Development of Human-Spacesuit Interaction Models

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Today's astronaut corps represents a wide range of various anthropometric dimensions. Accommodating this wide range of anthropometry and protecting for size variations in future crews, makes spacesuit sizing and fit a challenging and necessary aspect of suit development. Spacesuit fit can play an important role in performance, but a suit fit assessment, especially in dynamic postures, is difficult without extensive human-in-the-loop testing. One approach to address this issue is to model and simulate the human-spacesuit interactions for a target population early in the design process. The Anthropometry and Biomechanics Facility (ABF) at the NASA Johnson Space Center has been working to incorporate parametric human models based on 3D full-body scan data with spacesuit CAD models that can be driven by the user or imported motion capture data. An articulated spacesuit model combined with a poseable high-fidelity human model allows comparisons to be made between spacesuit capabilities and normal human ranges of motion. Furthermore, predictions can be made as to how a specific individual or population may perform in the suit from the perspective of reach and mobility. In this paper, we will present case study examples of reach, mobility, and fit analyses that can be done with these models and the methodology developed thus far. These models have the potential to become powerful tools for evaluating future spacesuit design architectures from the perspective of optimizing fit and performance.

Nomenclature

ABF = Anthropometry and Biomechanics Facility
DCM = Display and Controls Module
EMU = Extravehicular Mobility Unit
EVA = Extravehicular activity
HITL = Human-in-the-loop
HUT = Hard Upper Torso
IK = Inverse kinematics
IVA = Intravehicular Activity
LTA = Lower Torso Assembly
NASA = National Aeronautics and Space Administration
PLSS = Portable Life Support System
RE = Reach Envelope
ROM = Range of Motion
SAFER = Simplified Aid for EVA Rescue

I. Introduction

Extravehicular activity (EVA) spacesuits are essential for crew operations outside of a spacecraft. Not only do spacesuits need to provide the essentials for maintaining life, they also must allow sufficient mobility for an astronaut to carry out mission tasks that cannot be accomplished within the spacecraft. Crewmembers undergo

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extensive training exercises for each EVA[1] in addition to the actual EVA time spent on orbit. A suboptimal suit architecture design can lead to human mobility compensations that result in discomfort, reduced performance, or even injury. Optimization of the bearing type, size, orientation, and location with respect to human body joint centers of rotation reduces these risks by minimizing the amount of compensation needed to accomplish a given task. However, the impact on performance of different designs can be difficult to assess. Optical motion capture systems have been used to assess the motion and performance of suited individuals,[2] but this information only explains the motion of the surface of the suit. Understanding the motions of the subject inside the suit is not so straightforward. Optical motion sensors cannot visually track the body inside the suit, inertial measurement units (IMUs) are not reliable with all of the surrounding metallic components in the suit, and current forms of human-suit interaction sensors are not robust enough for the harsh in-suit environment. To add to these difficulties, it is logistically challenging and expensive to collect data through human-in-the-loop (HITL) suited testing. Furthermore, there is no perfect analog on Earth for simulating how a person fits or “falls” into a spacesuit in different gravity environments.

To combat some of these challenges encountered in suited human performance testing, the Anthropometry and Biomechanics Facility (ABF) has been developing morphologic and kinematic human and spacesuit computer models to assess spacesuit fit and mobility. This allows for a much more extensive assessment of how different body types might perform in a given spacesuit design. Specific suit design parameters can also be adjusted to see the impact on the modeled population, which can aid designers of future spacesuits in improving accommodation. This paper discusses some of the ongoing efforts the ABF has made in recent years to develop dynamic human-suit interaction models.

II. Model Development

Over the past decade, the ABF has been developing and improving upon various computerized models of both spacesuits and human manikins, and the following sections provide a brief overview of how they were developed and their current status.

A. Human Model Development

The ABF collects and maintains a large database of linear anthropometry and 3D volumetric scans in different poses for the astronaut population, as well as for a large number of engineering test subjects. However, sometimes there is a need for a unique pose or a specific body shape that was not collected in the dataset. Thus, a need exists for human computer models in order to make pose adjustments, generate different body shapes, and perform population analysis for virtual suit design and fit evaluations.

Initial efforts to develop a 3D human model focused on using the linear anthropometric measures pulled from 3D scans to build a “skeleton” of primitive shapes in SolidWorks (Dassault Systemes SolidWorks Corp., Waltham, MA). These “anthronauts” could represent any combination of anthropometric measures (Figure 1) and could even be put through very basic animations to demonstrate mobility. However, they lacked the compressibility of human tissues and were difficult to manipulate. Additionally, the shapes did not accurately portray the true volume and curvature of the human body.

