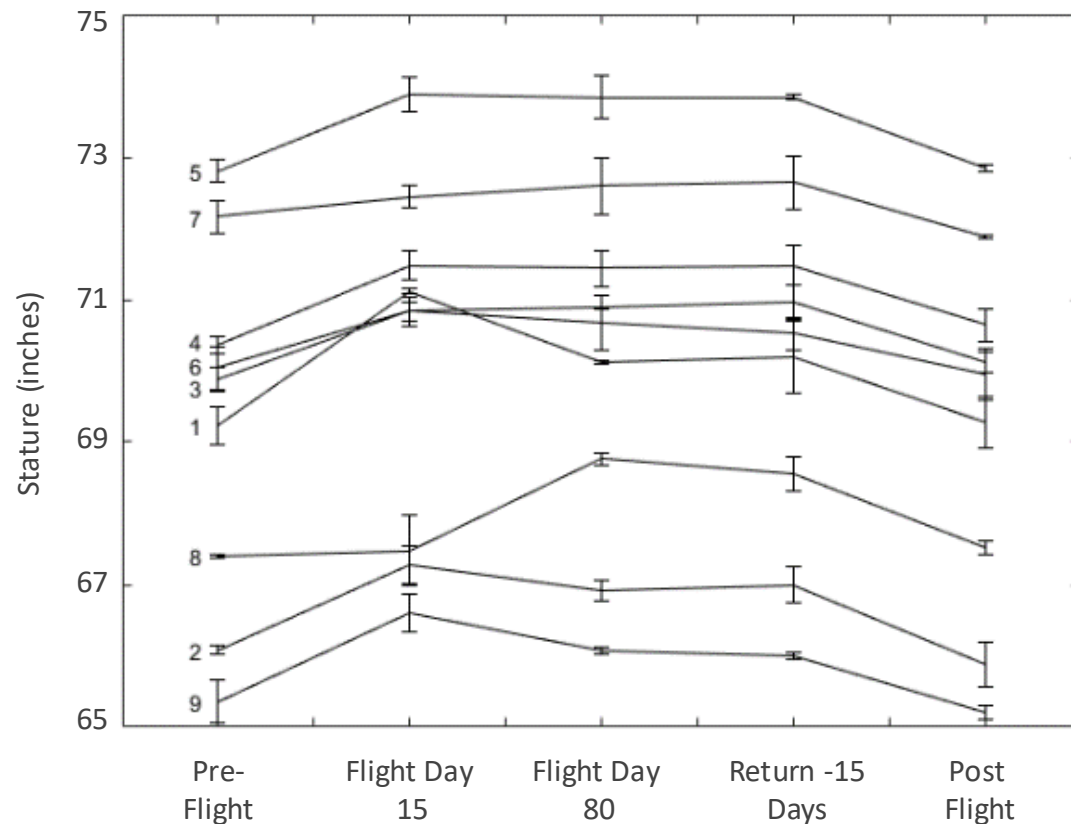
Standardized Measurements

< 0: Smaller than subject average

> 0: Larger than subject average

Other Considerations for Spacesuit Fit

- Spacesuit design should also consider anthropometry changes in microgravity, originating from spinal elongation, fluid shift and muscle atrophy
- Some suits are designed and patterned for prolonged sitting pose with the arms extended to control interfaces

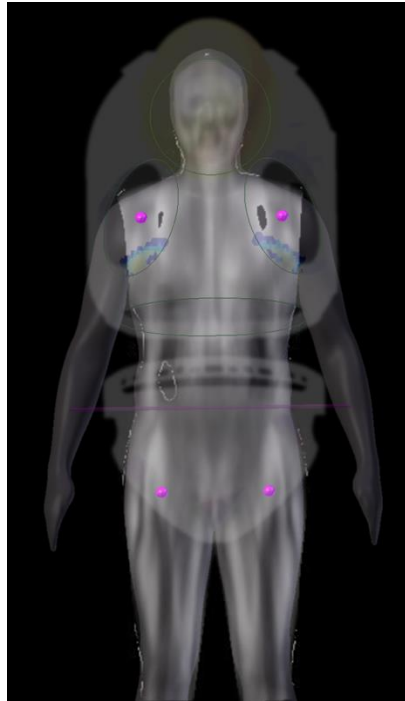


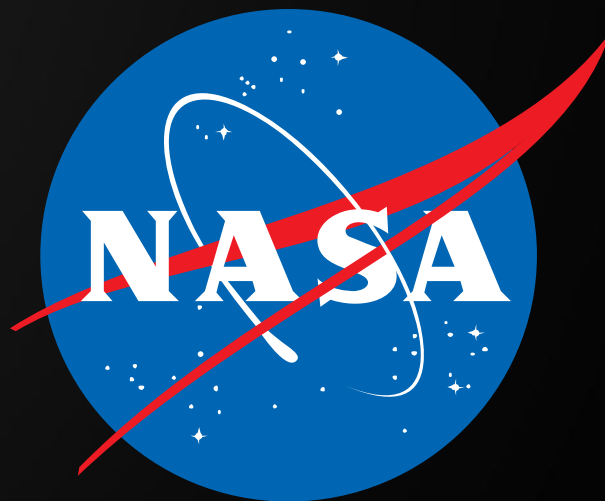
Young, Kim & Rajulu, 2018



Future Work in Spacesuit Anthropometry

- In-flight 3D body scanner can provide more detailed and precise body shape and size measurements
- Suit-to-body contacts can be directly measured and mapped with anatomical structure by medical imaging systems, for example, DEXA (dual x-ray absorptiometry) or CT scanning
- Glove sizing and fit assessments are critical important for future missions





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