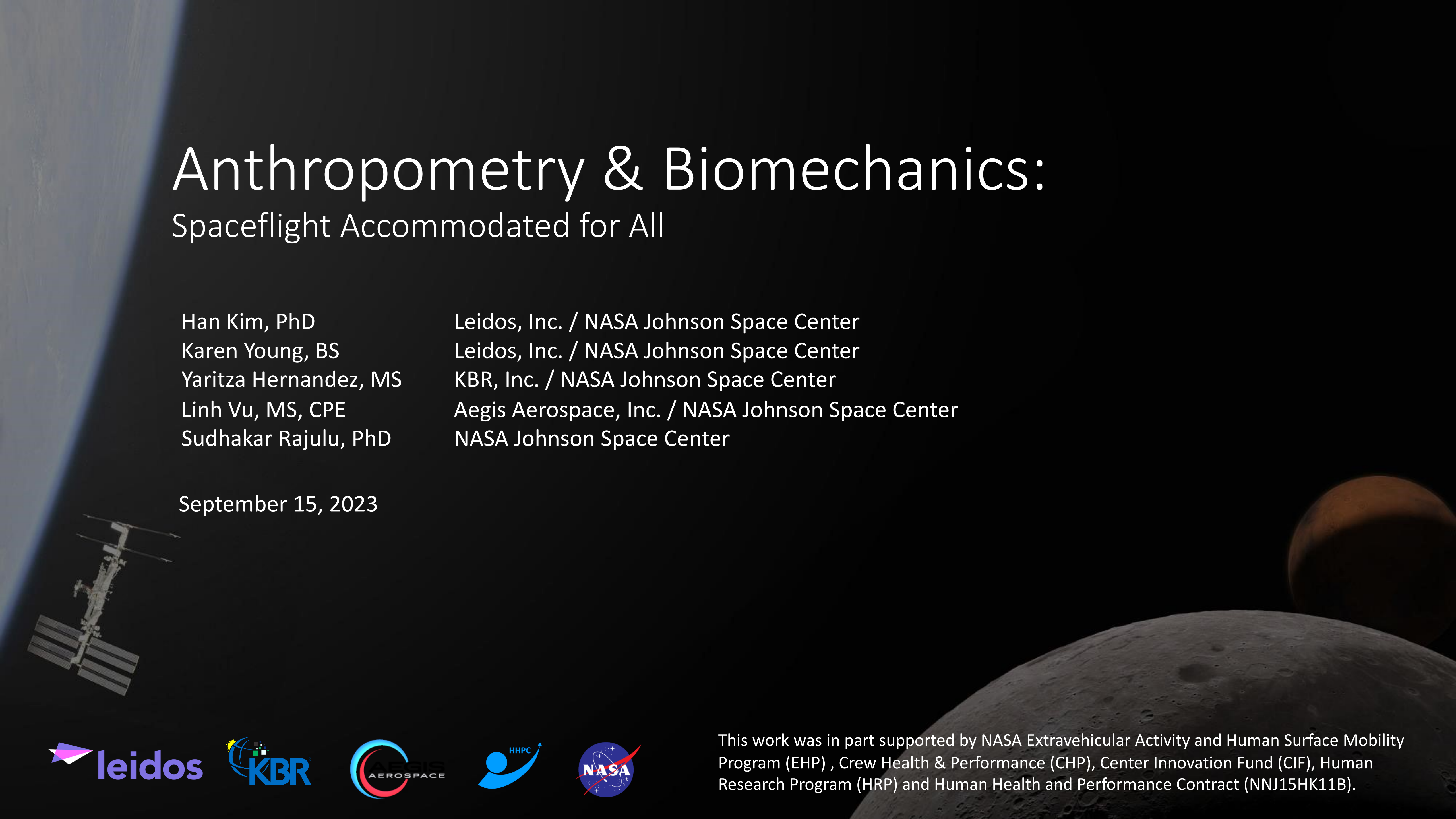

Anthropometry & Biomechanics:

Spaceflight Accommodated for All

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Anthropometry for Spaceflight

- Body sizes used to be “homogeneous” in early space ages
- Today, crews are in a wide variety of body sizes
- Optimal design and sizing are crucial for crew safety and performance

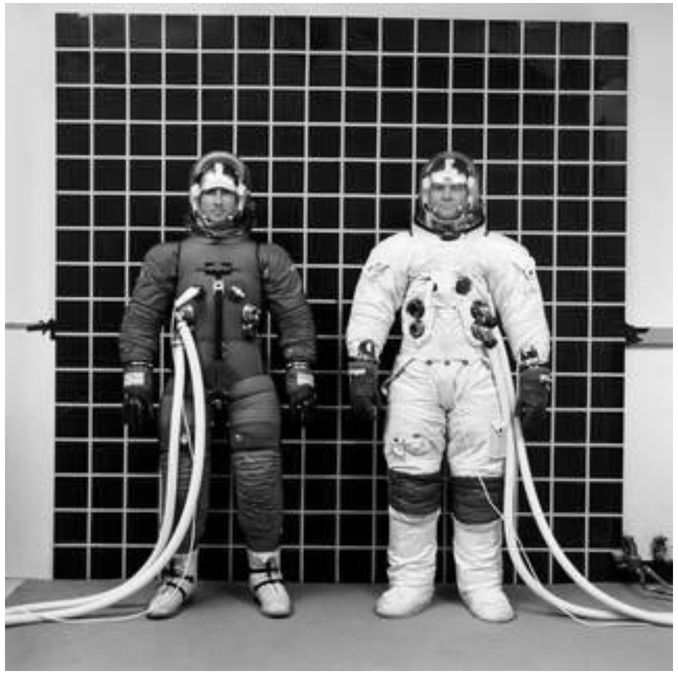
Crewmembers in 1960’s

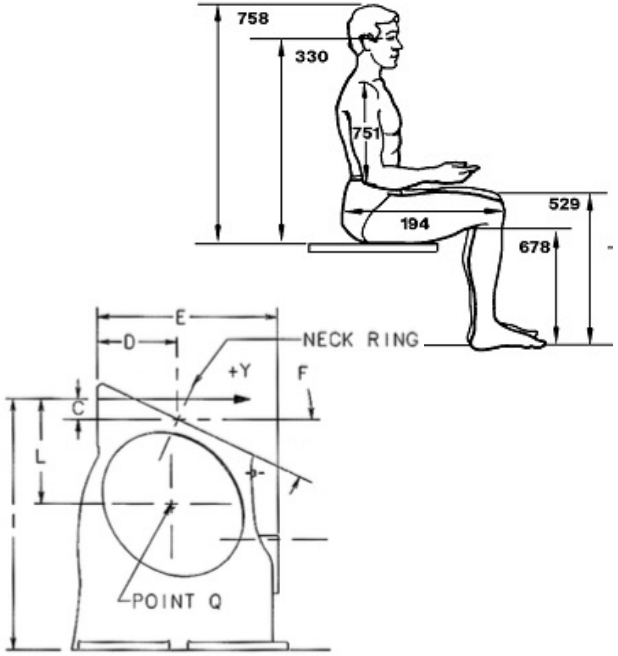
Crewmembers in 2000’s

Artemis Era Crewmembers

Spacesuit Fit for Early Space Programs

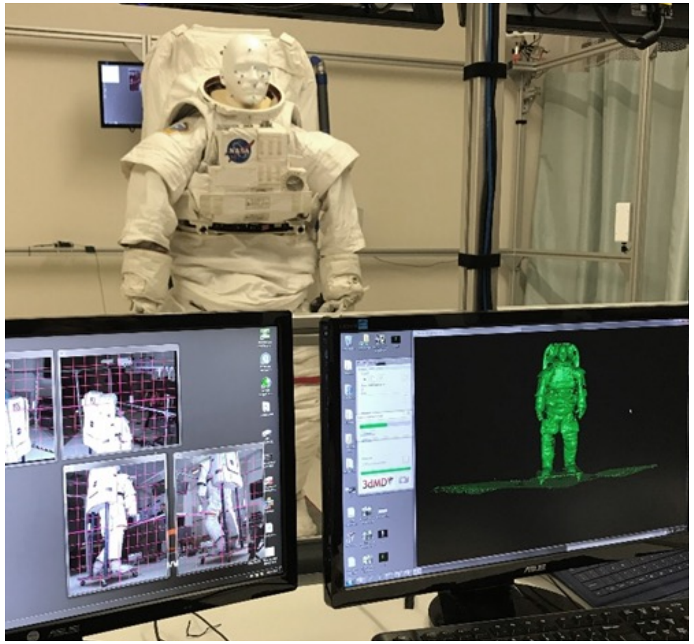
- During the early space programs (Apollo, Gemini, & Mercury), spacesuits were custom fitted to each astronaut
- With growing number of astronauts (24 in Apollo vs. 848 in Shuttle), cost and logistics became an issue
- For the Shuttle program (1980's), spacesuits EMU were developed in modular components and sizes (~~S~~, M, L & XL).
- EMU has been currently in active use through Shuttle and International Space Station Programs
- EMU design and fit based on linear dimensions of body segments, thus may not have captured details of 3D body shapes