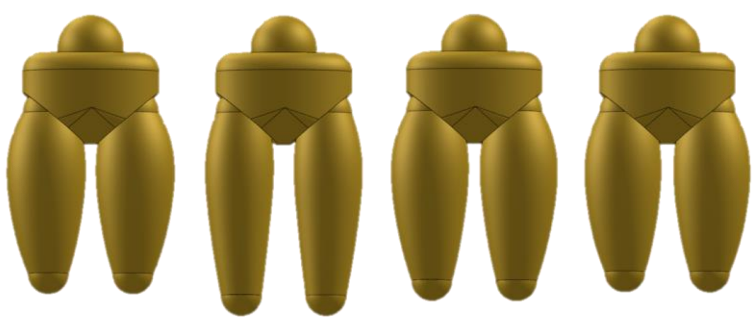
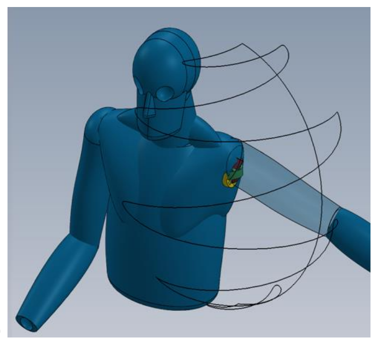
a)  b) 

Figure 1. First iteration of “anthronaut” models representing a range of anthropometry for the lower body (a); Anthronaut subject demonstrating a prescribed reach envelope of the shoulder (b).

The next phase of human modeling development was to move toward incorporating the actual 3D scans in a 3D modeling environment to improve ease of use and achieve a higher level of fidelity when looking more closely at aspects of suit fit. These 3D scans were imported into Blender (Blender Foundation, 2017), and a skeletal armature or "rig" was applied to the mesh to be able to dynamically adjust the posture of the subject. A vertex-weighting algorithm with respect to distance to the armature joint locations was applied to each vertex in the scan (Figure 2). As the armature is manipulated, the vertices associated with the armature segment are translated. The amount of displacement is based on the weighting. This will ultimately deform the body in response to armature articulation.

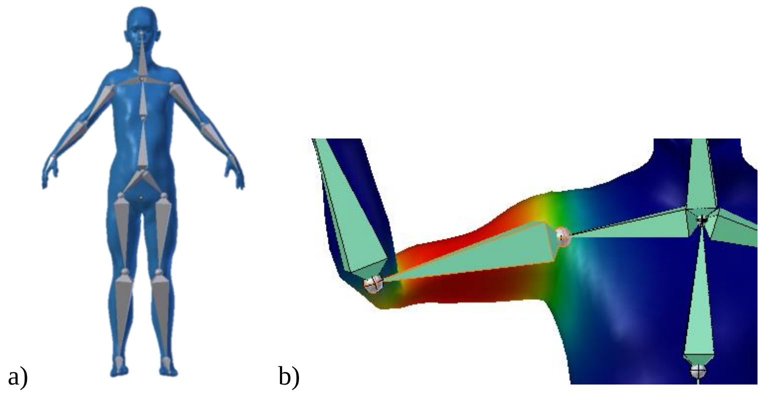


Figure 2. Subject with skeletal rig (a) and close-up example of the upper arm with the weight-painted region of the forearm highlighted by the color-map (b). Vertices in red are entirely affected by the movement of the selected armature bone. As the color fades into dark blue, the vertices are decreasingly affected by that bone's movement.

Repositioning the armature in this way, which is essentially a weighted sum of the linear transformations by the linked joints, works well for small adjustments. However, it cannot accurately quantify anatomically unique skin deformation or muscle bulging, especially in extreme positions at complex joints like the shoulder (Figure 3). This is not a major issue for basic range of motion assessments that do not rely on accurate body deformation, but it is critical for suit-to-body contact assessments. Furthermore, while the database of scans covers a wide range of anthropometry, it is possible that some specific body shapes exist in real life that are not represented in the database. To address these issues, statistical parametric human body models based on the 3D scans were developed to improve skin deformation simulation.

