



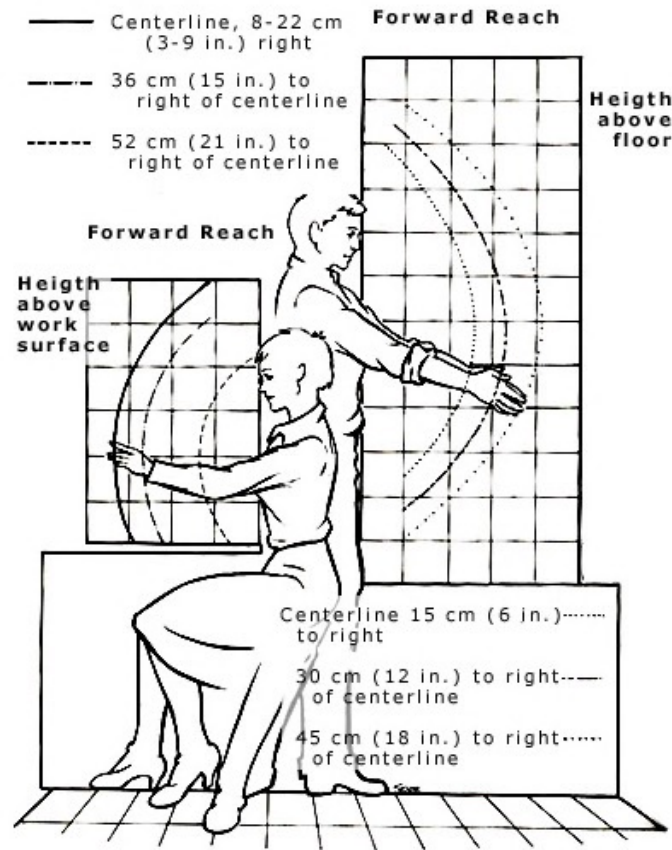
# Spacesuit Reach Capability and Work Volume Assessment

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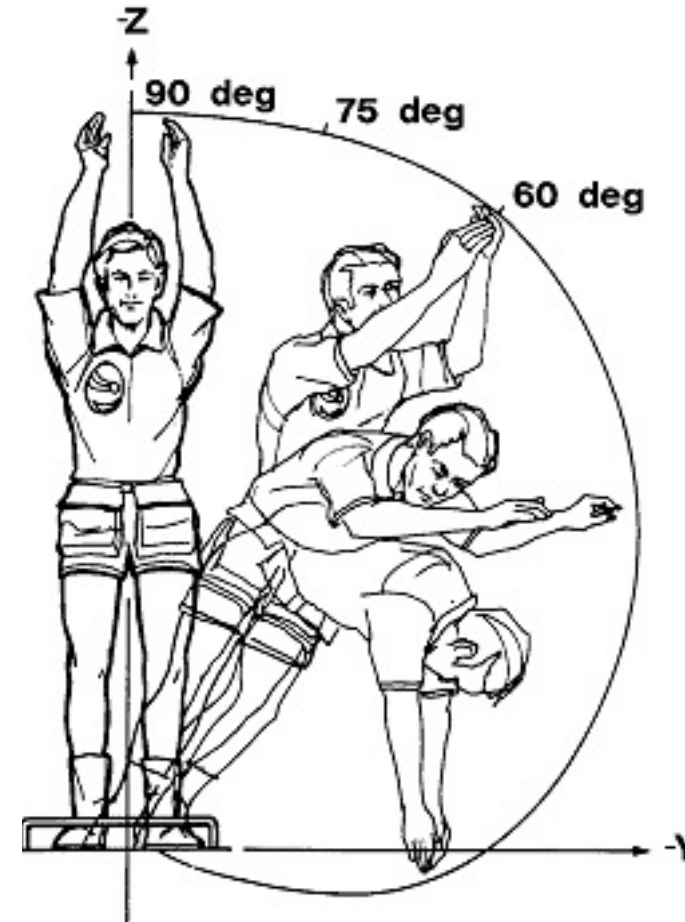
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# Reach Envelopes for Occupational Ergonomics

- Reach envelope defines the area that can be reached by a person in the workspace
- Reach envelope varies with anthropometry and task conditions



US Occupational Safety and Health Administration (OSHA)



NASA STD-3000

# Work Volume for Human-Spacesuit Interactions

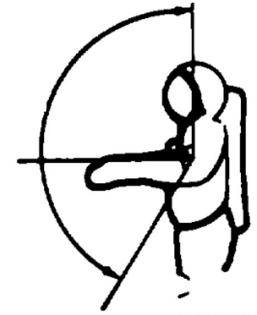
- Defining work volume is critical for spacesuit design and Extravehicular Activity (EVA) operations
  - Suited reach capabilities provide information for hardware and interface designs
  - Optimal placement of work object can help to mitigate ergonomic stresses to astronauts



SHOULDER ROTATION  
(Y-Z PLANE)  
(LATERAL-MEDIAL)



