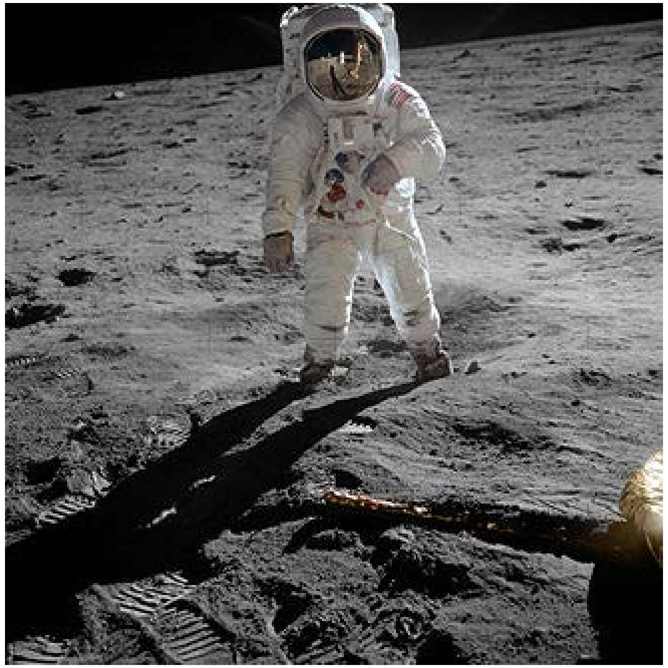
Predictive Assessments of Spacesuit Fit
Monte-Carlo Modeling and Analysis

K. Han Kim	Leidos Inc.
Linh Vu	MEI Technologies
Elizabeth Benson	MEI Technologies
Richard Rhodes	NASA Johnson Space Center
Sudhakar Rajulu	NASA Johnson Space Center

Background: Spacesuit Design & Fit

Custom Fit Design during Early Space Programs (Apollo and before)

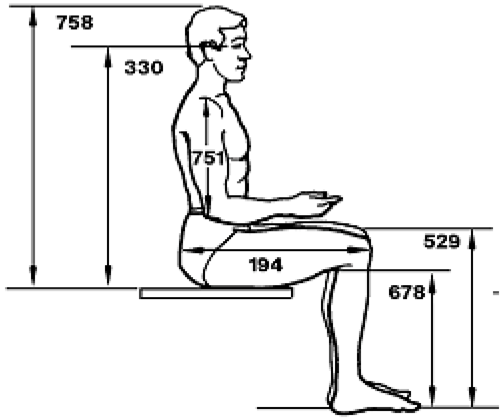
- Spacesuits were designed as a single mission garment and custom built to each astronaut's body
- With growing number of astronauts in various anthropometry, cost and logistics became an issue (Number of crewmembers flown: 24 in Apollo vs. 848 in Shuttle)

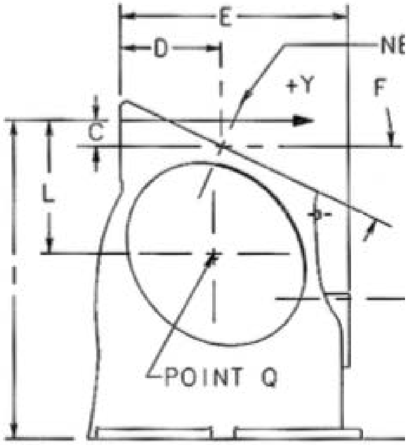


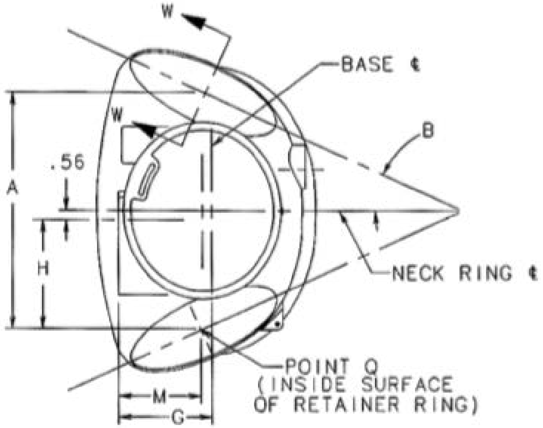
Linear Measurements Based Design

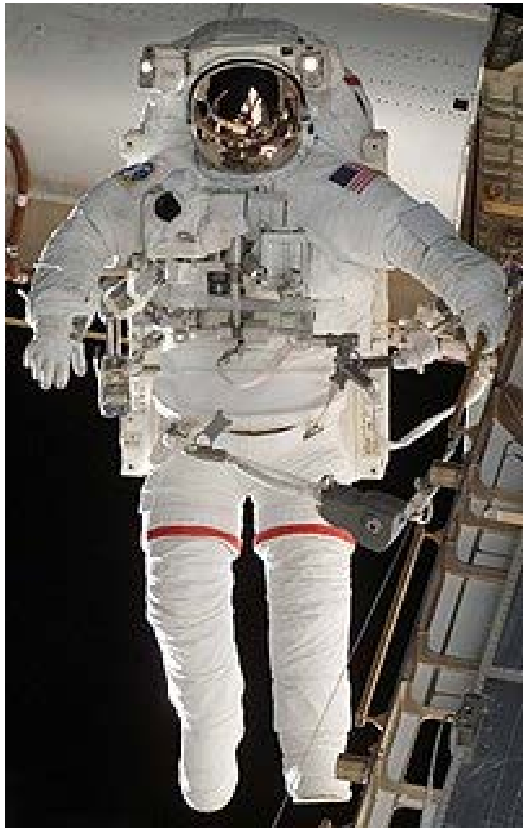
Shuttle Extravehicular Mobility Unit (EMU)

- Modular components and sizes (small, medium, large & extra large)
- Intended to fit 5th percentile female to 95th percentile male
- Design and fit based on linear dimensions of body segments
- Currently in use through Shuttle and International Space Station Programs
- Limitations of linear measurements not representing 3-D body geometry