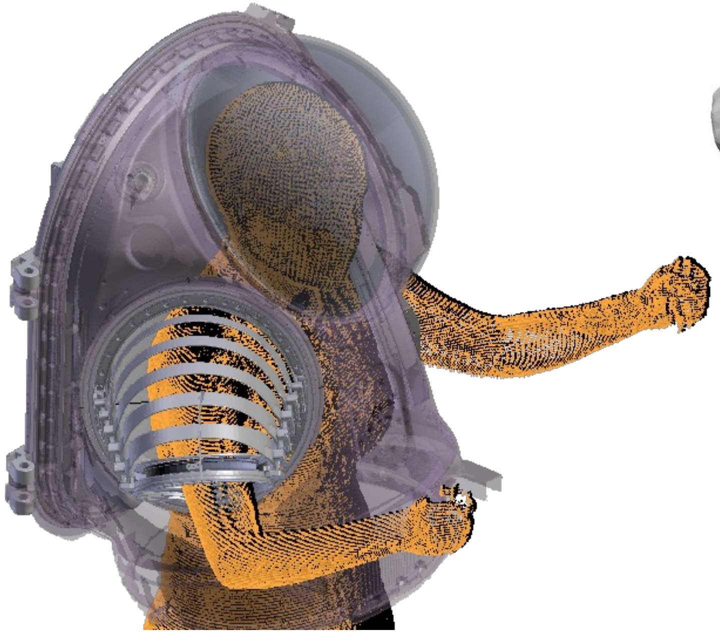


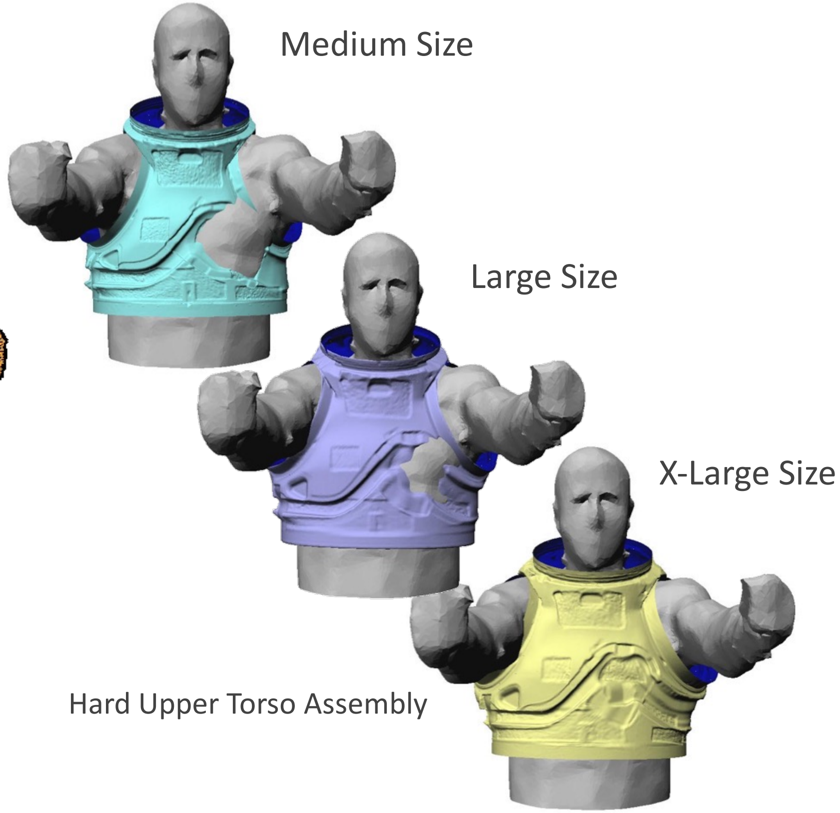


3D Body Scanning Technology for Suit Fit

- For new spacesuit designs since 2000’s (Z-2 & Z-2.5), 3D body scan and computer aided design (CAD) have been used
- Suits designs were validated using 3-D body scans overlaid with CAD drawing
- Fit was assessed using suit-to-body overlap and clearance and verified by 3-D printout
- This technique substantially reduced the time and cost of iterative human testing.
- However, limited number of scans may not represent the entire range of crewmember body shapes

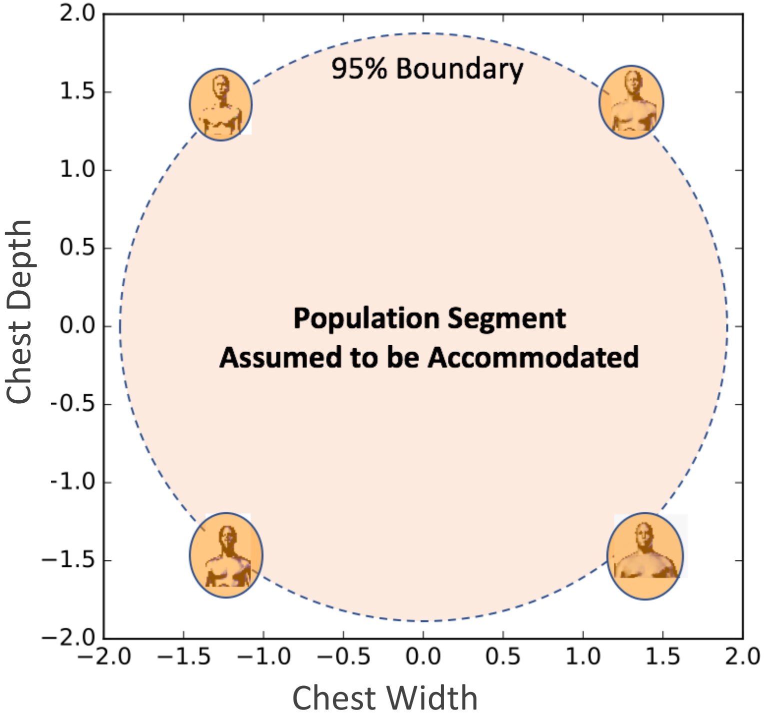


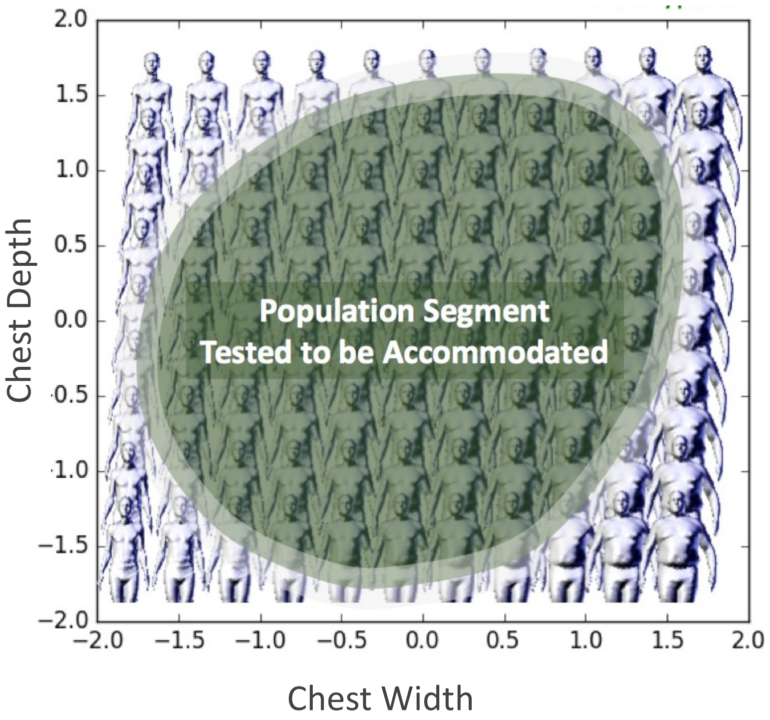




Monte-Carlo Virtual Fit Technique

- The next generation government reference design xEMU was based on a virtual fit with Monte-Carlo assessment technique
- Previously, fit assessments relied on boundary manikin techniques.
  - Boundary subjects were sampled to cover a prescribed population group (e.g., 95 or 99%)
  - If the boundary samples ”pass” the tests, the suit is considered to accommodate 95 or 99% of population
- The new approach was based on a Large-scale Sample Monte-Carlo Testing
  - A large number of scan samples were explicitly tested, examining the exact proportion of accommodated population
  - Requires automatized fit tests by 3D scans, thus can be computationally intensive