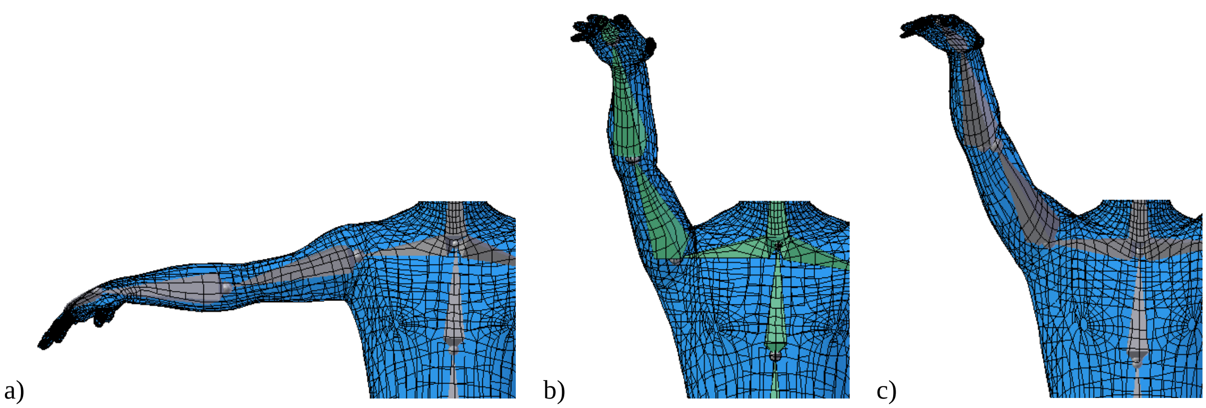


Figure 3. Comparison of subject shoulder deformation from a neutral posture (a) to an overhead reach based on vertex-weighting (b) and statistical parametric modeling (c). The wrist was constrained to the same target in both cases.

Due to the large point-cloud data that is associated with each 3D scan, a template-based nonrigid registration and morphing technique[3] was used to create homologous surface models with the same point-to-point correspondence across all scans. This allowed for a more manageable point cloud size, and vertex mapping similarity across models to facilitate incorporation into the integrated model. Correlations between shape and pose deformations across individuals were statistically modeled to generate a wide range of body shapes. Using critical anthropometry dimensions that are relevant to spacesuit fit, such as stature and shoulder breadth, the scan geometry data can be scaled and interpolated to produce the approximate body shape of an unrepresented individual with those critical dimensions. Figure 5 illustrates a variety of body shapes that can be generated and visualized based on an arbitrary set of anthropometry dimensions.

B. Spacesuit Model Development

Several spacesuit models have been developed to build a database of different suit designs that can not only be positioned around the user's body shape in 3D space, but that can also rotate and bend at the various bearings and soft goods breakpoints as they do when worn by a user. Only EVA suits currently exist in the model database because intravehicular activity (IVA) suits have a very different architecture and often have less stringent mobility requirements because they nominally are not fully pressurized nor worn outside of a spacecraft.

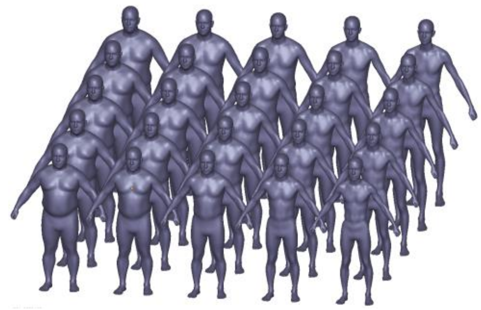


Figure 4. Statistically generated human models showing an arbitrary range of body shapes that can be created using the statistical model.

1. Extravehicular Mobility Unit (EMU)

The EMU 3D model was developed initially in SolidWorks via reconstruction from a combination of 3D scans and manual measurements of the hard upper torso (HUT) and scye bearings. The shoulder in the actual EMU is made entirely of soft goods, aside from the scye and upper arm bearing components, and has two fabric restraint-line seams that run down the sides of the shoulder convolute. In the model, a pivoting linkage was added between these two bearings, which allows it to mimic the types of motions seen in in this region of the suit during human testing (Figure 5). The pivoting linkage was designed to represent the longitudinal restraint line along the side of the joint, which is considered to be inextensible while allowing the joint to flex open and closed. The lower arms and lower torso assembly (LTA) of the actual EMU consist entirely of soft goods with the exception of bearings between segments. These portions of the suit were added to the Blender model by capturing a 3D scan with full texture and color data (Artec3D, Luxembourg) that was converted into individual mesh objects for the arms and LTA.