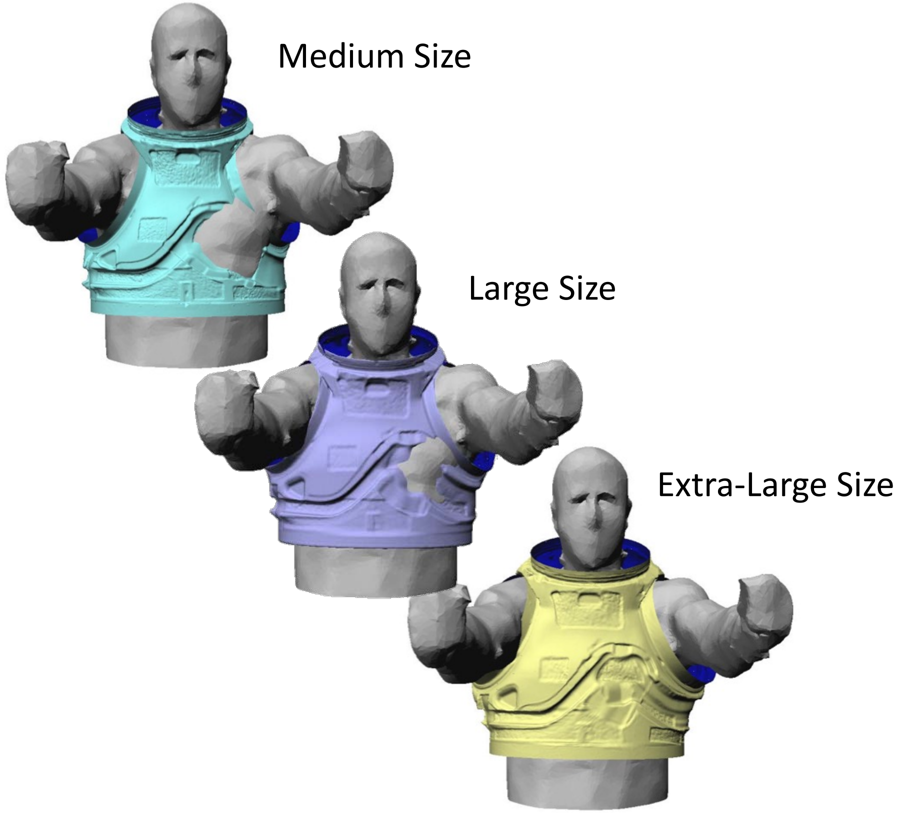


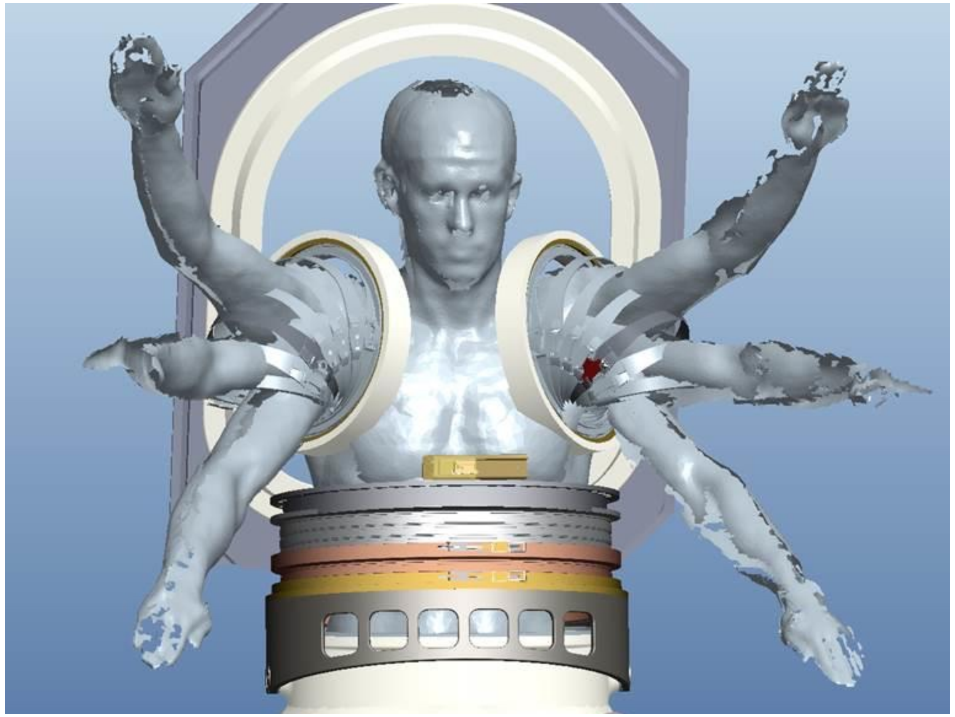
Design Assisted by 3-D Scans and Mockup Print

Z-2 Prototype Suit (2016-)

- Suits designs validated using 3-D body scans overlaid with CAD drawing from early design stages
- Fit was assessed using suit-to-body overlap and clearance and verified by 3-D printout
- However, limited number of scans may not represent the entire range of crewmember body shapes

Hard Upper Torso Assembly





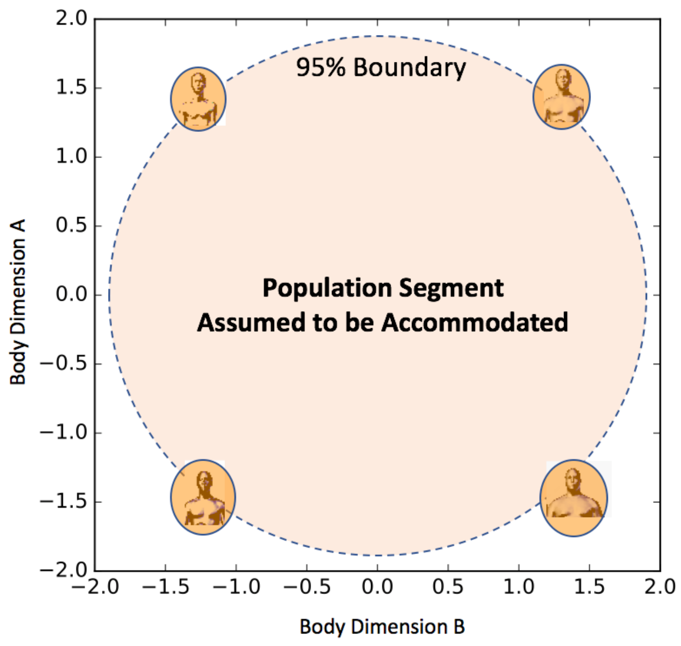
Boundary Manikins vs. Large Scale Sample Testing