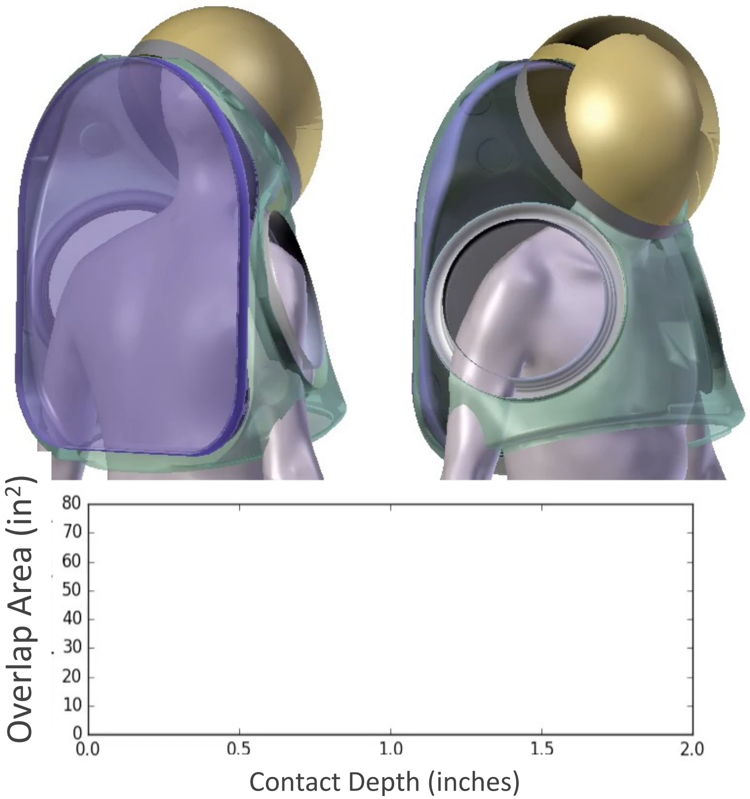


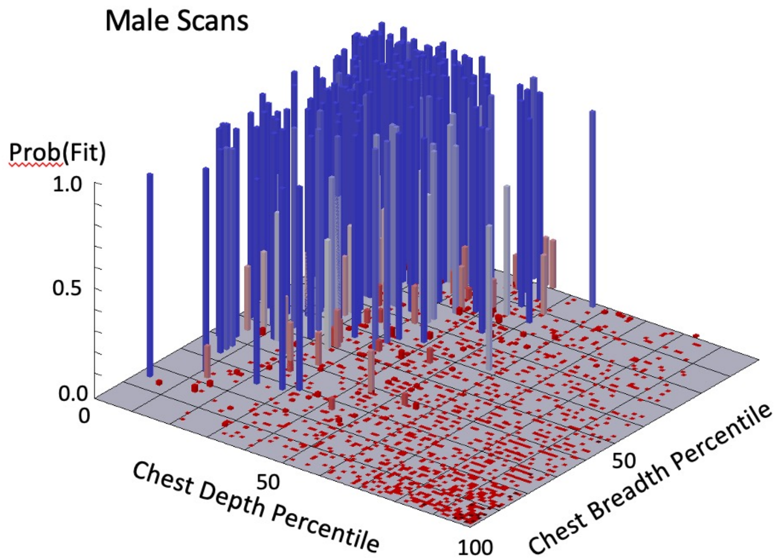
Kim et al., 2019, 2020, 2021

Virtual and Physical Fit Hybrid Test

- From 3D scans overlaid with CAD, suit-to-body contact location and magnitudes were calculated
- Subjects were selected from the “borderline fit” group and performed physical tests using 3D printed mockup
- The contact patterns were used as parameters for a fit probability model, which was trained by physical fit test outcome

  Probability(Fit) = f(suit-to-body contact patterns)
- The model was projected to a large astronaut-like population to assess accommodation performance

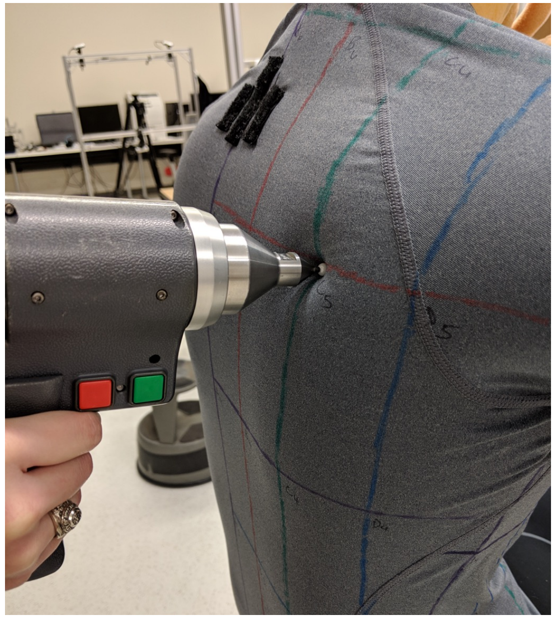


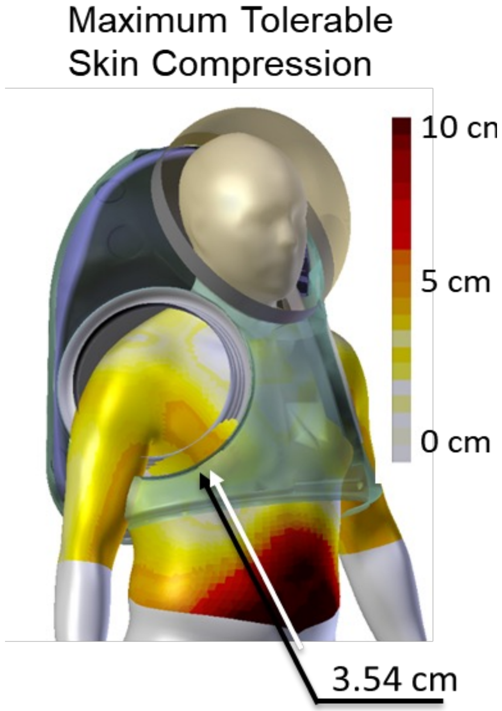


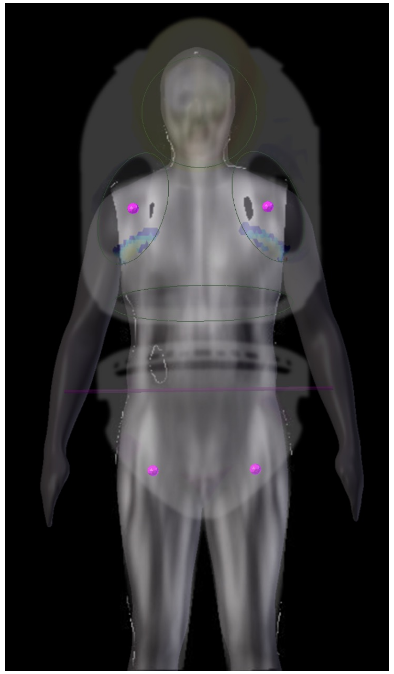
Kim et al., 2019

Suit-to-Body Contact: Enhanced Modeling & Measurements

- 3D scans quantifies the outer surfaces only, without considering of skin compressibility or individual tolerance. However, body compressibility often matters for spacesuit and hardware designs
- A NASA study explicitly measured body compressibility, and matched with suit-to-body contact assessments
- Suit-to-body contacts were “virtually” assessed through 3D scans. However, a new technique used different imaging systems, for example, DEXA (dual x-ray absorptiometry) scanning, which allowed for direct contact measurements