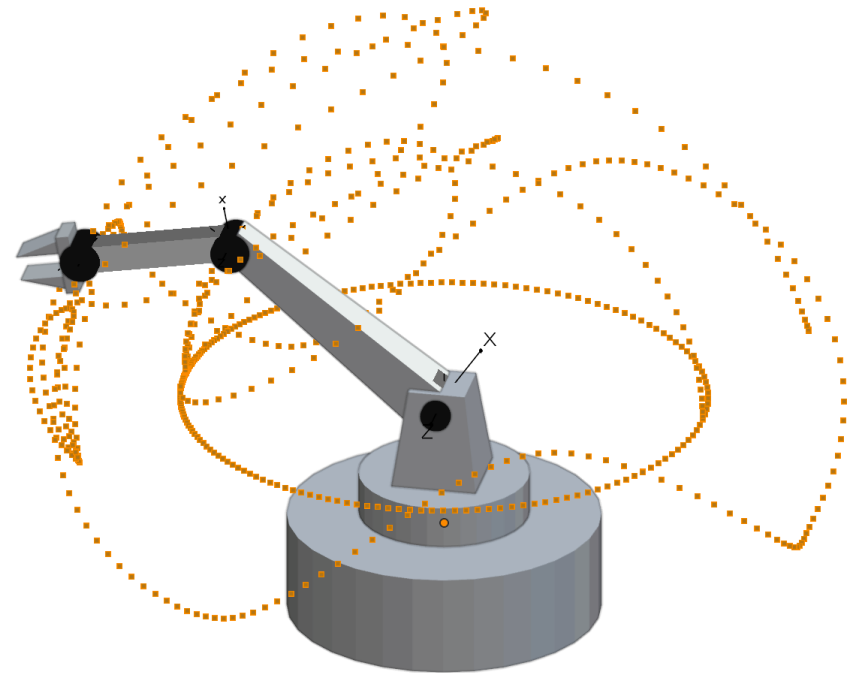
SHOULDER FLEXION  
SHOULDER  
EXTENSION



SHOULDER ROTATION  
(X-Z PLANE,  
DOWN-UP)

# Study Goal

- Work volume shape and size have been often used as a metric for new spacesuit design
  - This is based on an assumption that spacesuit capability can be measured like an articulated robot (i.e., joint-wise range of motion improvement can directly transfer to increased work volume)
- However, spacesuit work volume is an outcome of complex human-suit interactions, thus interpretation and design integration need caution
- The goal of this study is, therefore, to address the various aspects and variables that should be considered for spacesuit work volume



# Case 1: Isolated Arm-Hand Reach Envelope

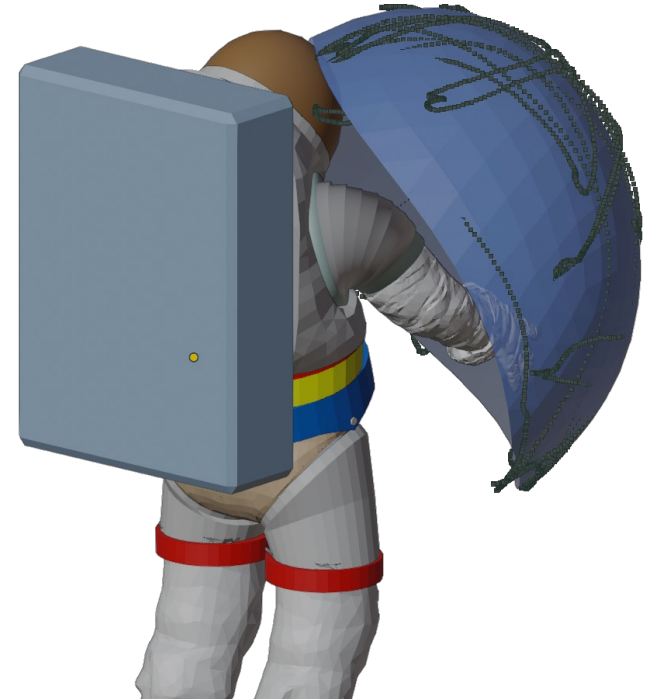
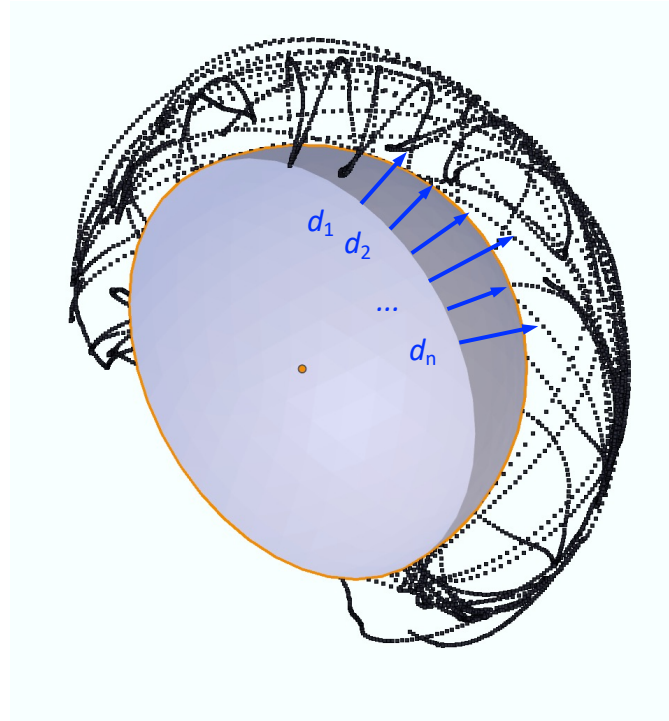
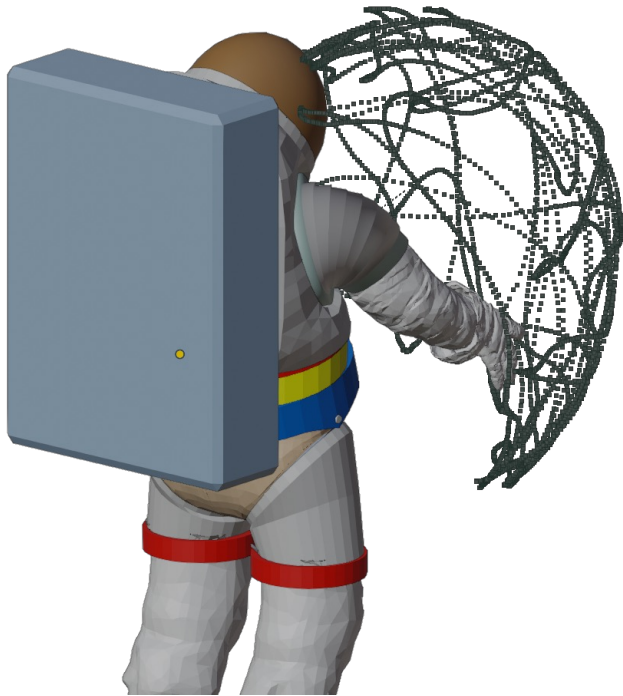
- Maximum sweeping motions were measured with extended right arm/hand
  - Vertical (up-down) at different azimuths
  - Horizontal (left-right) sweeps at different elevations
- Vicon motion capture system recorded the motions of the hand and body/suit landmarks
- This is one of the most common types of work volume measurements