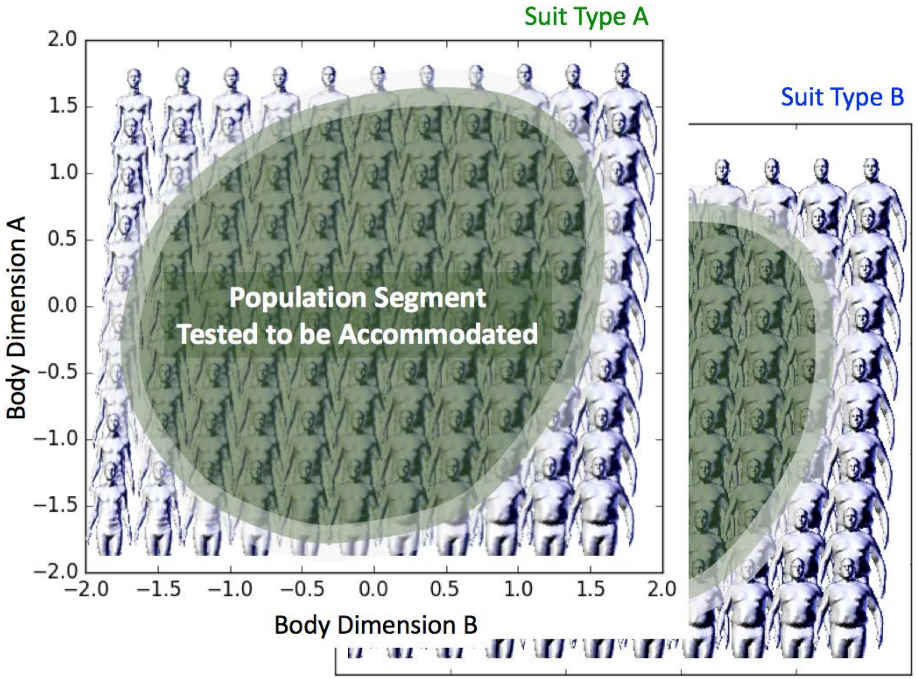
Boundary Manikin Testing

- Body geometries ("boundary subjects") were sampled to cover a pre-targeted proportion of population (e.g., 95 or 99%)
- If the selected samples "pass" the tests, the suit is considered to accommodate 95 or 99% of population
- However, the fit boundary is hypothetical approximation only, not exact quantification of accommodation

Large Scale Sample Monte-Carlo Testing (Newly Proposed)

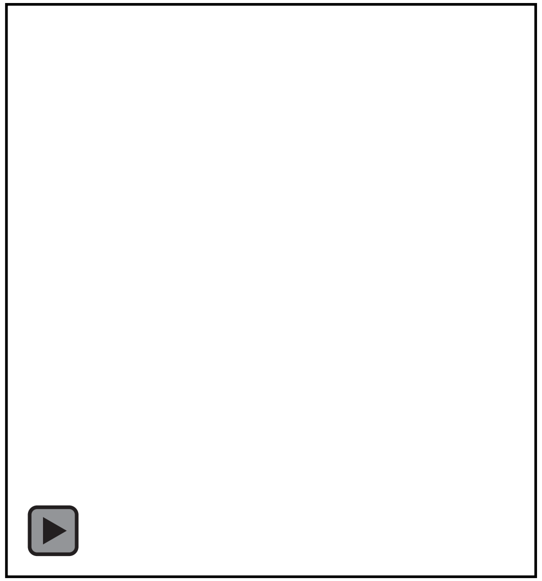
- A large number of samples are explicitly tested for fit, estimating the exact proportion of accommodated population
- Provides quantifiable evidence for engineering decisions (e.g., boundary case analysis, deltas between suit type A vs. B)
- Requires automatized fit tests using virtual manikins, which can be computationally intensive

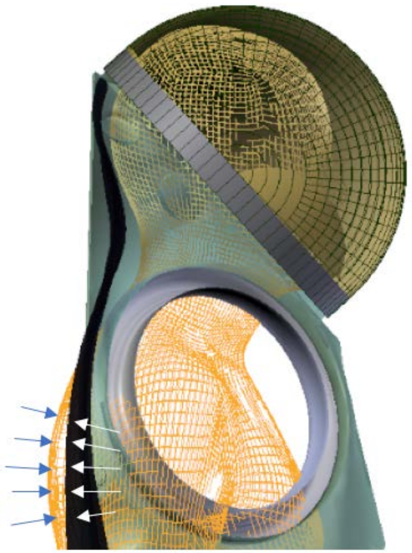


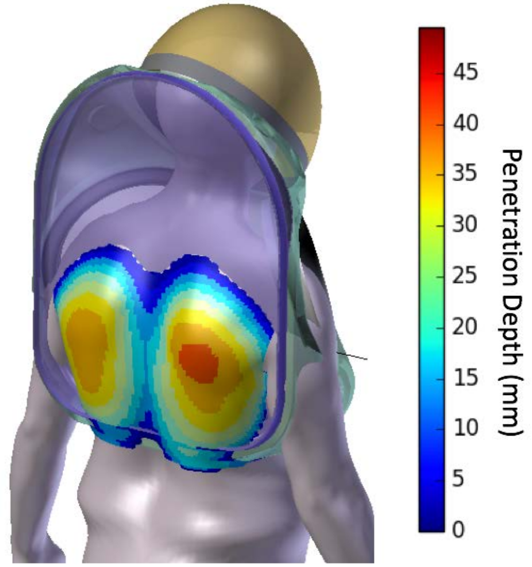


Goals & Methods: Monte-Carlo Suit Fit Analysis

- **Goal**:
  - Perform virtual fit tests for the new generation spacesuit design (Z-2.5) using large-scale samples
- **Methods**:
  - Analysis concerns a prototype design for a *small/medium size* hard upper torso (HUT) assembly
  - Manikins were iteratively positioned inside the CAD geometry of HUT for an optimal position (minimizing suit-to-body overlap, which simultaneously meets suit fit rules and requirements)
  - The resultant suit-to-body penetration depth and areas are quantified