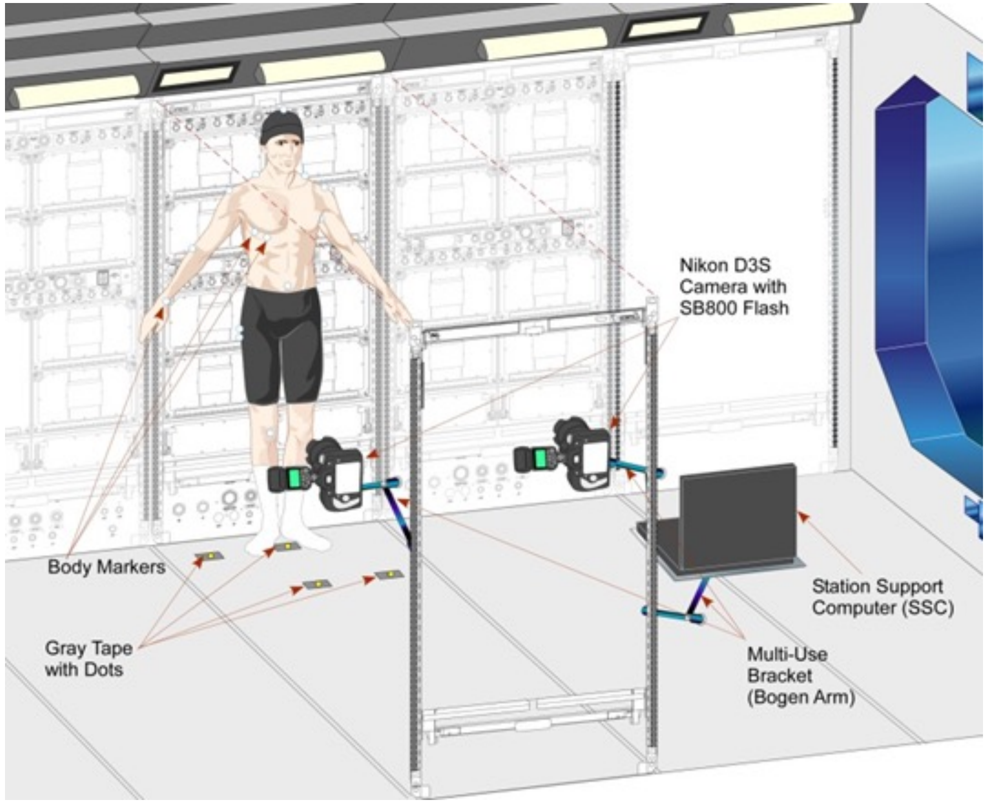

Hernandez et al., 2019




Leong, 2020

In-Flight Body Shape Changes

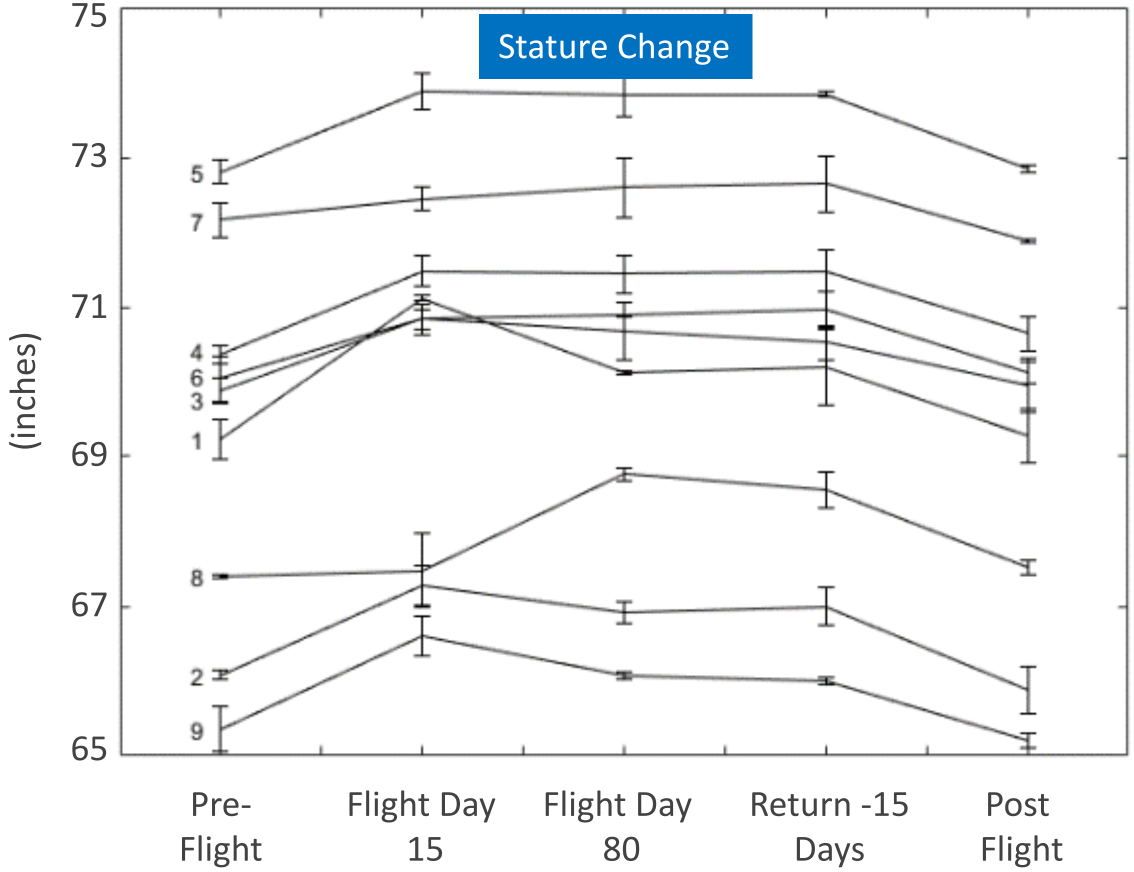
- Spacesuit design should also consider anthropometry changes in microgravity, originating from spinal elongation, fluid shift and muscle atrophy
- Study was performed to measure anthropometry change in International Space Station (ISS) and Shuttles
- 3D photogrammetric technique measured landmark coordinates to assess body segment lengths
- Manual measurements were additionally taken for circumference measurements

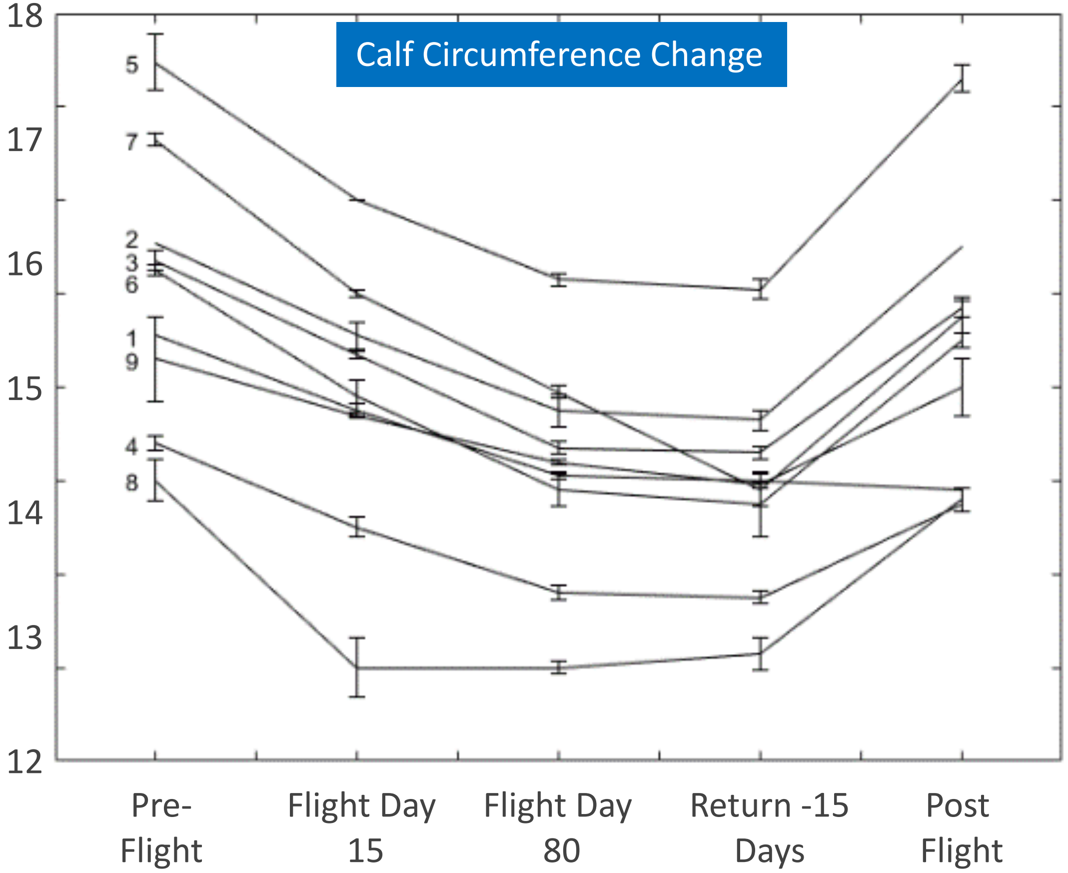


Young et al., 2020, 2021

In-Flight Body Shape Changes (Cont’d)

- Upon exposure to microgravity, stature increases by 3% on average (about 2 inches)
- Calf circumference decreased by 11% (1.5”) up to flight day 80.
- Fluid shift and spinal elongation have been identified as primary causes
- Anthropometric changes take place within the first 15 days of flight, and return to nominal after return

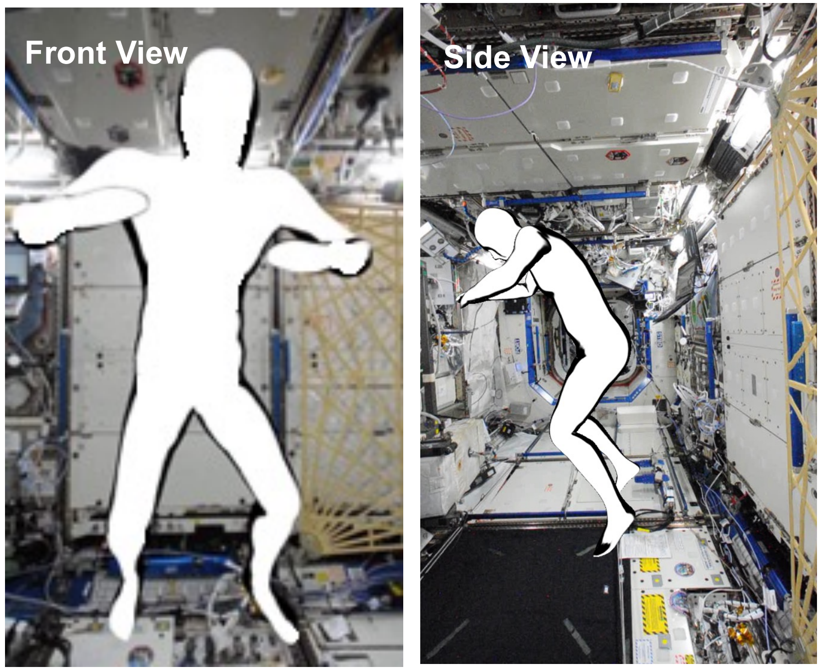

Stature Change


Calf Circumference Change

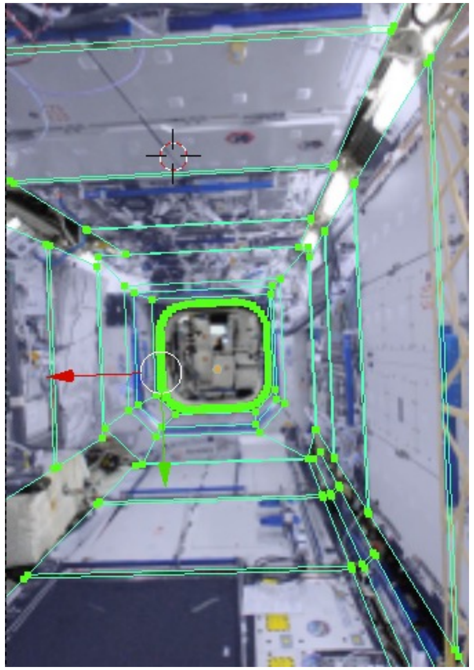
In-Flight Body Shape Changes (Cont’d)

- Human body in 0-g exhibits a unique posture (neutral body posture; NBP), when relaxed and no external forces are applied
- The early designs for spaceflight hardware were based on upright standing or sitting postures without consideration of NBP, resulting in crew discomfort. Maintaining a body posture other than NBP requires significant strength exertions
- The NBP patterns were measured from ISS using photogrammetry techniques and used to build corresponding 3D manikins