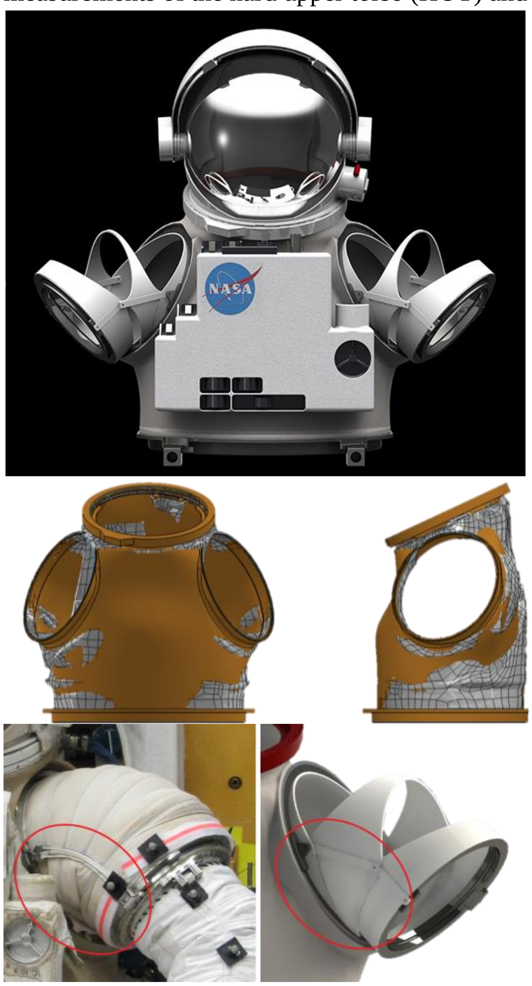


Figure 5. EMU CAD model of the upper torso hard goods (top); the comparison between the 3D scans and the modeled HUT (center), and the comparison between the actual EMU shoulder (bottom left) and modeled 3-convolute shoulder (bottom right) with the restraint line circled.

2. Mark III Space Suit Technology Demonstrator

Similar to the EMU, the hard-good components of the Mark III suit were constructed in SolidWorks based on 3D scans and manual measurements (Figure 6). The shoulder convolutes were modeled to match the actual mechanism configuration with a series of six pivoting metal convolute rings. The Mark III LTA consists of a waist bearing that allows for horizontal rotation and a waist ring pivot joint and rolling convolute that allow forward/aft motion. A rigid pelvis with three rigid hip bearings and a thigh abduction/adduction convolute allow the ability to ambulate and do other lower body tasks such as bending down to pick up objects. After importing the hard-goods geometry model into Blender, the soft goods components that make up the lower arms and legs were modeled as simple tubes with generic boots and gloves.

3. Z2 Series

The Z2 series of spacesuits carry a lot of similarity in architecture to that of the Mark III, having a rear-entry and rolling convolute shoulder design. However, unlike the EMU and Mark III suits, which were designed before modern CAD modeling programs, a 3D model was available for the Z2. Therefore,

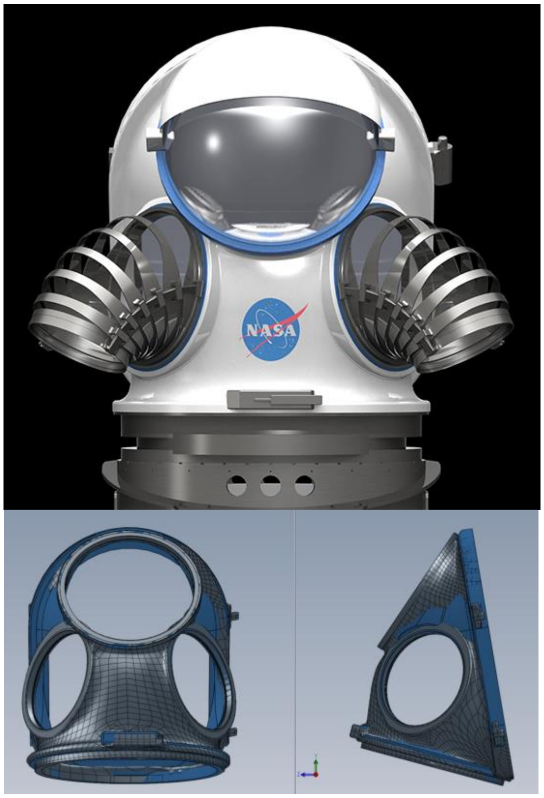


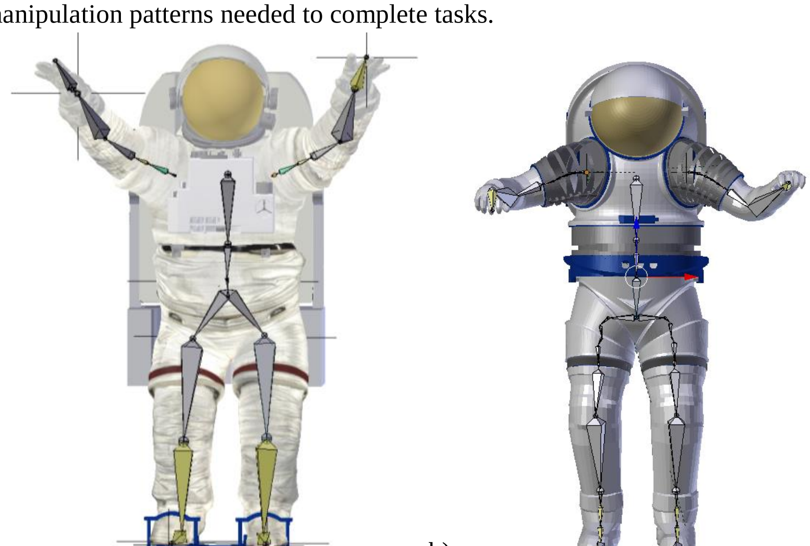
Figure 6. Mark III upper torso showing the internal 6-convolute structure of the shoulder (top), and the comparison between the 3D scans and the modeled HUT (bottom).