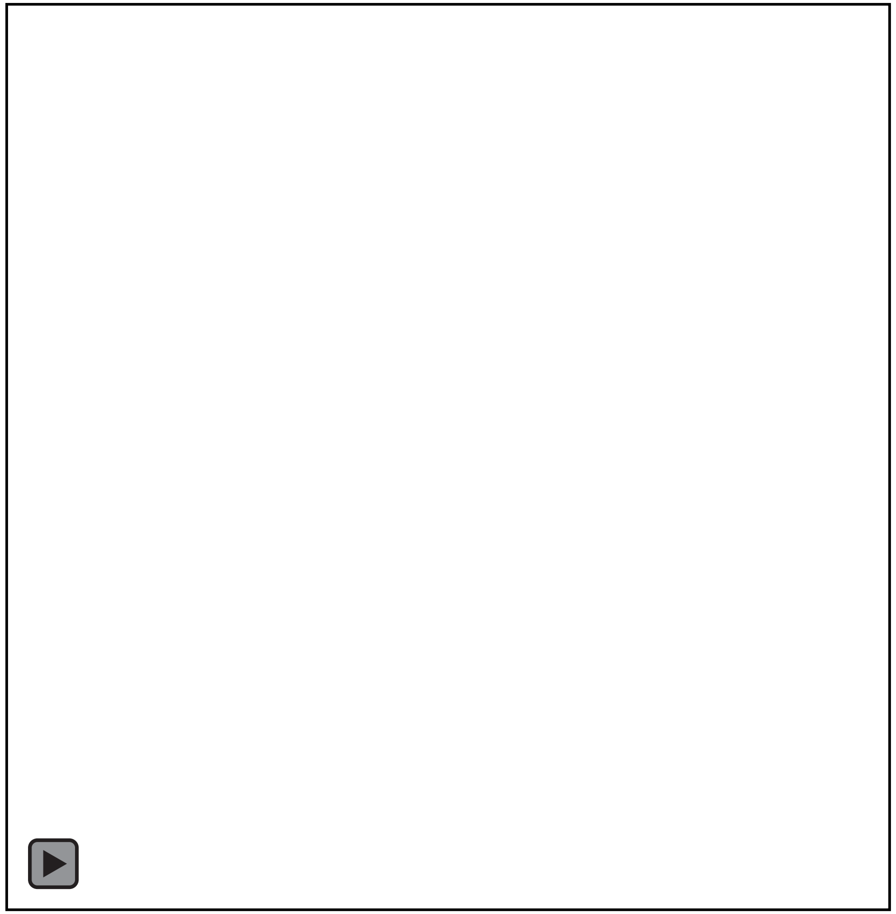




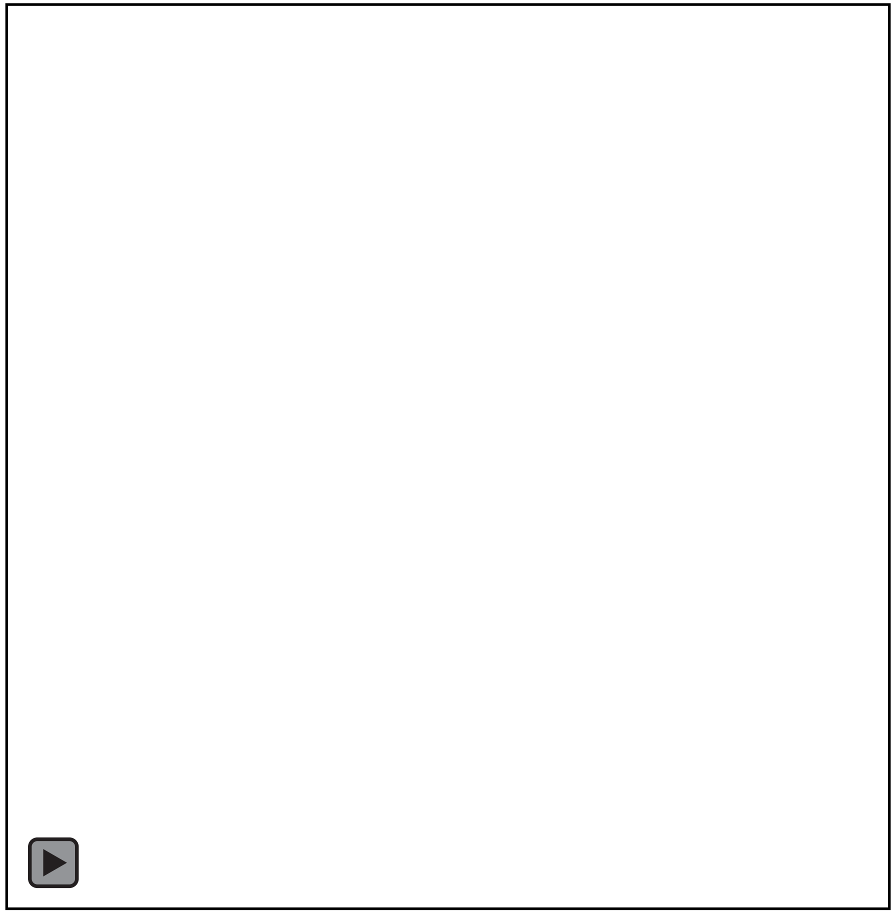
Preliminary Virtual Fit Test

- 172 male and 79 female manikins from NASA scan database were preliminarily tested for virtual fit
- Each manikin produced a unique suit-to-body overlap histogram (overlap area by penetration depth profile)