Anonymized images from ISS



3D Calibration



Kim et al., 2019

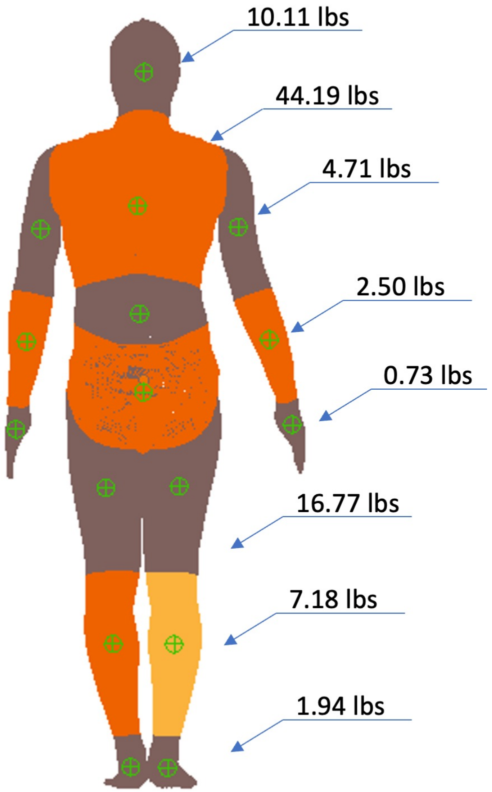
Center of Gravity for Artificial Gravity Simulations

- Artificial gravity simulations are used for astronaut training, including Neutral Buoyancy Laboratory (NBL) and Active Response Gravity Offload System (ARGOS).
- However, the motion characteristics and performance vary greatly with center of gravity (CG) locations.
- Accurate identification of the CG positions of the human body and spacesuit is critical for simulation quality and training effectiveness

Anthropometry for Spacesuit Weighout

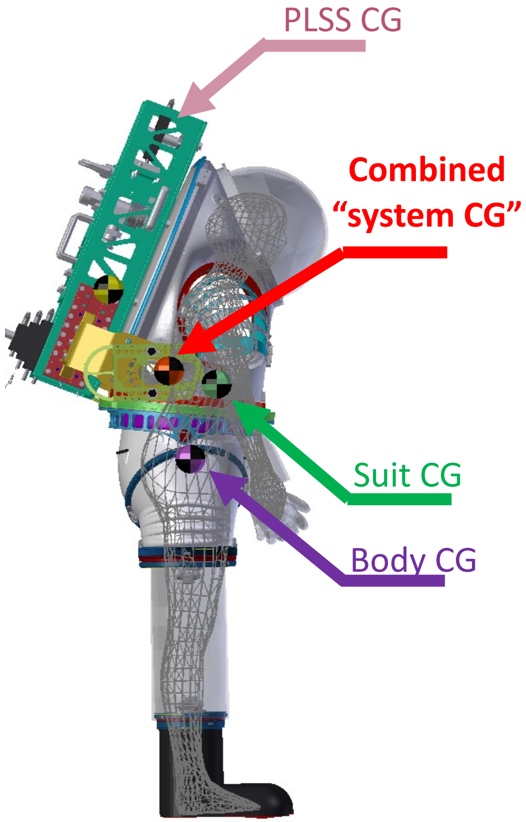
- 3D body scans were segmented and calculated for segment-wise CG
- Suit CG was also calculated by measuring each component, then combined with body and PLSS for system CG
- Weight packs were added to cancel out the buoyancy effect and match the CG with the model calculation (NBL)
- In ARGOS, the gimbal settings were adjusted to match with model calculated CG position
- The weighout performance was assessed by motion and center of pressure measurements

Body Segment-Wise CG

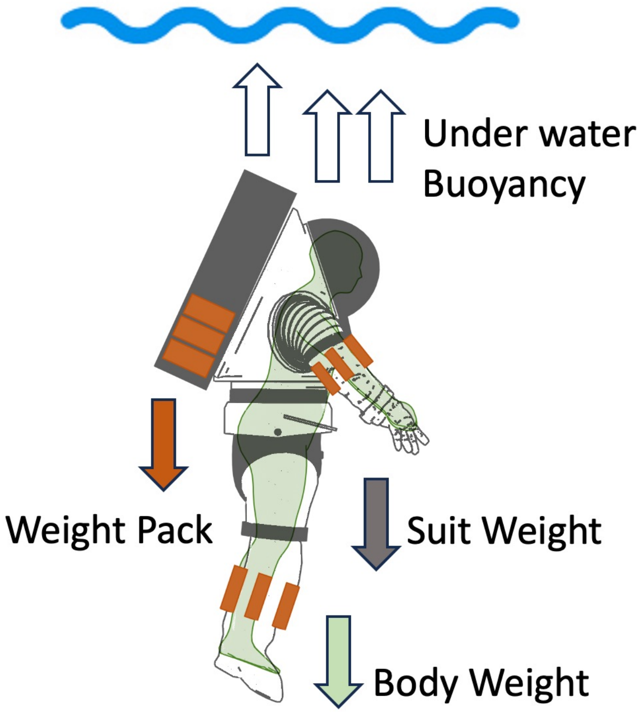


Suit Component-Wise CG

Combined System CG



CG Adjustments by Weight Pack



Vu et al., 2021

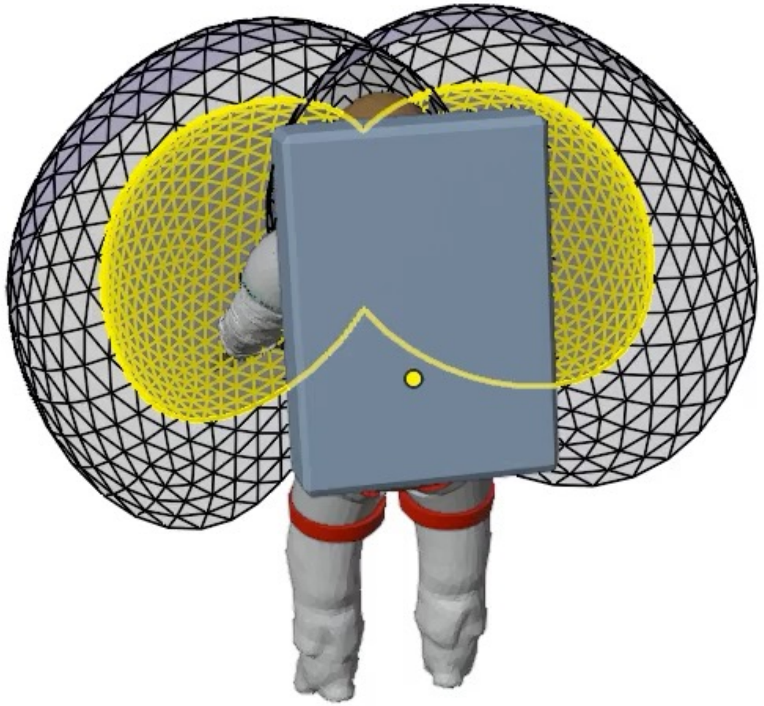
Spacesuit Mobility and Performance

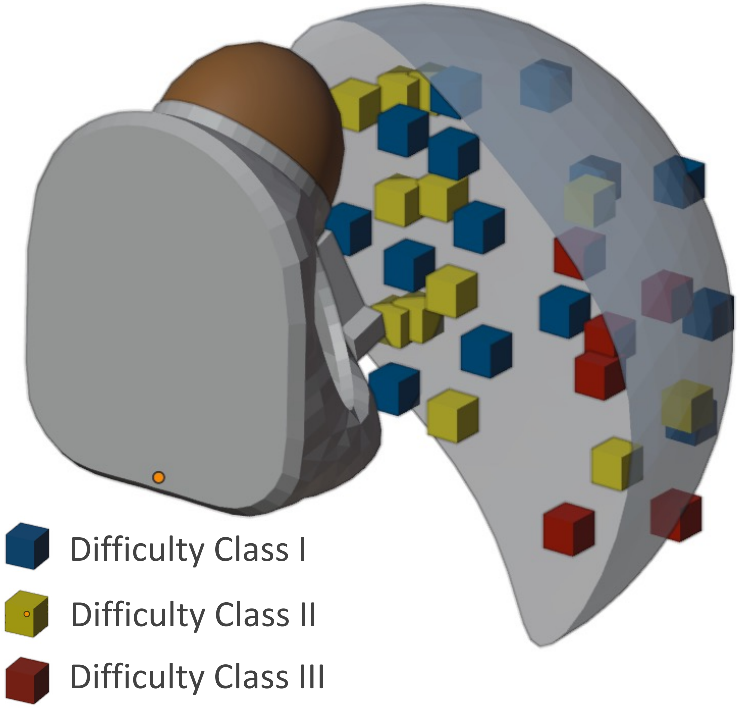
Motion in the suit can be substantially different from "natural" unsuited motions due to:

- Suit weight (~150 - 200 lbs)
- Pressurization
- Mechanical limitations
- Sub-optimal size matching

Reach Capability Analysis

- Reach envelopes have been commonly used to assess spacesuit mobility performance
- The size and shape of a reach envelope vary with anthropometry, strength and suit mechanical characteristics
- Reach envelopes can define the wearer’s work volume for task and interface designs
- However, a reach motion is associated with different level of difficulty across target positions, assessed by subjective ratings