reconstruction via scans and manual measurements was not necessary to build a kinematically poseable Z2 model. In this case, the original model files for the hard-good components were imported. At the time of this paper, only the HUT and shoulder components of the articulating model are complete, and it is expected that the rest of the arms and legs will be built out over the coming year using a combination of 3D laser scans and solid-body modeling to result in a fully articulating suit model.

4. Integrated Hard and Soft Goods Deformation

The process for embedding an armature system to repose the suit is largely the same for each suit model. The armature is essentially a series of bones that originate at the HUT and extend outward to the arms and legs. It controls both the hard (e.g., HUT and shoulder bearings) and soft good (LTA and arm) components of the suit (Figure 7). The head and tail of each bone is coincident with the center of rotation of the corresponding segment on the suit. Each bone is also assigned x, y, and z-axes constraints to prevent or limit the degrees of certain rotations to simulate the mechanical range of motion (ROM) of each joint in the actual suit. For example, bones controlling the shoulder convolute rings are only allowed to bend about the axis of rotation of the connecting pins and have ROM limits that prevent them from interfering with one another in ways that are mechanically impossible.

Sections of the suit that do not deform in real life are constrained to remain un-deformed in the model. On the contrary, soft goods are allowed to deform based on the same vertex weighting method used in the human models. Similar to the human model, there are limitations in using this type of deformation method as it becomes increasingly inaccurate in extreme postures. Future soft goods modeling will incorporate parametric modeling techniques to improve the fidelity of the soft goods deformation. A hybrid suit model incorporating bearing movement and modeled statistical deformation is currently under development. The hybrid suit model will enable a detailed understanding of volumetric constraints and suit manipulation patterns needed to complete tasks.



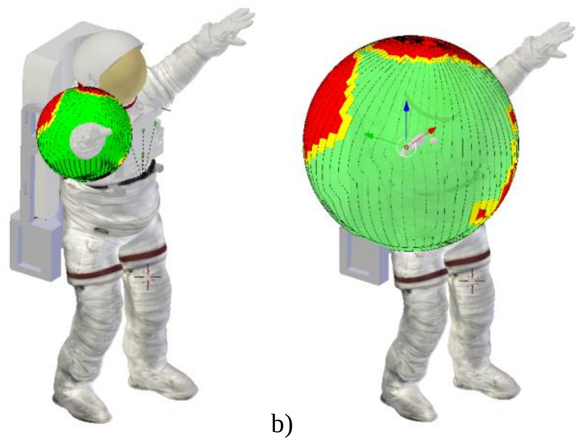
a) b)

Figure 7. Full EMU (a) and Mark III (b) models showing the internal rig armatures.

III. Applications and Uses

While these articulating human and spacesuit computer models have a multitude of applications, this paper focuses on some of the efforts that are being made to analyze reach and mobility. Reach and mobility analyses can provide early insight into what the suit is capable of and how design adjustments might impact a wearer's capabilities in the suit.

A. Reach Envelope Analysis



a) b)

Figure 8. EMU mechanical reach envelope of the elbow joint center (a), and the palm (b) with the elbow constrained to remain straight. The green area represents non-interfering elements of the mesh, and the red indicates areas where interference between the suit arm and other suit components (i.e. the helmet, PLSS, SAFER, or DCM) were found. The yellow band dividing the green and red contact areas is an indication of the mesh elements that were only partially in collision. The black tracing overlaid on each heat map is the path followed by the end effector during the simulation as it followed a spherical grid while adhering to the mechanical ROM limits built into the suit armature.

Early iterations of the human-suit model attempted to assess range of motion as a set of Euler angles, such as degrees of flexion/extension or abduction/adduction. These metrics have been extensively studied and commonly assessed for kinematic performance of unsuited persons in human biomechanics research. However, a spacesuit makes these motions far more challenging to perform with its added bulk and unique kinematic constraints (often referred as "programming") for complex joints like the shoulder. Current spacesuits have scye bearings that angle inward toward the neck to minimize hard contacts with the bony prominences of the human shoulder, but this limits motion of the arm. For example, data that are meant to strictly capture movement in the sagittal plane (flexion/extension), often show out-of-plane motions because the arm tends to rotate out away from the body as the person sweeps their arm backward in extension. This confounded pattern may not be uniquely represented in an Euler angle term about a fixed axis of rotation. Furthermore, planar motions do not capture the entire reach area and may miss important information about areas that are difficult for certain individuals to reach. A better measure of spacesuit mobility at the shoulder and the hip has been the reach envelope (RE), in which a subject moves an outstretched limb through all possible ranges of motion. Motion capture data from the RE can then be converted into visual representations of reach around the body that can be used for a number of different analyses, such as comparison of reach capabilities in different suit designs.