172 Male Scans

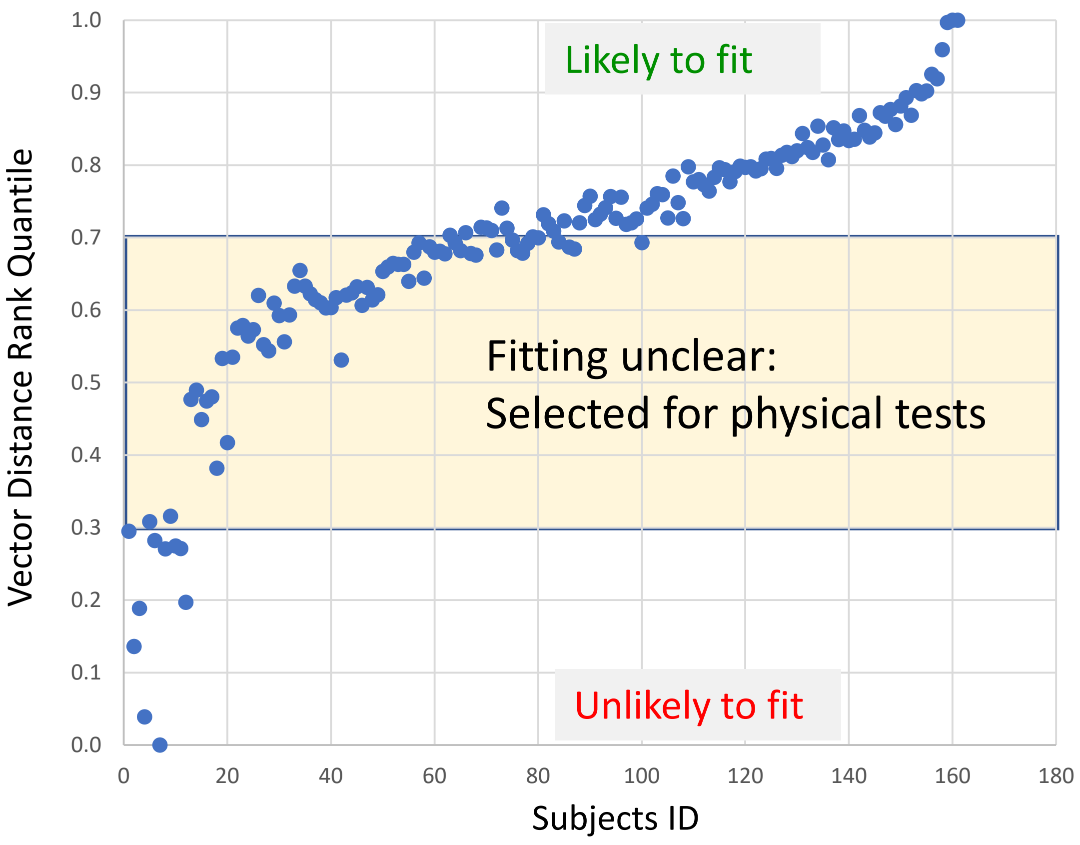


79 Female Scans

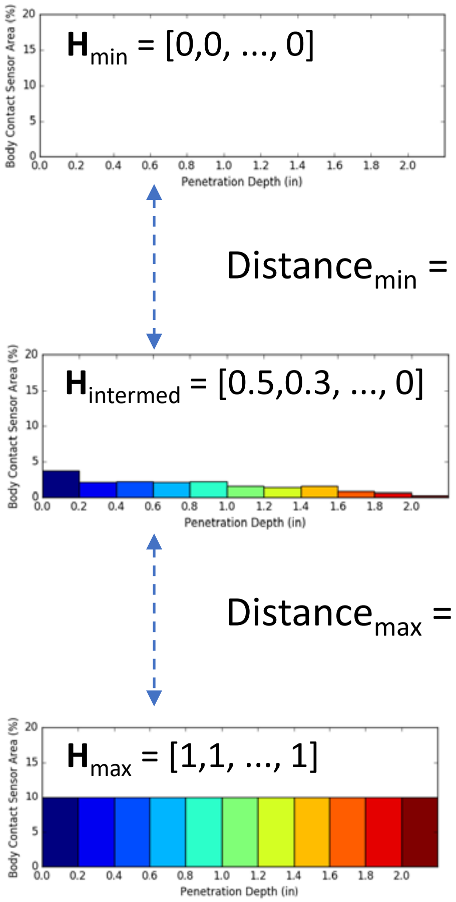


Selection of Physical Fit Test Subjects

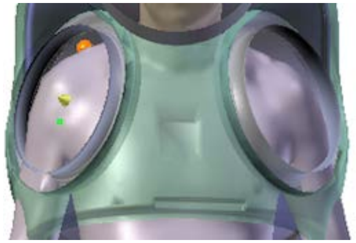
- Physical tests are necessary to define the fit vs. unfit threshold with strategically selected subjects
- Scans were sorted by histogram vector distance from hypothetical minimum and maximum overlap scenarios
- Subjects were selected from the intermediate ranks in histogram vector distances



Histogram Vector



Hypothetical Minimum Overlap

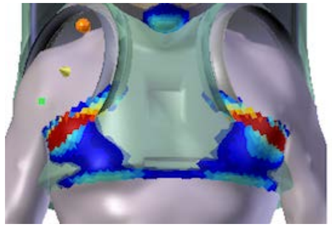


$\text{Distance}_{min} = \|\mathbf{H} - \mathbf{H}_{min}\|$

Intermediate Overlap

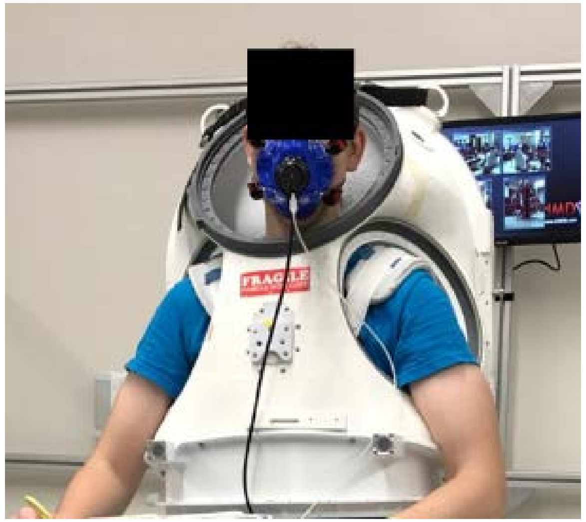
$\text{Distance}_{max} = \|\mathbf{H} - \mathbf{H}_{max}\|$

Hypothetical Maximum Overlap



Physical Fit Tests

- Selected subjects are tested using a 3-D print mockup and pressurized suit (work in progress)
- Fit vs. unfit decisions are made on subjective assessments from the wearers and experimenters





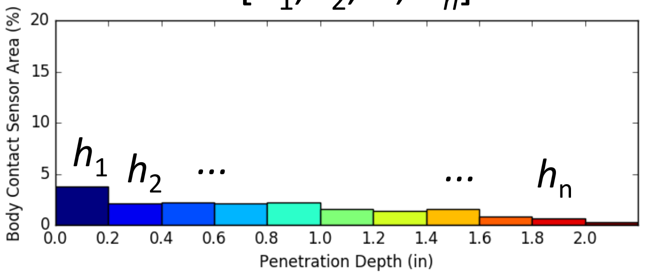
Fit Probability Model Development

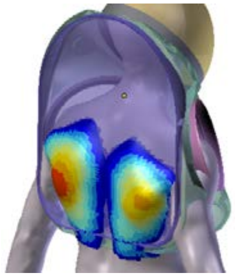
- A fit probability model was developed using *both* the virtually (manikins only) and physically tested subjects
- A logistic regression model describes the fit probability as a function of the histogram vector
- The model is iteratively and progressively updated with physical fit tests

$$Prob(\text{Fit}) = f(\mathbf{H}) = \frac{1}{1 + e^{-(\beta_0 + \beta_1 h_1 + \cdots + \beta_n h_n)}}$$

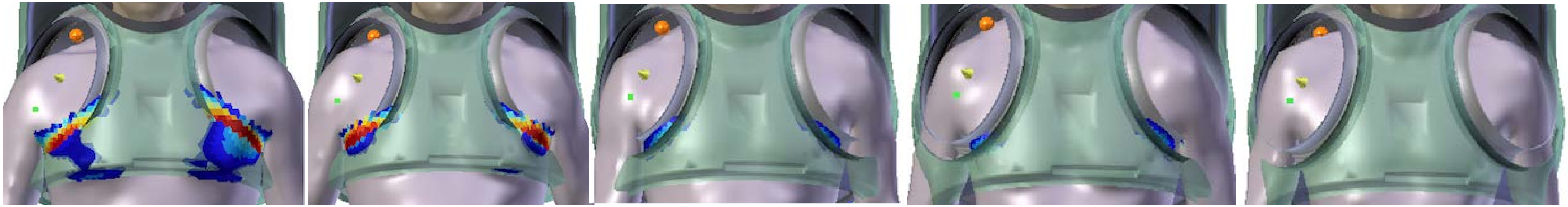
where $h_1, \ldots h_n$ represent the histogram vector elements
coefficients $[\boldsymbol{\beta}_0, \ldots, \boldsymbol{\beta}_n]$ minimize the prediction error