Kim et al., 2022

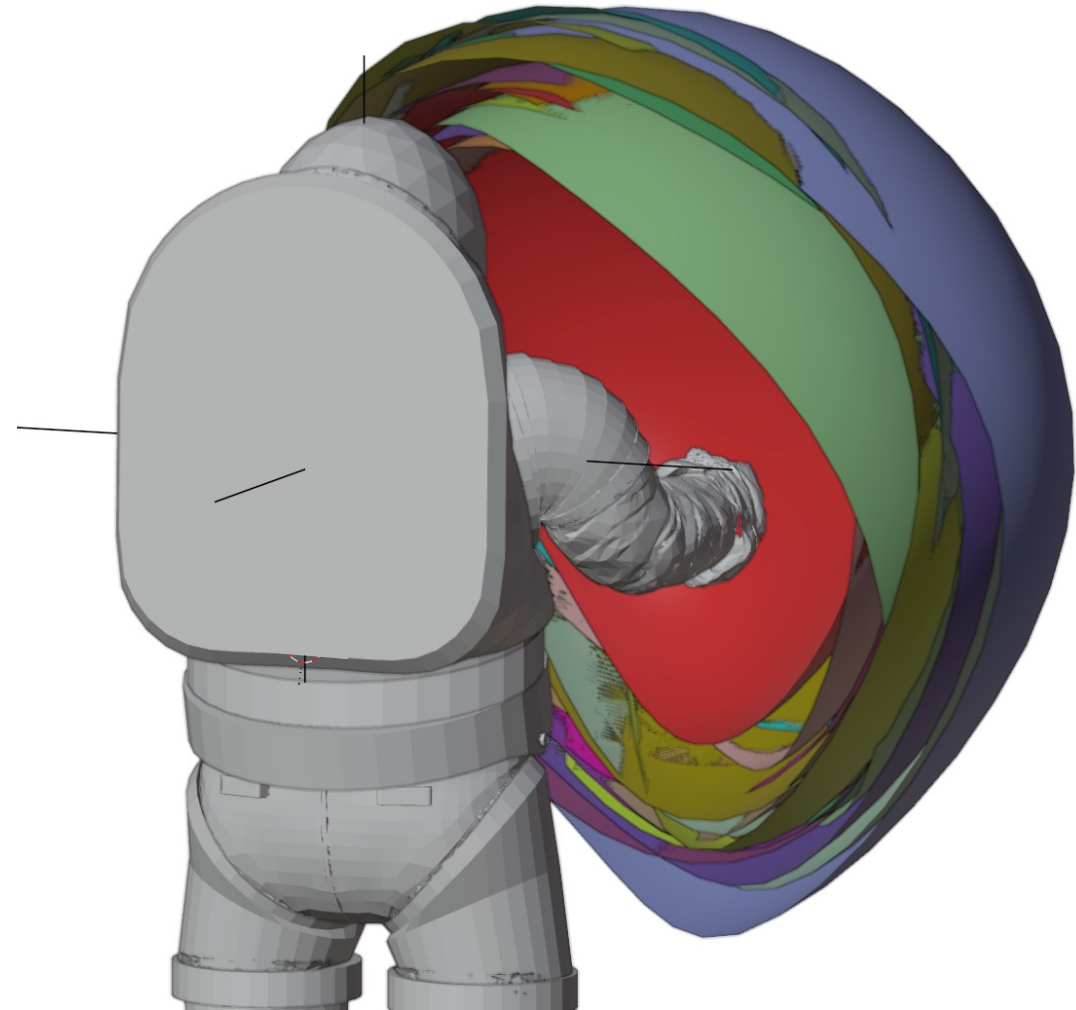
## Case 1: Isolated Arm-Hand Reach Envelope (Cont'd)