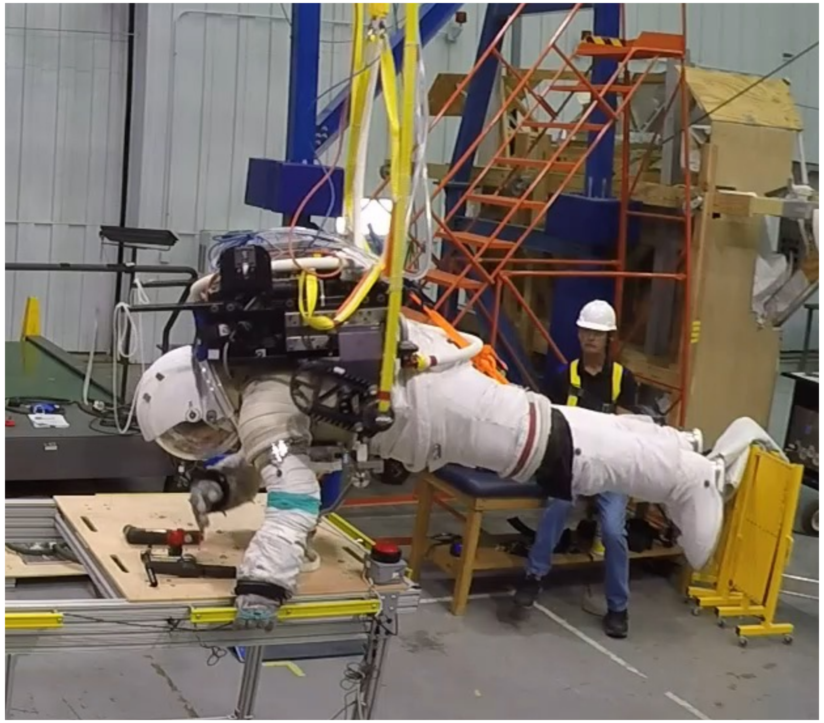


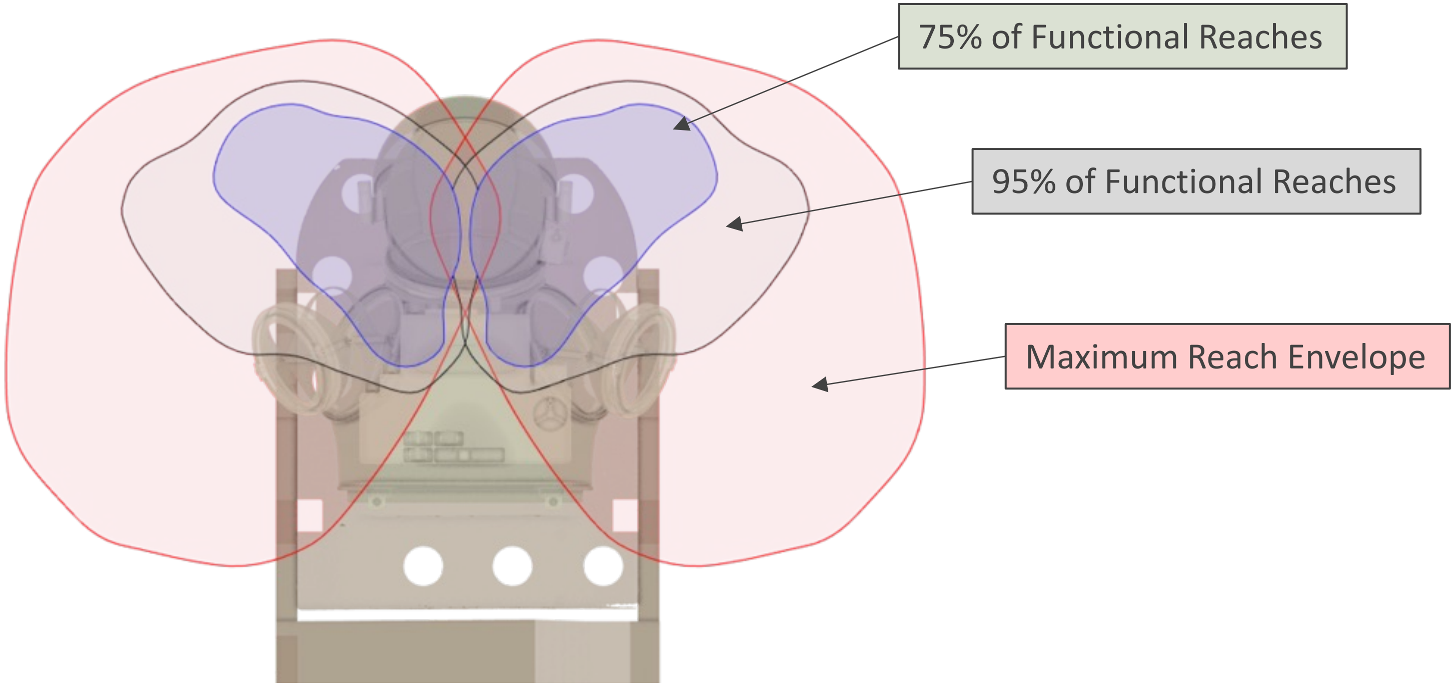


Kim et al., 2023

Reach Envelope Analysis

- As the difficulty ratings vary with target locations, some subsections of the reach envelope are utilized more frequently during prolonged functional work
- 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





75% of Functional Reaches

95% of Functional Reaches

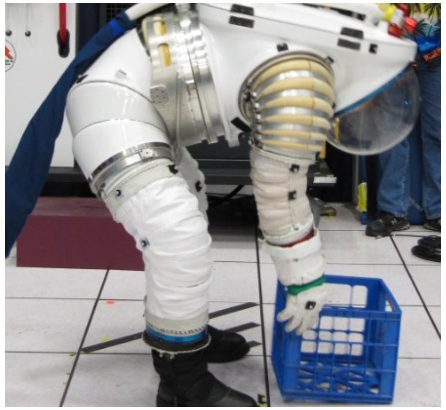
Maximum Reach Envelope

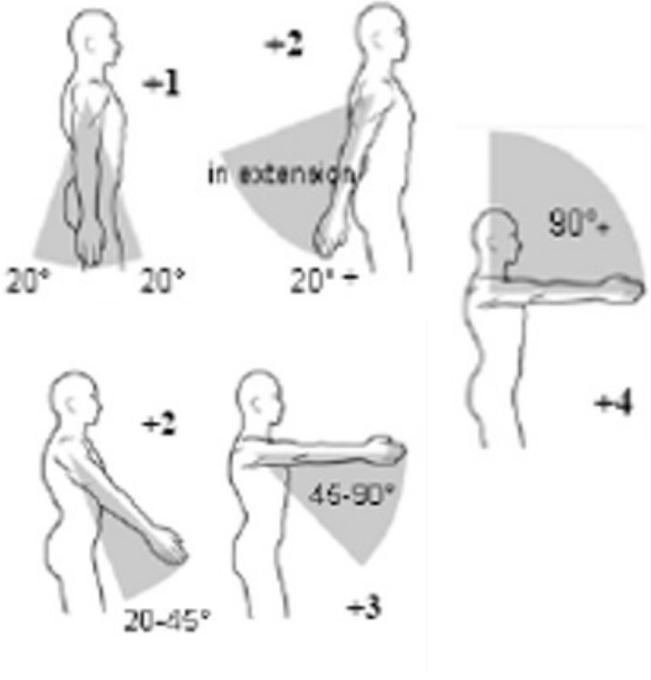
Benson et al., 2019

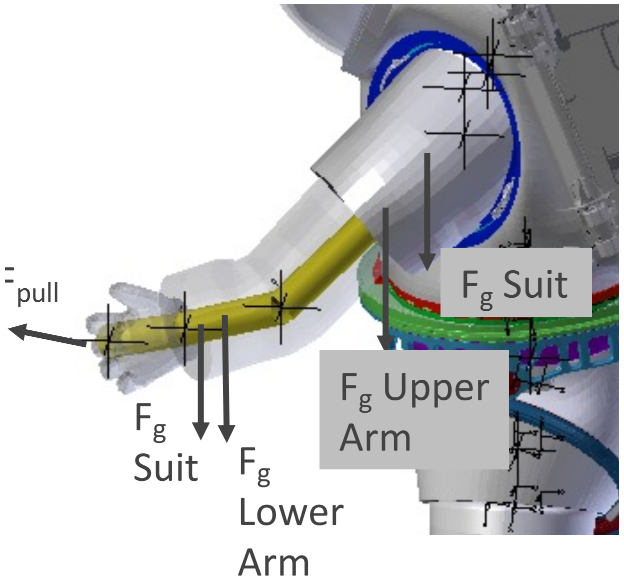
Ergonomic Risk Analysis

- Due to the suit weight and mechanical constraints, astronauts are under risks of musculoskeletal injuries
- Multi-faceted approaches have been taken to analyze the risk factors and identify mitigation strategies
  - Video-based observation analysis for the frequency and duration of awkward postures or forceful exertions
  - Model-based estimations of forces and joint torques for different external loading and suit posture
  - Determining unique demands for individuals with different body sizes and capabilities