$\mathbf{H} = [h_1, h_2, \ldots, h_n]$



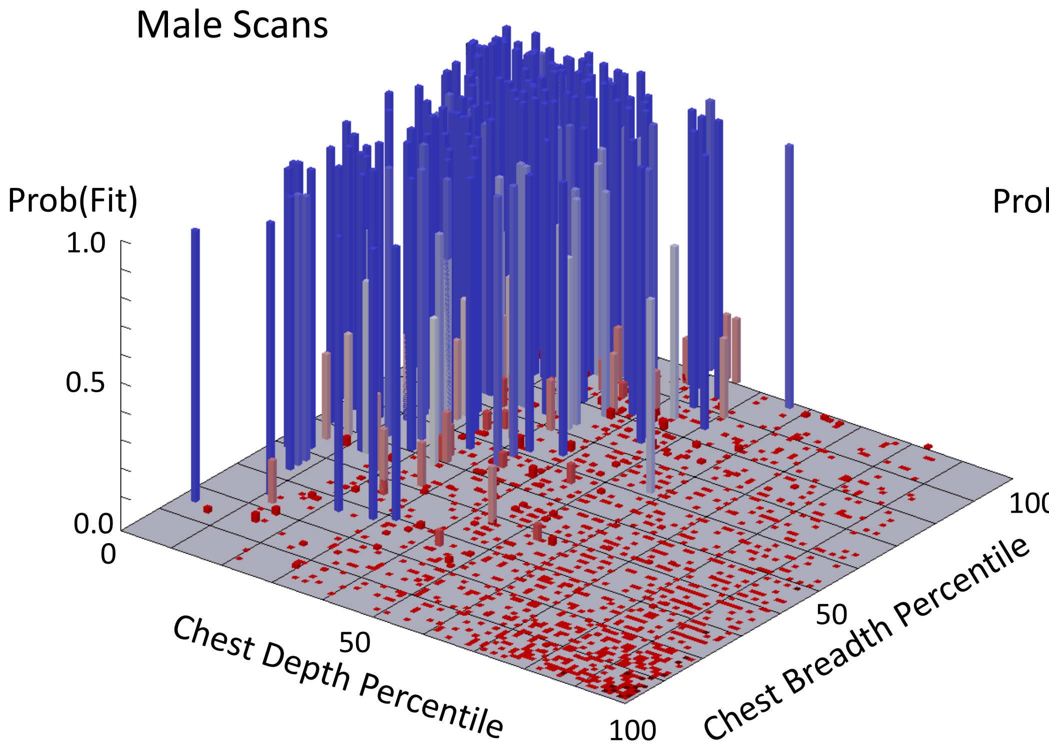


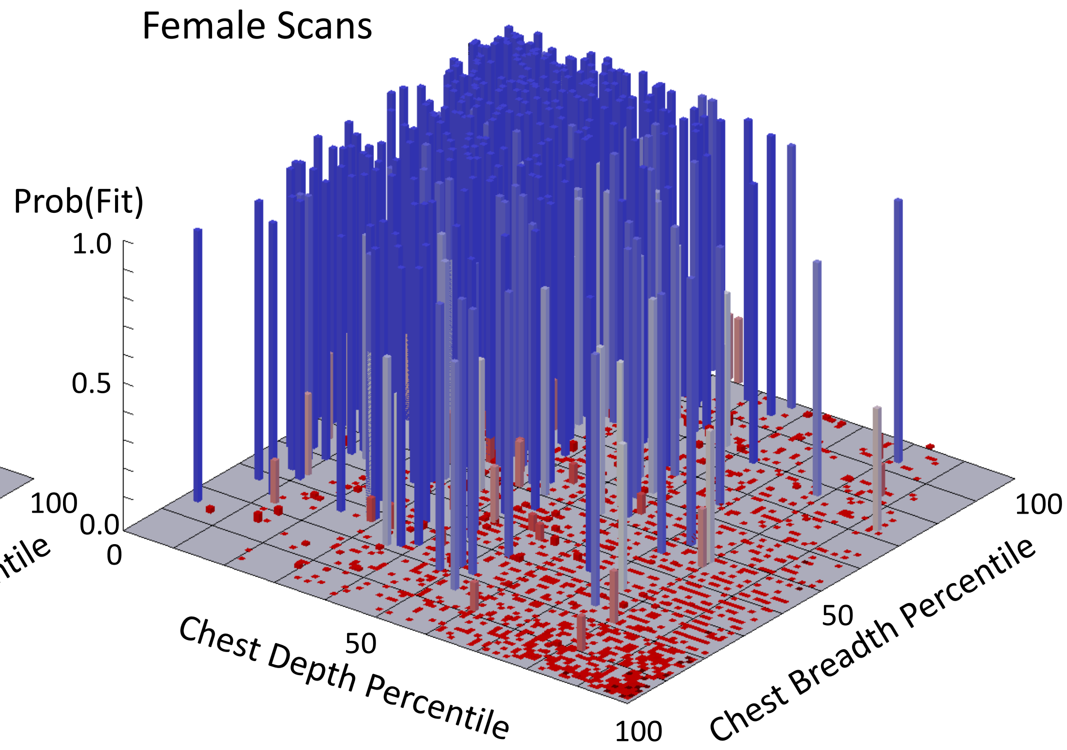
Pr(Fit): 0.001 0.255 0.508 0.754 0.994



Projection to a Larger Population Database

- The fit model was projected to a large scale sample database to approximate the accommodated population of the current and future crewmembers
- Virtual fit procedures were repeated on ANSUR2 scan subsets (1,734 males & 628 females), whose anthropometry meets NASA Human System Integration Requirements
- Each scan was estimated for suit-to-body overlap and produced a corresponding histogram vector