- The hand position was traced, and represented by a fixed torso (suit hard upper torso) coordinate system
- Hand trace for each subject was abstracted using a smooth surface template
- The template was parametrically deformed to minimize the surface-to-trace distances



## Case 1: Isolated Arm-Hand Reach Envelope (Cont'd)

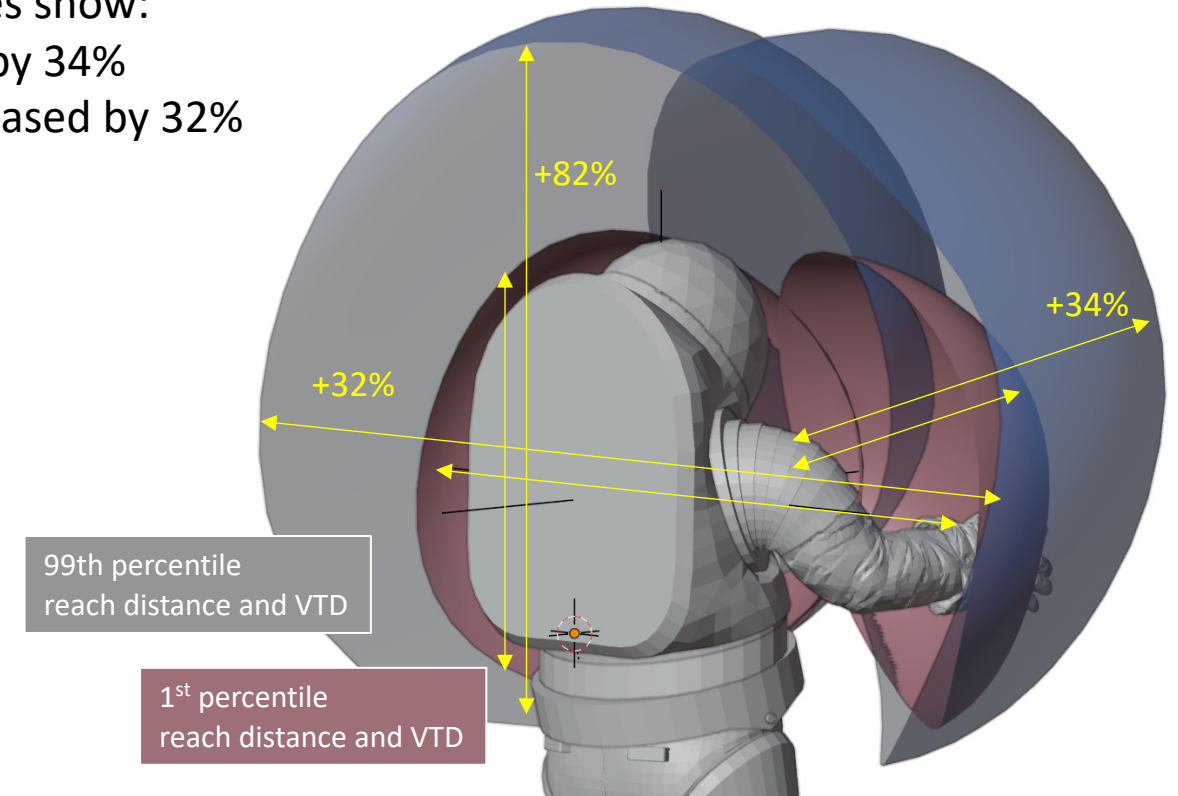
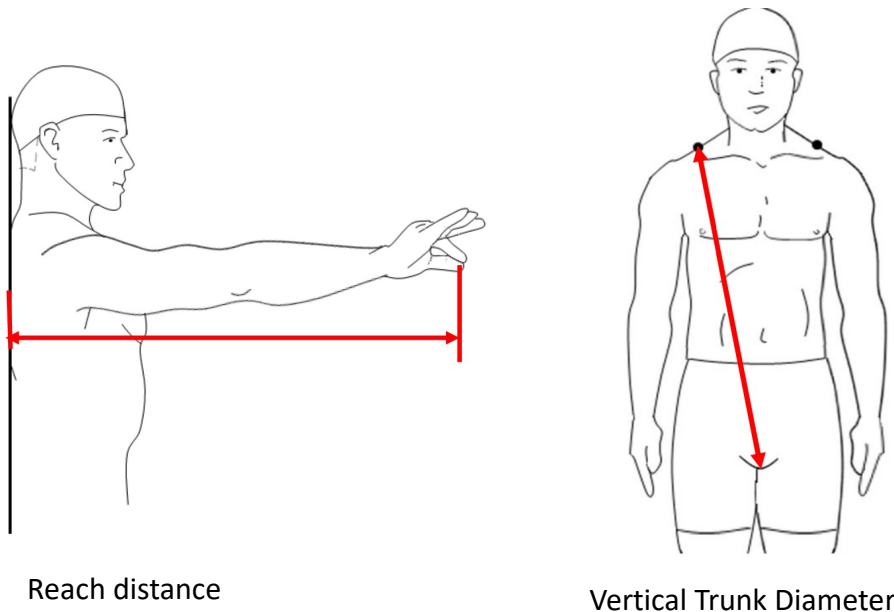
- Reach envelopes were collected from 18 subjects
- Despite the nearly identical architecture and mechanisms of the suit, a large variations were observed of the shapes and sizes