The shoulder reach envelope can be thought of as a portion of a sphere centered about the shoulder joint center with a radius that extends to the end effector of interest, such as the elbow, wrist, or hand. The elbow is ideally kept straight throughout all reach motions to maintain a consistent radius across the RE shell providing a true representation of shoulder mobility. However, at times it may be helpful to allow bent elbow motions to see all of the reachable areas of the hand. The articulated suit models developed thus far have been built with flexibility in mind to be able to accommodate all of these different types of analyses. Individual joints can be locked out such that they will not move relative to the joint above it and range of motion restrictions can be added to mimic realistic human limits.

The current spacesuit model provides the opportunity to compare the "mechanical" RE, or the RE that the suit architecture is capable of, against HITL motion capture data and human model predictions as well as other suit architecture designs. The mechanical RE is simulated by constraining the suit arm to follow a spherical grid-like pattern such that it covers the entire space around the suit within the mechanical limit of the joint in consideration. Overlap between the suit arm and other suit components is simultaneously detected and recorded during the simulation to further refine the spherical segment to exclude areas that are limited by the arm bumping into other parts of the suit (i.e., the helmet or display and controls module (DCM)). This simulation results in a spherical segment that visually represents the RE specific to that suit configuration.

Figure 8 shows the mechanical RE of the EMU shoulder-elbow and shoulder-palm segments with the regions of self-interference indicated in red and the non-interfering areas in green. The arm segment (shoulder-to-palm) was put through two different simulations (elbow restricted to full extension or elbow allowed to bend) to look at the reach area and arm-to-suit collision throughout the RE simulation. In both cases, the elbow position was traced throughout the span of the spherical grid representing the mechanical RE. The elbow was kept extended either entirely (restricted to full extension) or as much as possible (bent elbow allowed). This resulted in nearly identical plots between the two conditions over the areas reachable with a fully extended elbow, but allowing for bent elbow motion expanded the color-coded distribution ("heat-map") to include more coverage in the front of the suit (Figure 9). While this example is specific to a particular arm length and EMU HUT size, this case study demonstrates important knowledge about the mechanical RE of the suit and the possibility that there may be unexpected areas in the RE that are difficult to reach.

The human body shape models, in conjunction with the articulating suit models, provide an opportunity to better quantify the impact on performance of different human-suit size combinations. To evaluate how anthropometry affects the RE of the person inside the suit, simulations of suit-human interference were conducted. A parametric shoulder model to predict shoulder postures across different body shapes[4] was combined with the reposable EMU model. Two body shapes with different anthropometry were placed inside the suit and the arm was directed to follow the same spherical pattern from the mechanical RE tests. Interferences between the human body and suit bearings were detected and recorded. These areas of interference are indicated across the reach envelope as a heat map overlay (Figure 10). Across different body sizes, it becomes apparent that in this simulation, the RE, as defined as coverage of an ideal sphere, decreases as the anthropometry dimensions increase, presumably because the circumference of the limb increases proportionally with size. There are limitations to this in that humans can tolerate a certain amount of compression that varies throughout the body, which currently cannot be represented in the model. Furthermore, while the comparisons made here were done with bodies that were identically positioned in the suit, the initial position of the body within the suit is a best guess at its current state, particularly for small individuals in large suits who have a lot of empty space to move around in. It is also important to