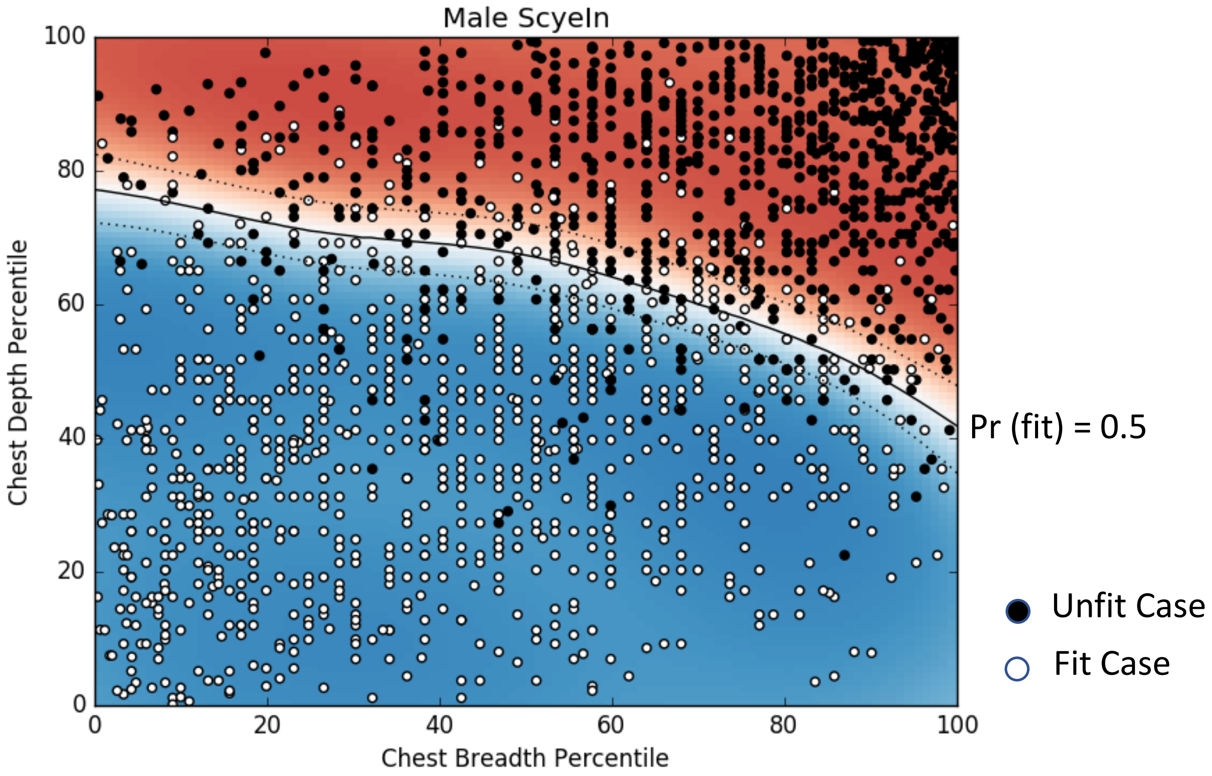


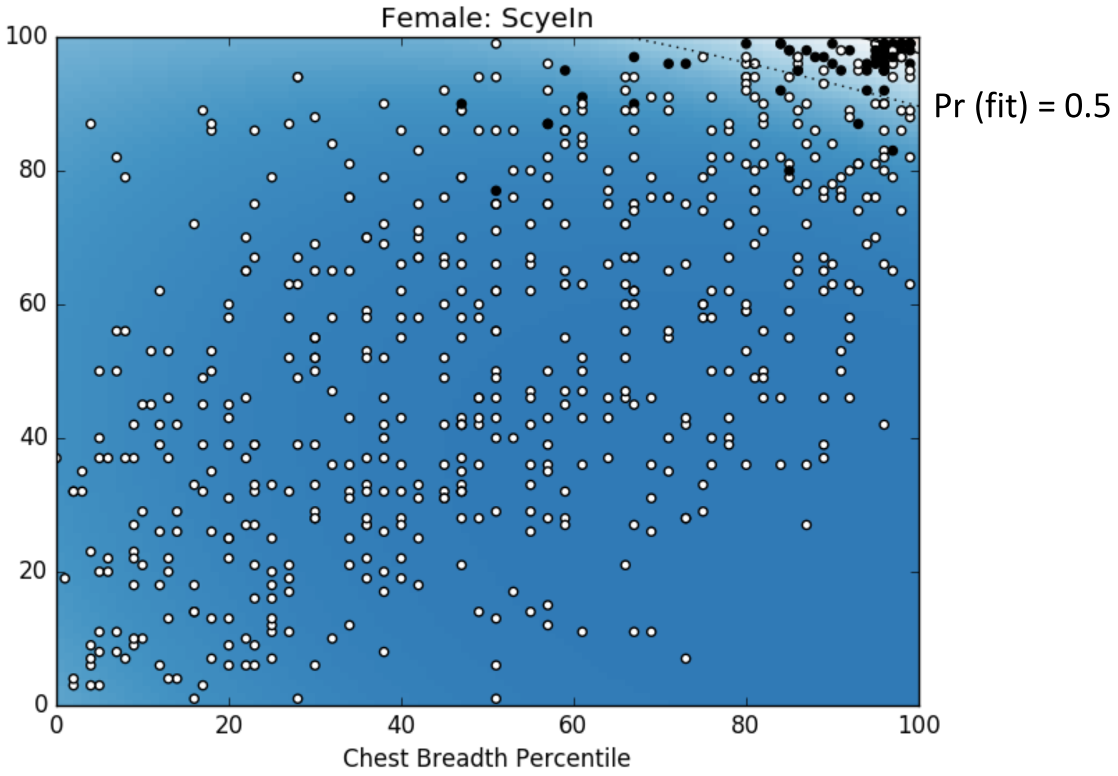


Preliminary assessments for illustration purpose only. Results may change with further iterations.

Projection to a Larger Population Database (Cont'd)

- With the same logistic model described before, the fit probability for each ANSUR manikin was assessed
- Area under curve (AUC) below *Pr*(Fit)=0.5 was calculated to represent the estimated proportion of accommodated population