## Case 1: Isolated Arm-Hand Reach Envelope (Cont'd)

### Source of Variability (1): Anthropometry

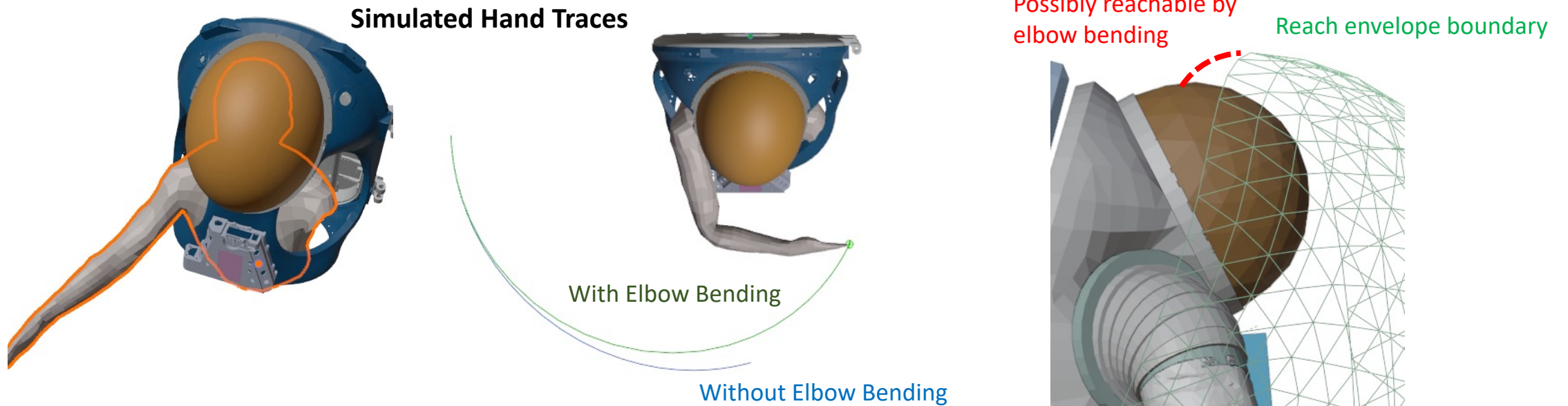
- One of the primary sources for reach volume variability is anthropometry
- The envelope shape and size were statistically modeled as a function of anthropometry (reach distance and vertical trunk diameter (VTD))
- The envelopes were predicted for persons with 1<sup>st</sup> to 99<sup>th</sup> percentile anthropometry measurements
- Compared to a person with 1<sup>st</sup> percentile, 99<sup>th</sup> percentiles show:
  - Envelope depth (shoulder to furthest point) increased by 34%
  - Width (left to rightmost point, left-right mirrored) increased by 32%
  - Height increased (top to bottom point) by 82%



## Case 1: Isolated Arm-Hand Reach Envelope (Cont'd)

### Source of Variability (2): Elbow Bending Behavior

- Although instructed to keep arm extended, the subject bends the elbow, especially near the extreme positions
- This natural elbow bending tendency can lead to variations in reach envelope shape and size
- In this specific test, elbow bending was not controlled, thus there can be some bending but not always to the full range of motion, even at the extreme position.
- Thus, reach envelope should not be interpreted as if the subject may not be able to reach the area beyond the boundary (e.g., helmet surface). With elbow bending, these areas may be reachable.