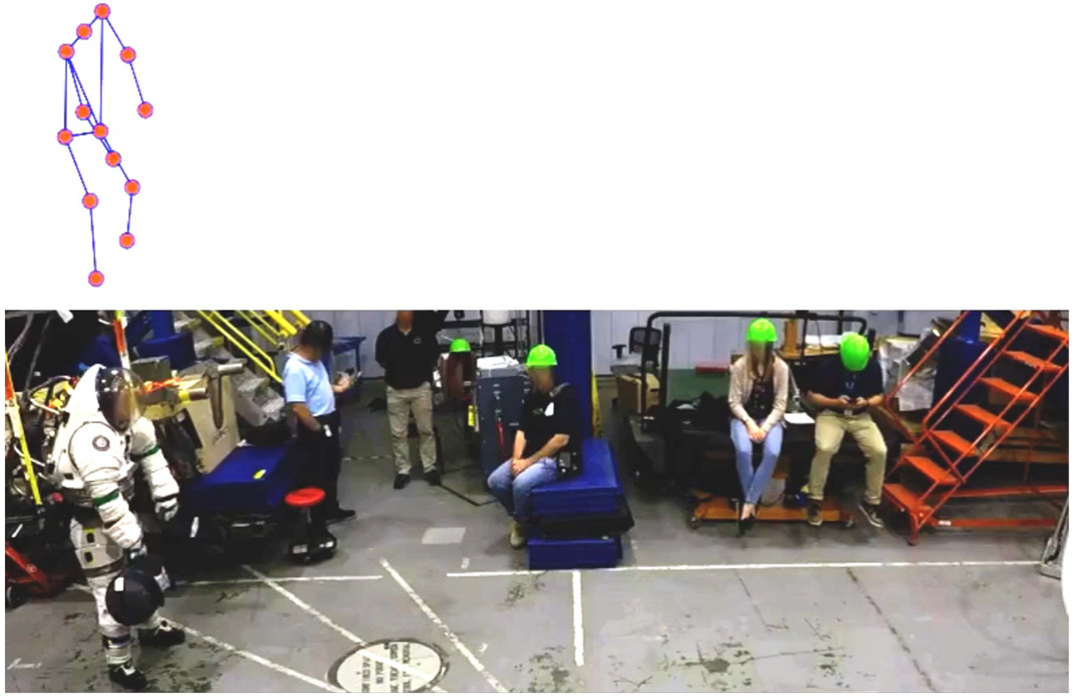




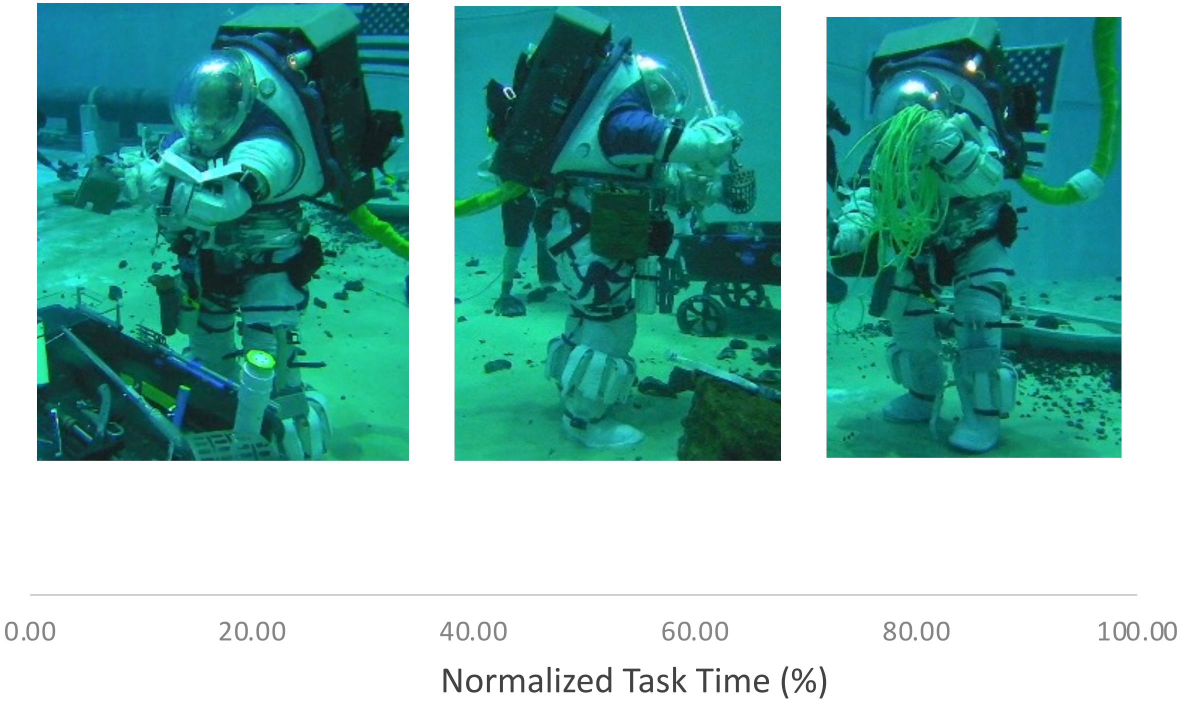
Artificial Intelligence for Motion Tracking

- Motions and postures of a spacesuit provide useful information for spacesuit design and EVA operation
- However, many existing techniques are cost-prohibitive for operations and unfeasible for retrospective analysis of past missions
- A software tool was developed based on the state-of-the-art artificial intelligence and machine learning systems
- The aim was to estimate 3D poses of a spacesuit from conventional photographs or videos, without special sensors or equipment
- The system can be used to estimate spacesuit joint cycles or musculoskeletal stresses of the astronauts

Motion Tracking from GoPro Video



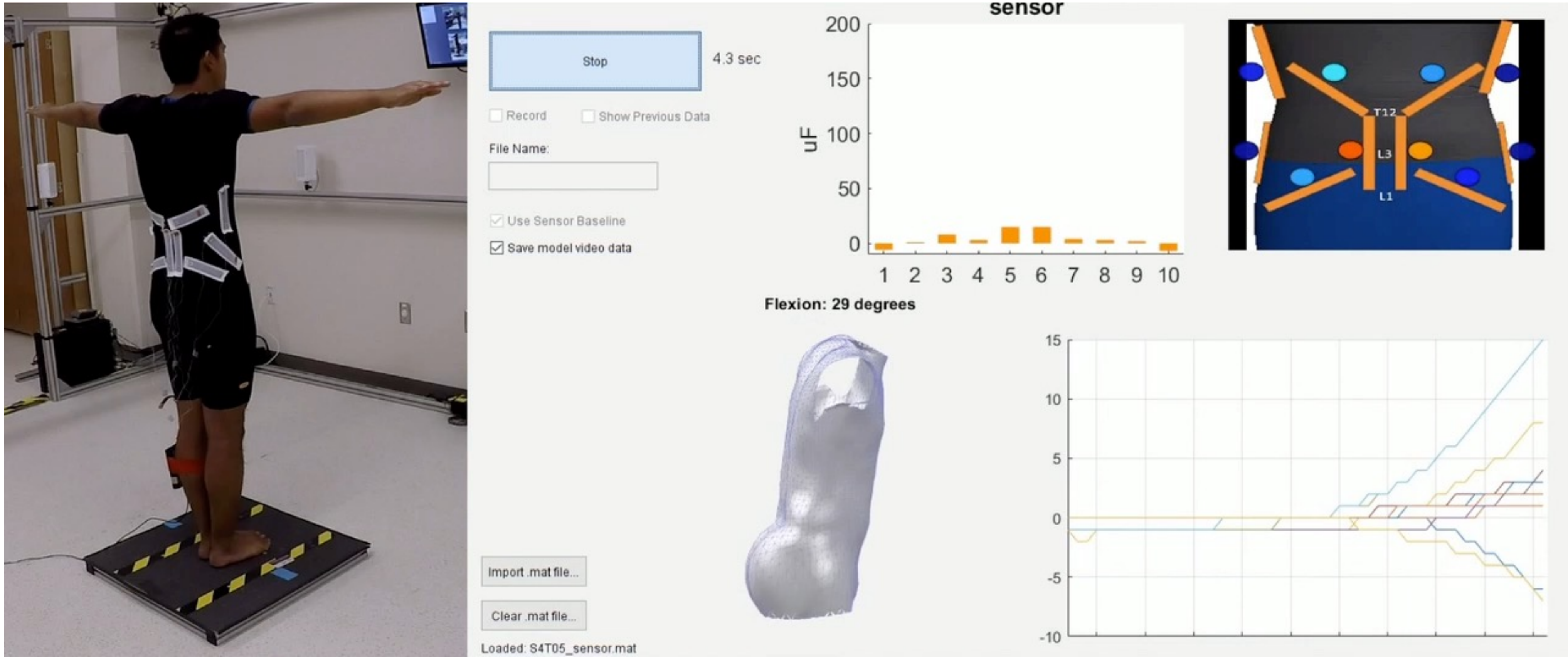
Shoulder Joint Motion Events



Vu et al., 2022

Stretch-Sensing Garment for Posture and Body Shape Estimation

- Measuring the posture of a subject inside the suit can provide critical information for assessing suited injury risks
- A garment sensing system was developed with fabric stretch sensors to predict torso shape and posture inside of the spacesuit



4.3 sec

☐ Record
☐ Show Previous Data

File Name:

☑ Use Sensor Baseline
☑ Save model video data

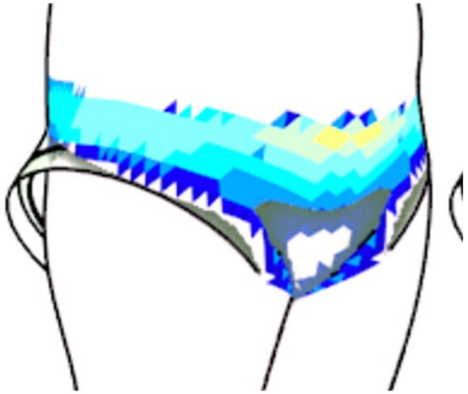
Flexion: 29 degrees

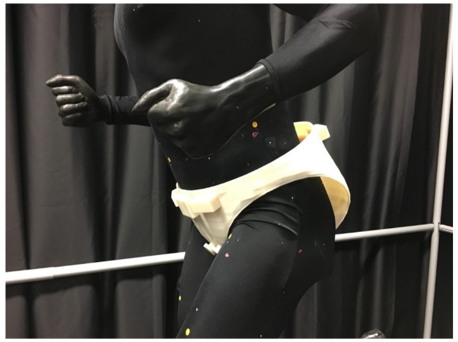
Loaded: S4T05_sensor.mat

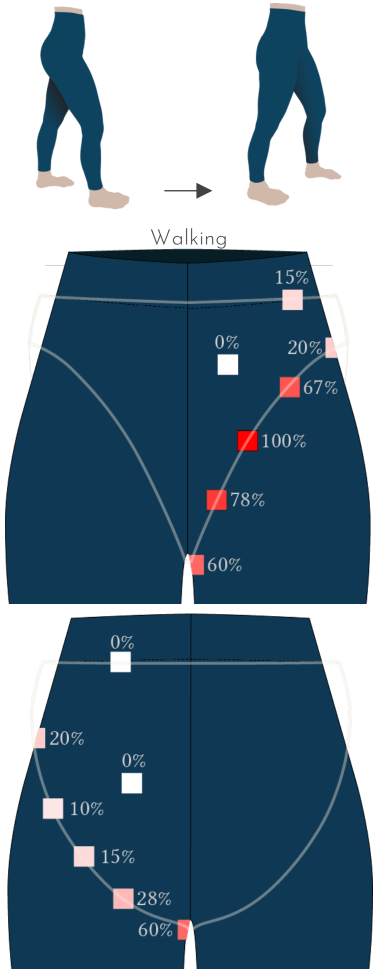
Vu et al., 2020

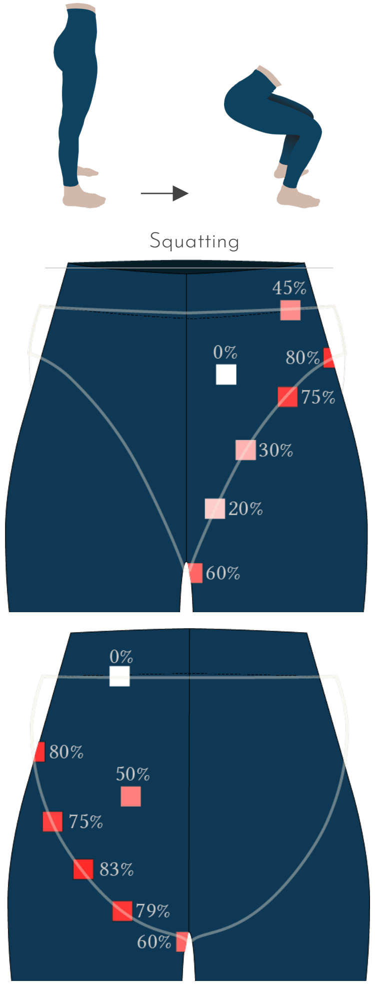
Textile-Based Wearable Contact Sensing System

- A textile-based, wearable contact sensing garment was developed to measure dynamic interactions that occur between the body and space suit; A prototype system was tested using 3D printed mockup lower torso assembly for contact assessments





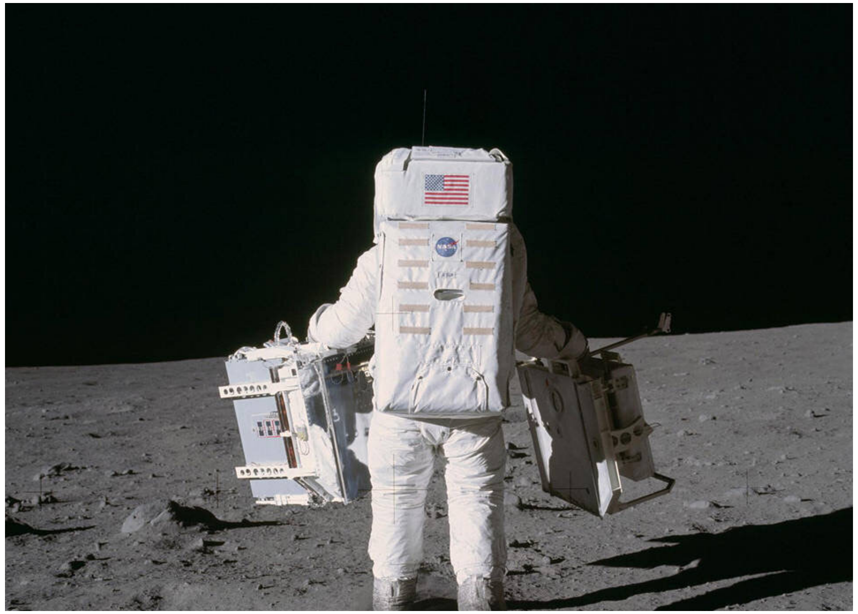




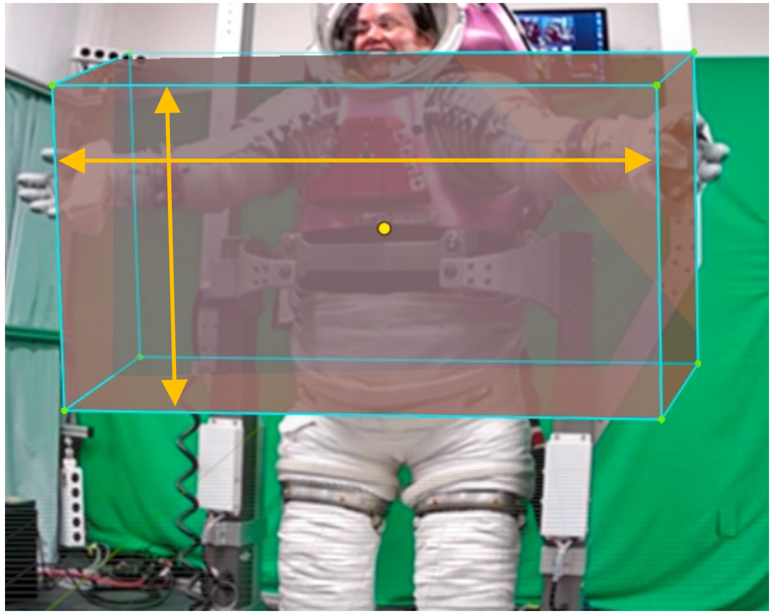
Compton et al., 2021

Requirements Development for Lunar Gravity

- Specific requirements need to be defined for biomechanical capabilities of suited crewmembers in lunar exploration tasks
- Through modeling and human testing, maximum capability metrics have been defined and measured, including maximum hand-held load weight, volume and step parameters

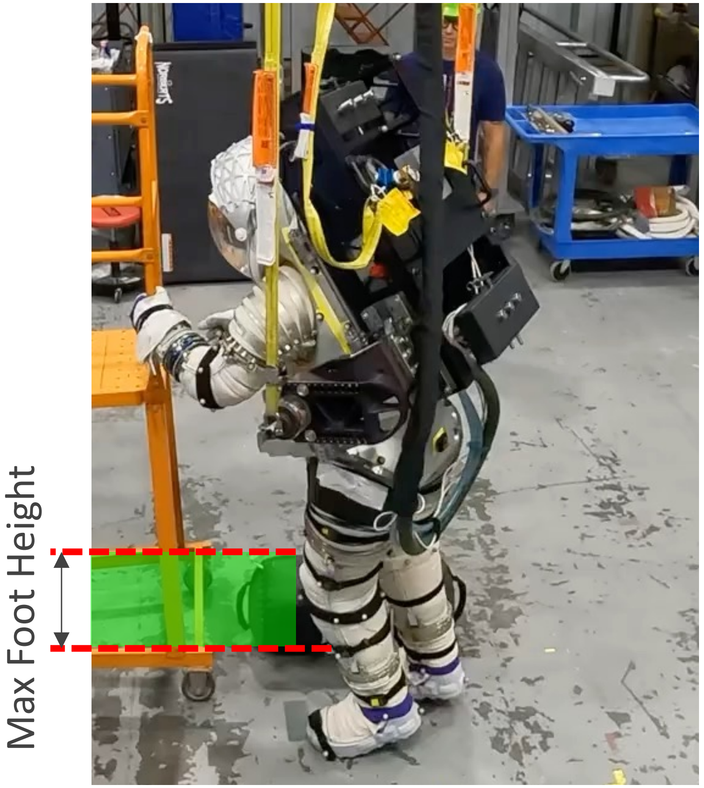


Payload Mass



Maximum Volume

(Fictional Synthetic Image)



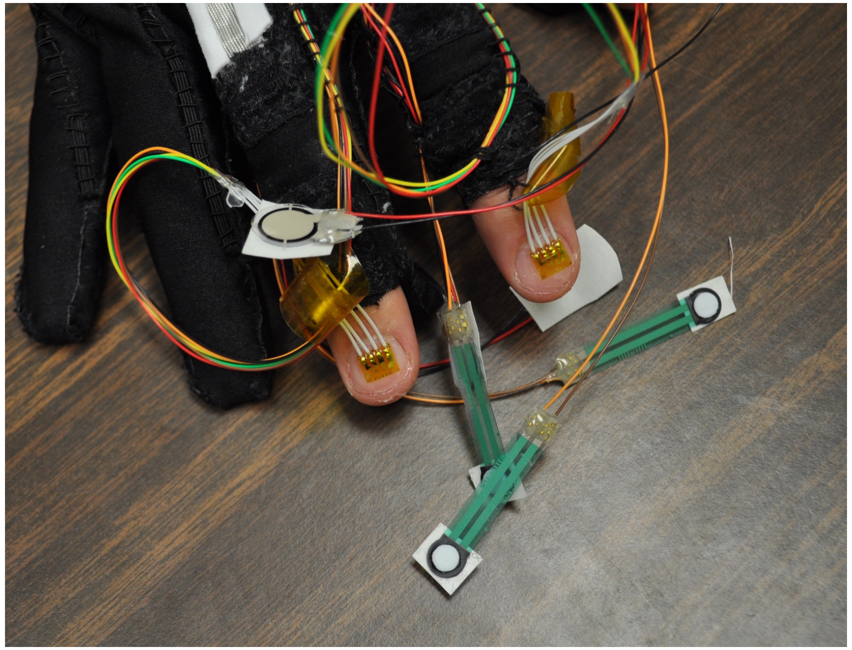
Step Design Parameters

Future Studies

In-flight 3D body scanner development

Glove sizing and fit

Force and contact sensing



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