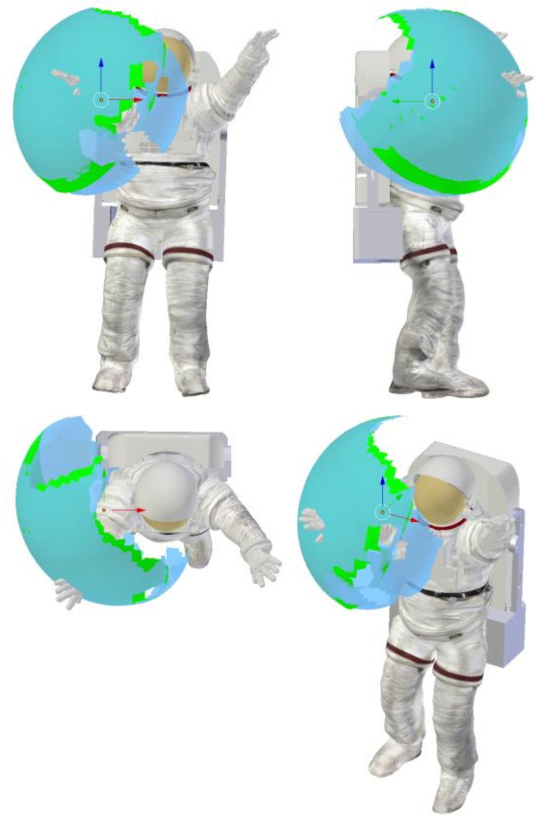
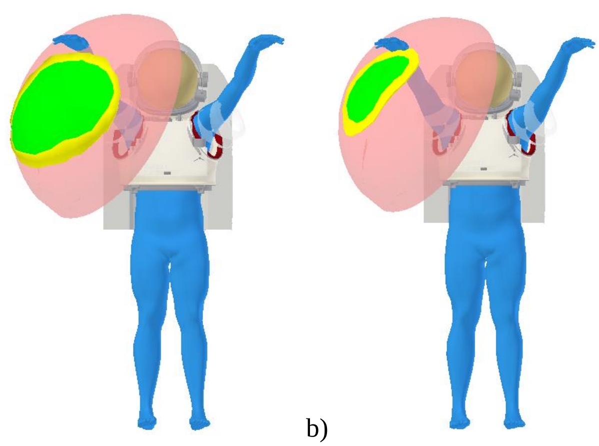


Figure 9. EMU mechanical reach envelope of the right palm with the elbow constrained to remain straight (blue) overlaid with the mechanical reach envelope of the palm with the elbow allowed to flex within normal physiological ROM (green). The teal sections are the overlap between these two conditions.



a) b)

Figure 10. Comparison of human-suit interference over the mechanical reach envelope of the EMU between subjects with different anthropometry that corresponded to a person with a normal BMI (a) and a person with a larger BMI (b) . The green area is the region the human model could reach without interference with the suit, while the red area is the region of the extended elbow mechanical reach envelope of the EMU that cannot be reached by these subjects. The yellow band is an area of uncertainty in the model between these two regions.

understand that a bigger non-suit-interfering RE is not necessarily better. It could be an indication that the suit is too big for the individual, which can be as equally problematic as a suit that is too small. Nonetheless, this collision detection mapping can provide great insight into how different suit architectures may affect fit and performance.

B. Mobility Analysis

One of the latest developments in the articulating suit models is motion capture integration. Data captured from HITL testing can be used to drive the motion of each segment of the suit model armature (Figure 11). When human motion is overlaid with the predicted mechanical RE, it becomes apparent that there are areas that the suit can theoretically reach that users cannot due to other factors such as strength, suit stiffness, or individual ROM limits. Understanding where these overlaps exist provides an opportunity to compare how well the suit accommodates human mobility patterns and to see where adjustments could be made in the design to improve fit and accommodation.

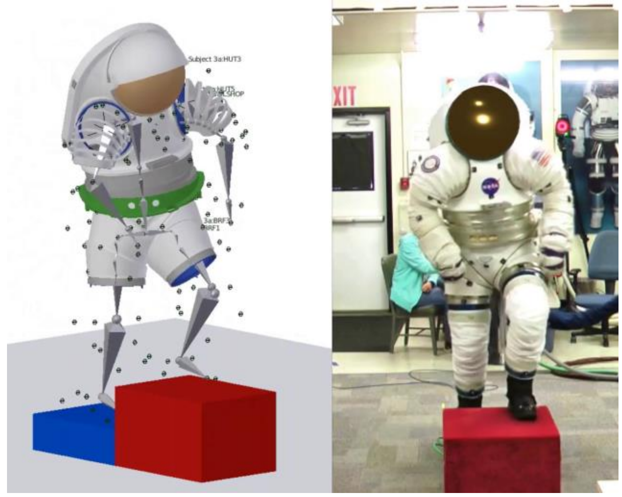


Figure 11. Mark III model being driven by motion capture (left) as compared to the actual video footage (right).

Many aspects of suit mobility are of interest, particularly as we move toward future planetary missions. Functional activities, such as walking, navigating up and down terrain, and bending down to pick up objects, are important functions for a planetary spacesuit. Animating these activities with the suit model can help to demonstrate the kinematic variations that different suit design architectures will exhibit while performing such tasks.