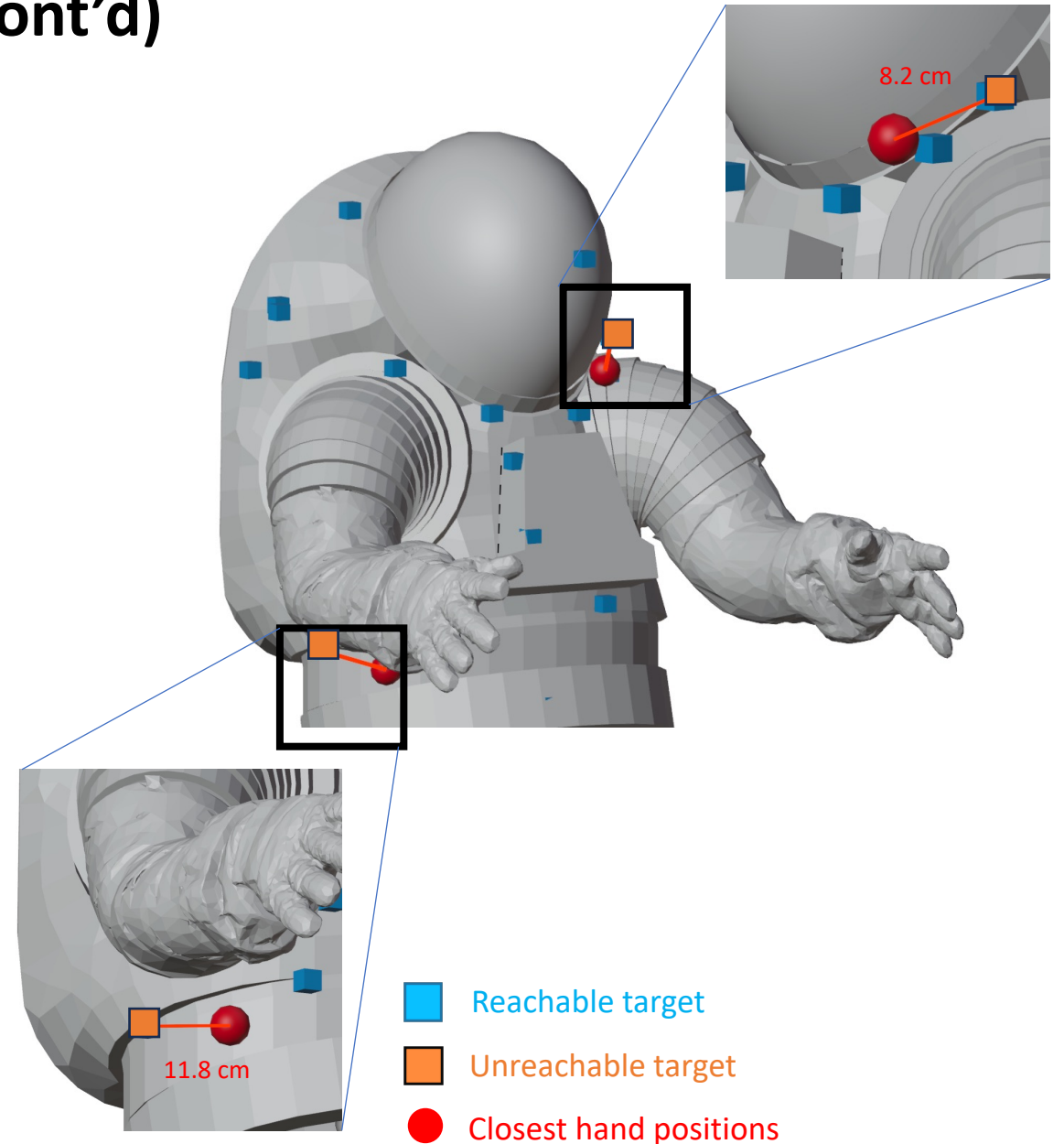
## Case 2: On-Suit Reach Assessments

- The maximum reach envelope is related to the reachable areas outside of the suit and body
- Thus, reach envelope does not represent which areas on the suit surface can be reached by the subject
- A separate test was needed to assess on-suit reach capabilities
- This test is critical for interface and control placement on the suit
- The subject moved the arm and hand to reach and contact a target placed on the suit surface by the test operator



## Case 2: On-Suit Reach Assessments (Cont'd)

- Most targets were reached by the subjects, including those on the front suit surfaces
- Some targets were not reachable, especially those placed on the lower side and opposite neck area
- For the unreachable targets, the closest hand positions were 8.2-11.8 cm off from the target



## Case 3: Targeted Reach for Difficulty Assessments

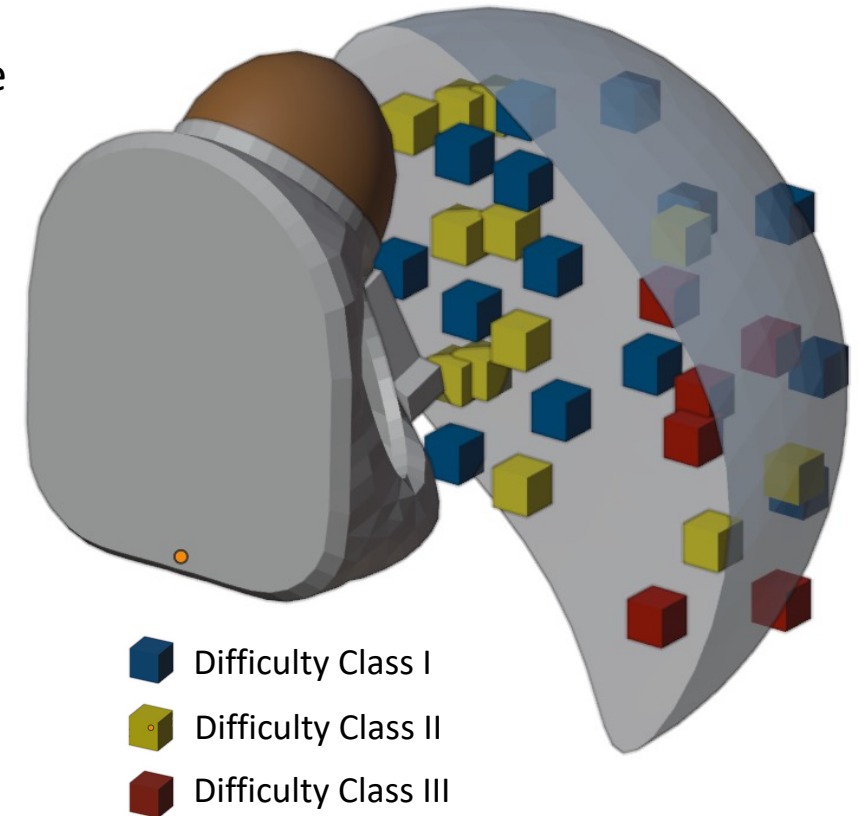
- Although most points inside of the envelope might be reachable, the effort level required for different reach motions can be different
- The effort differences can be due to the mechanical characteristics of the suit, especially at the shoulder
- The subject moved the arm and hand starting from the reference pose (the hand on the lap) to the wand-attached sphere
- Then the subject verbally reported the perceived difficulty of the reach motion using a score from 0 (easiest) to 10 (most difficult)
- Data analysis in progress



### Case 3: Targeted Reach for Difficulty Assessments (Cont'd)

(Preliminary results, data analysis in progress)