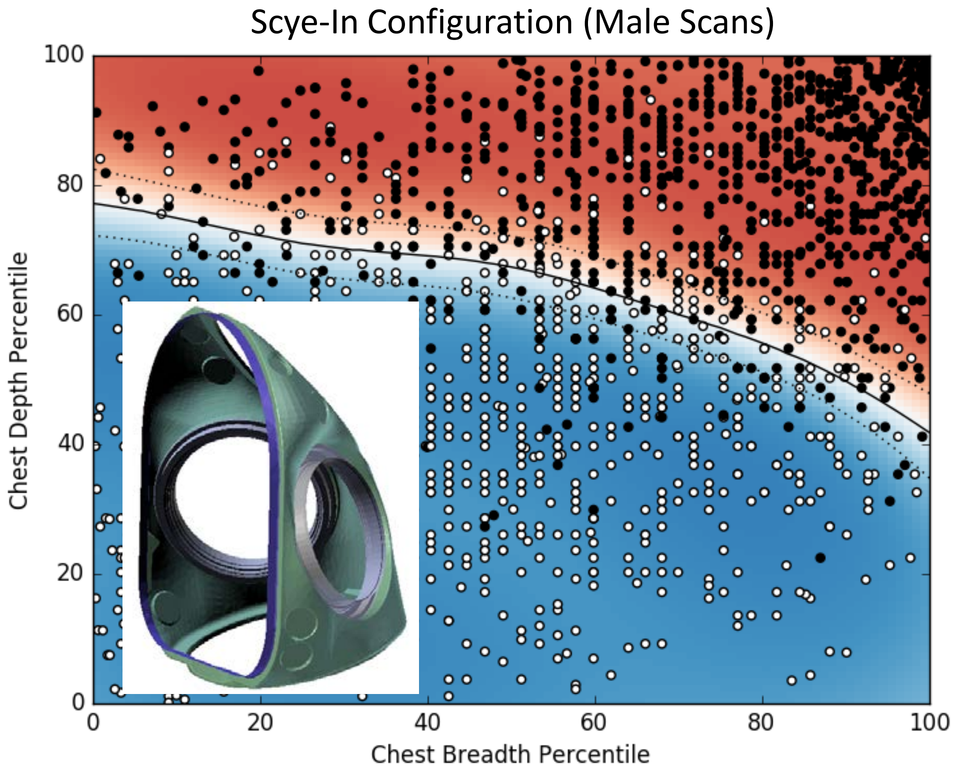


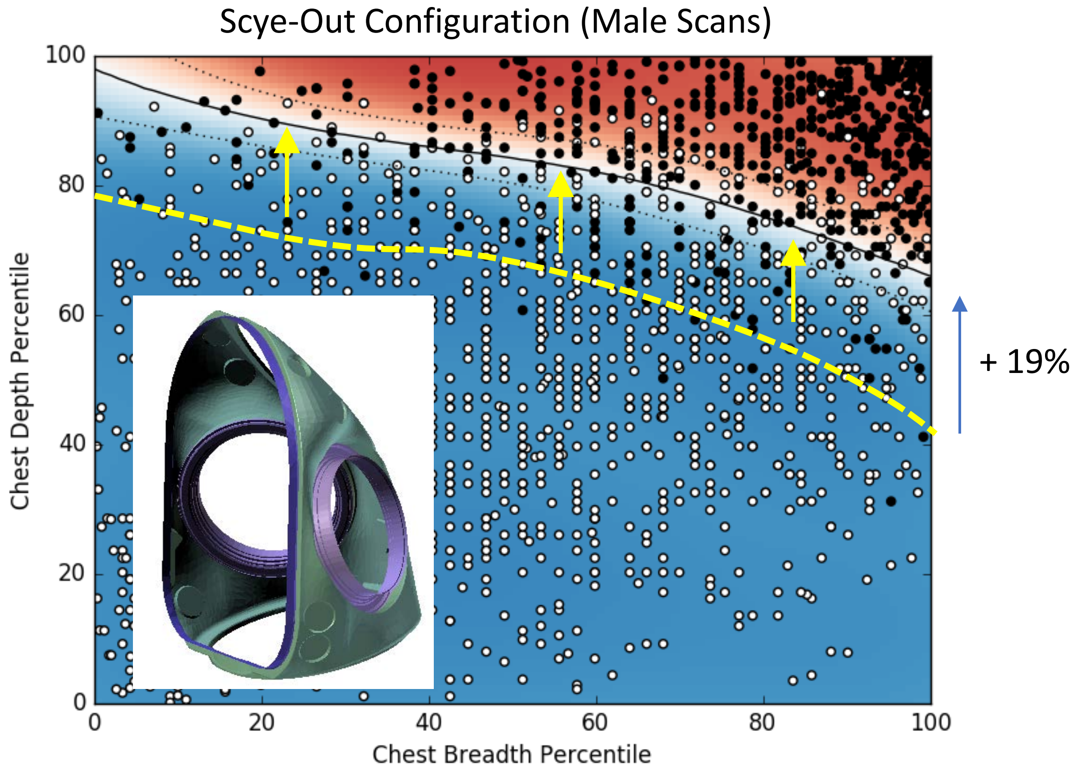


Preliminary assessments for illustration purpose only. Results may change with further iterations.

Advantages of Monte-Carlo Fit Analysis

- Boundary manikin technique (worst case analysis) allows a binary assessment only (i.e., yes/no to 95% accommodation, but unable to tell specific percent of accommodation)
- However, Monte-Carlo analysis enables an explicit quantification of accommodated population
- Thus, engineering decisions can be made based on quantifiable evidence (e.g., suit type A vs. B)
- This study found a scye-out configuration accommodated an additional 19% compared to the scye-in





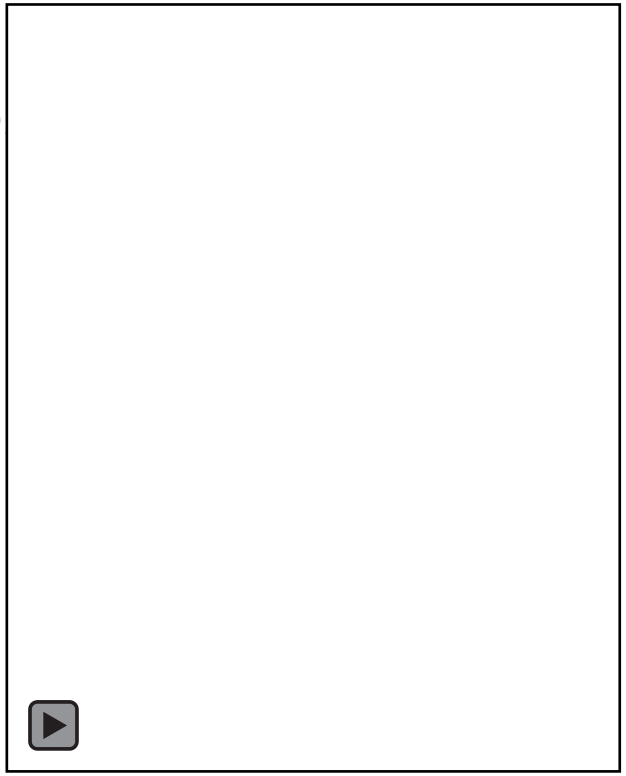
Preliminary assessments for illustration purpose only. Results may change with further iterations.

Advantages of Monte-Carlo Fit Analysis (Cont'd)

- Monte-Carlo analysis can also identify marginally fitting cases, i.e., *Pr*(Fit) = 0.5 or nearby
- Marginally fitting cases provides important information about the critical anthropometry dimensions and suit components associated with clearance restrictions or excessive overlap

Subjects with Prob(Fit) around 0

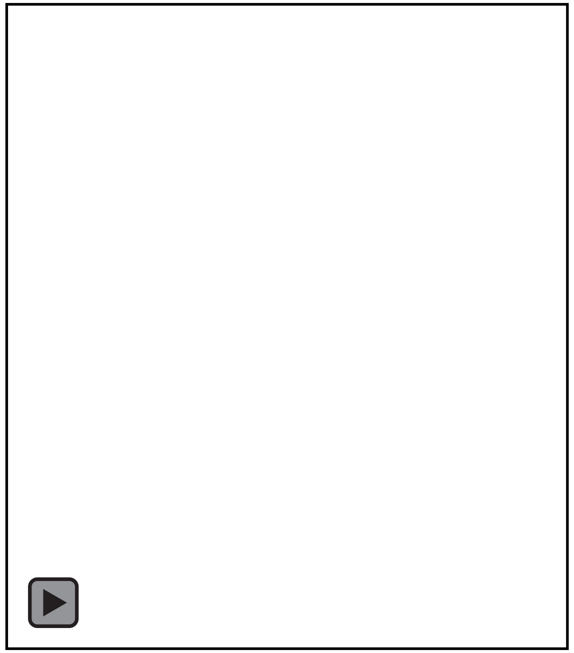
Worst cases analysis provides only binary fit/unfit decision

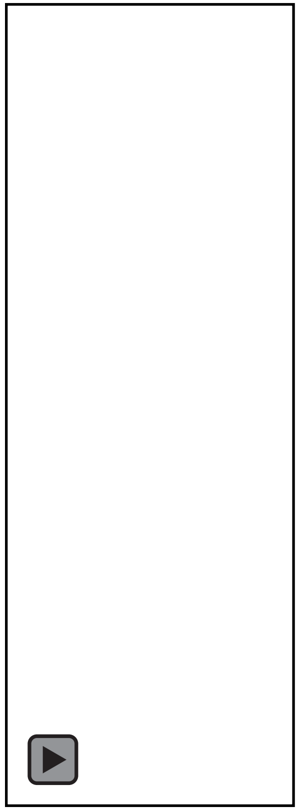


Marginally fitting cases inform of the specific location of interference (e.g., scye ring)

Conclusion and Future Work

- The new technique provides a more comprehensive assessment of suit fit and accommodation compared to traditional methods using boundary manikins
- Future work include:
  - Performance Assessments: Range of motion, subjective ratings
  - Individual tolerance to suit-to-body overlap
  - Posture variations (e.g., maximum inhaling)
  - Suit ingress/egress capabilities





Contact Information

K. Han Kim

han.kim@nasa.gov