Hip mobility is important for EVA suits that are designed for planetary operations. Accommodating the complexity of a human's hip range of motion is particularly difficult to do with a spacesuit. Without bearings, the rigidity of the pressurized soft goods places severe restrictions on hip flexion and abduction, as was apparent in footage from Apollo astronauts ambulating on the Moon.[5] The Mark III hip includes two angled rigid hip components that were designed in an effort to accommodate as much hip mobility as possible. The mechanical reach envelope of the hip was simulated similar to that of the shoulder reach envelope of the EMU. Motion capture from a subject of a previous study that included activities such as manipulating cargo, bending over to make boot adjustments, kneeling, sitting down, prone-to-stand recovery, side stepping, and ladder climbs was combined and compared between unsuited and suited conditions. This data was overlaid with the Mark III hip simulated RE as seen in Figure 12. One can see that the hip design clearly provides a wide range of mobility, yet only about half of that region is used during the suited tasks. Additionally, there is actually very little overlap with what the subject used during functional activities in the unsuited condition compared to the suited condition. This means that the person inside the suit may have to significantly

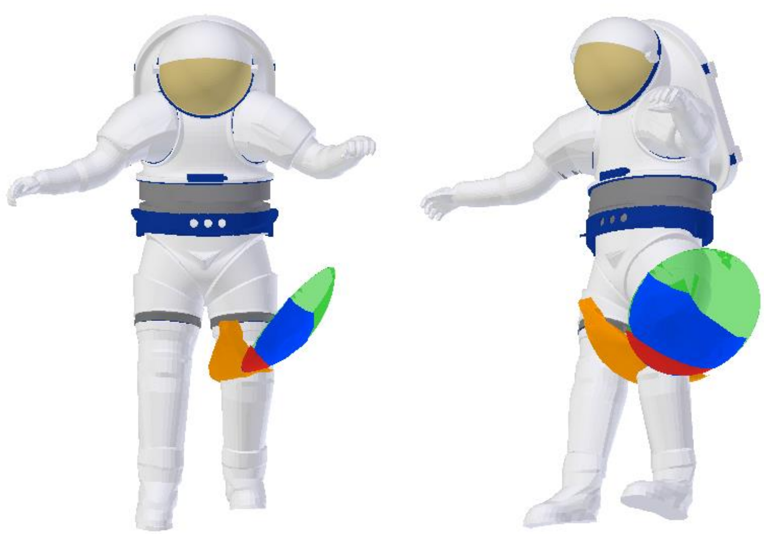


Figure 12. Mark III hip mechanical RE (green) overlaid with the RE envelope found from HITL motion capture data during functional tasks that were done unsuited (orange) and in the Mark III (blue). The red region indicates the area of overlap between the functional ROM used by the subject in the unsuited condition and the mechanical RE of the Mark III.

alter their normal mobility patterns to accomplish certain tasks (i.e., spreading the hips much further out to the sides to squat down as compared to a normal unsuited squat). Impacts to mobility such as this are important to understand as they may have implications for injury risk in future planetary missions.

IV. Future Work

Future work on the reach envelope analyses is expected to expand on the case studies demonstrated here by incorporating a greater variety of subject anthropometry and suit component sizes. With a greater range of body shapes, more informative and quantitative reach envelope assessments can be made about a particular suit configuration or design. This is expected to be an area of focus once the articulating Z-series spacesuit model has been developed.

As mentioned earlier, motion capture integration with the dynamic suit models is still in the early stages of incorporation, and several tools to improve the mapping of the motion capture data to different suit configurations are currently under development. Motion capture integration allows for manipulation of the virtual suit models with representative suited movements, and could potentially be used to test the mobility of future spacesuit designs in predictive analyses. Furthermore, a model can be created from the suited motions to assess the movements used to complete EVA tasks.

Another significant area of work currently underway in regards to human-suit modeling in the ABF is the suit fit analysis. There are several projects in progress in the ABF that are aimed at better understanding skin compression tolerance across the torso for HUT fit, and the specific impact of overall fit on EVA performance. The results of these analyses will be used to enhance interactions between the human and suit models. Additionally, work is still underway to improve the fidelity of the soft goods deformation by means of statistical modeling to better represent how the shapes of the suit arms and legs change through various ranges of motion.

Human-suit modeling is a complex endeavor and one that is continually improving as better models are developed and technology advances. This paper represents the current state of these models and some of the applications that they have. While more analysis on the reach envelope, motion capture integration, and fit aspects is expected, the case studies represented here highlight the utility of these models. They have the capability to influence suit design decisions that could affect the population accommodated by different suit sizes and geometry, and could influence the design and location of various workstations that astronauts will need to interact with during an EVA.

Acknowledgments

The authors would like to thank Han Kim, Gabriel Roper, Seth Abramczyk, Matthew Cowley, Yaritza Hernandez, Lauren Elizondo, Scott Cupples, the EVA Project Office and the Advanced Suit Lab for their contributions to this paper.

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