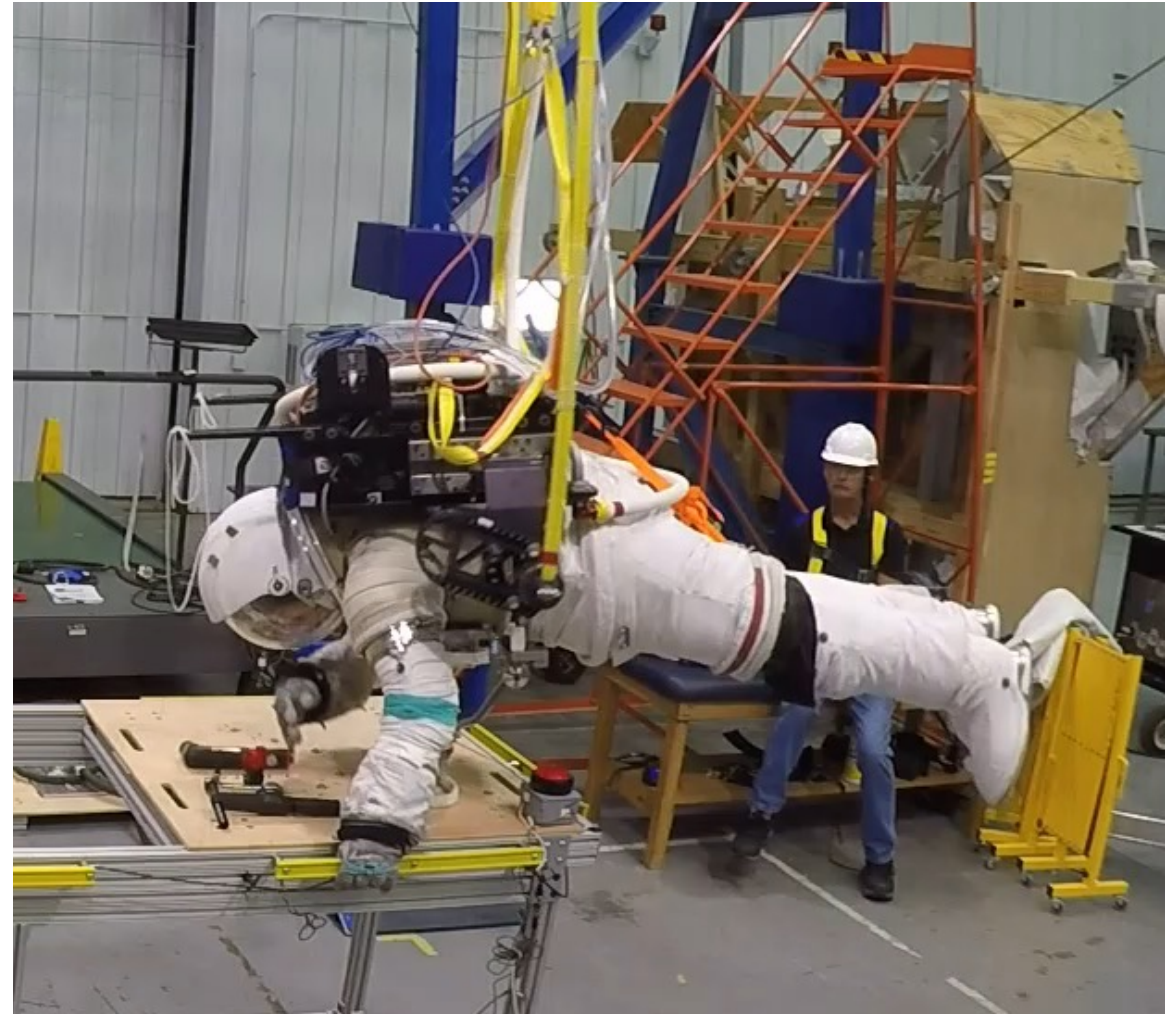
- The collected difficulty ratings were re-categorized into three difficulty classes (Class I: easiest, Class III: most difficult)
- The preliminary observations from one subject indicated that the middle regions (near sagittal plane) show more **Class I** difficulty ratings (i.e., lowest difficulty)
- The cross-reach regions (beyond the sagittal plane) more **Class II** ratings (i.e., medium difficulty)
- The lateral regions (lower right corner) show more **Class III** ratings (i.e., highest difficulty)



Data from one subject, shown for illustration purpose only

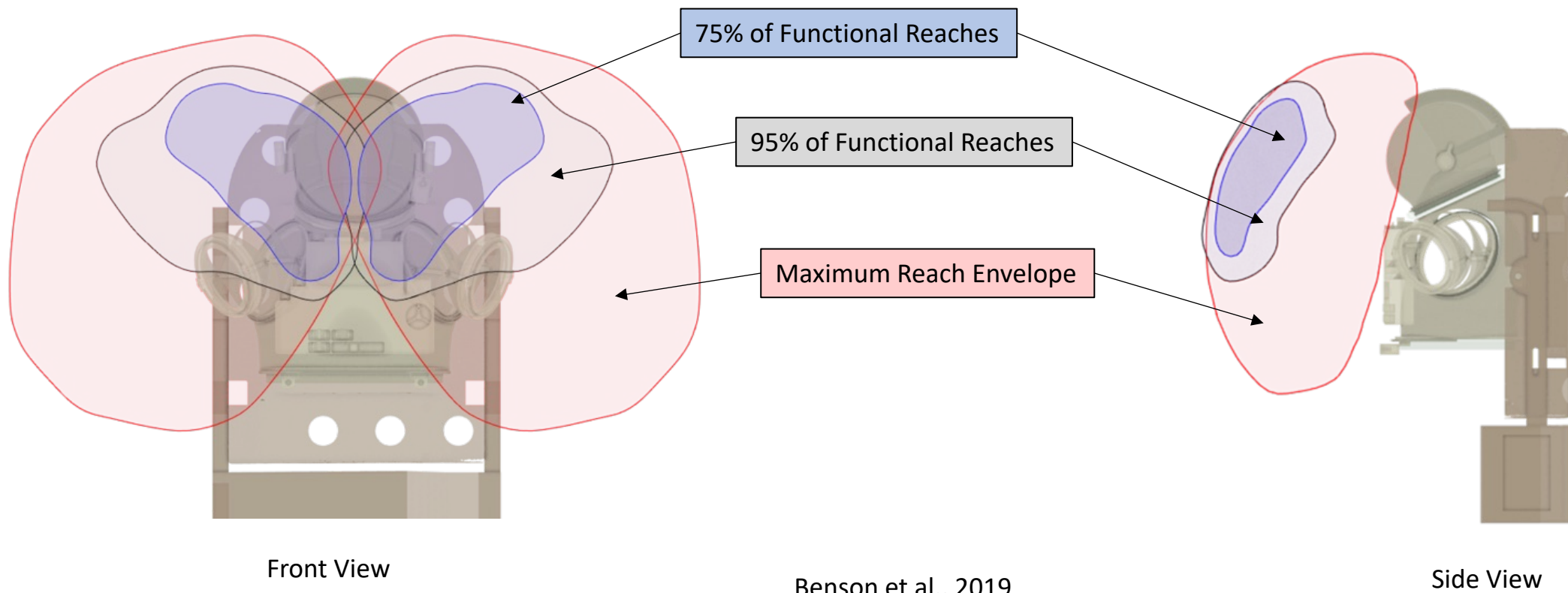
## Case 4: Maximum vs. Functional Reach Envelopes

- Maximum reach envelopes represent the furthest point a person can reach around the suit/body, often measured from dedicated tests (i.e., not exact simulation of EVA)
- However, the subjects often choose to use only the sub-region of the maximum volume, especially during the EVA-like functional tasks
- This pattern is anticipated given the different level of reach difficulty across target positions
- Suited subjects were suspended from a robotic crane to offload the suit weight and allow translation through the volume
- While offloaded, subjects completed a series of functional tasks simulating EVA for an extended duration



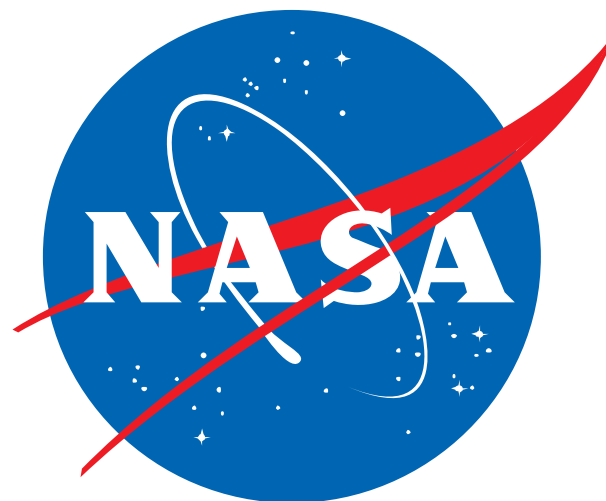
## Case 4: Maximum vs. Functional Reach Envelopes

- Kernel density estimation indicates that only a small proportion of available reach is utilized for functional work
- Overall, only small areas are utilized for functional work compared to maximum reach envelope
- 40% and 19% (front projection) of the reach envelope area are used for 95% and 75% of functional work
- Reaches were most concentrated in the area in front of the helmet
- Lower lateral regions and cross-reach regions are less frequently used in functional reaches



# Discussion

- The reach envelope represents the furthest points a person can reach without moving the torso or lower body. In other words, the envelope should be interpreted in a way that any objects/interfaces placed beyond the envelopes may not be reached without moving or rotating the torso or lower body.
- Anthropometry and subject-specific motion patterns (e.g., elbow bending) substantially change reach envelope shape and size. Thus, reach envelope alone may not be interpreted as metric of suit mechanical characteristics, as reach motion patterns vary with human interactions with the suit.
- Due to the soft good stiffness and mechanical constraints, suited individual strength level can also change the reach capabilities. As a result, on suit surface reaches, which significantly require extreme bending and joint articulation, should be assessed separately from maximum reach envelopes.
- Similarly, difficulty rating varies greatly with target positions. The regions associated with higher difficulty tend to be used less frequently during the functional task simulating prolonged EVA. In these regions, the subject is hypothesized to move the whole body to align the target with the preferred reach zone.
- The reach pattern can be substantially different depending on gravity or hand load conditions. In addition to anthropometry, suit fit may also play a role in reach capabilities.
- Overall, reach volume measurement can sensitively capture the various aspects of human-suit interactions. As multiple different reach measurements represent the different characteristics of the human-suit interactions, however, reach/work volume should be interpreted with caution, especially for integration with hardware or task designs.



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