Considerations of Spacesuit Stepping Mobility for Lunar EVA Crew Interface Design

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As NASA aims to return humans back to the lunar surface through the Artemis Campaign, careful considerations regarding suited human factors in partial gravity are required during crew interface design to reduce overall NASA program risks. The unique environment of the lunar surface presents significant challenges for human mobility, particularly while wearing a spacesuit. Given the altered spacesuit kinematics, defining proper step or platform heights that are safe and accessible for suited crewmembers across the anthropometric range is an important aspect of human factors in spacecraft design. In this work, an analysis was performed using a 3D spacesuit model scaled appropriately to specific anthropometric properties, then combined kinematics data gathered during previous spacesuit data collection events using a motion capture system. The kinematics data previously collected included tasks such as suited test subjects performing forward steps up onto a surface and sidesteps over an obstruction on the floor. The collected data were then projected onto a virtual wearer, whose anthropometry corresponded to a 1st percentile female and a 99th percentile male in stature and vertical trunk diameter (VTD) to assess different what-if scenarios for extreme anthropometric ranges. The influences from other crew interface configurations, such as handle placement, were also investigated. This paper demonstrates how suited test data integrated with human-suit modeling can effectively be used to develop recommendations for EVA systems requirements. These recommendations are expected to reduce biomechanical stresses and risk of injury for the crewmembers while improving EVA mobility and performance.

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Acronyms and Nomenclature

ARGOS = *Active Response Gravity Offload System*
HITL = *Human-in-the-Loop*
DVT = *Design Verification Testing*
EPG = *Environmental Protection Garment*
EVA = Extravehicular Activity
HLS = Human Landing System
PLSS = Portable Life Support System
VTD = Vertical Trunk Diameter
xEMU = Exploration Extravehicular Mobility Unit
1/6th-g = 1/6th gravity

I. Introduction

NASA's Artemis Program involves taking a wide range of humans to the surface of the Moon. The program requires the systems to be designed to accommodate the maximum proportion of the crew population, heuristically represented by 1st percentile female to 99th percentile male critical measurements. This requirement creates unique challenges in designing interfaces for human systems. Similarly, to ensure the crew's safety while in space, a set of additional requirements need to be made regarding human interfaces to reduce the risk of injury and fatigue while performing EVAs on the surface. Specifically, defining an appropriate step height requirement is critical for human systems design. The requirement should allow crewmembers to ingress/egress systems, without adjusting their body or spacesuit, in a way that may cause excessive biomechanical stress. This can be especially challenging with additional overhead restrictions above the step, such as translating through a hatch; specifically, for 99th percentile stature male crewmembers, having to bend down or duck. Conversely, the step must also accommodate a female with the 1st percentile measurements leg length and knee height, allowing them to safely lift and place their foot on the step. Additionally, the step depth and hatch width strongly influence crewmember's technique when performing a hatch ingress/egress or step up. Stability aids, such as handles, should also be considered to reduce the risk of physical fatigue and increase stability during step/hatch translation.

To gather appropriate data for assessing step and hatch designs, a set of human-in-the-loop (HITL) tests and modeling efforts were performed at NASA Johnson Space Center. Testing was performed in both a 1-g laboratory environment and an offloaded 1/6th-g environment at NASA's Active Response Gravity Offload System (ARGOS). Subjects wore NASA's government reference design spacesuit, the exploration Extravehicular Mobility Unit (xEMU) suit, and motion capture data was collected during each test event. The data was then used to further analyze the full range of anthropometry through digital human-suit modeling, to drive recommendations for safe step requirements. Additional analysis was performed using the anthropometrically extrapolated xEMU human-suit models to develop handle placement and hatch corner radius requirements.

II. Methods

A. Human-in-the-Loop Tests

During NASA's xEMU Design Verification Testing (DVT)[1], a group of subjects across varying anthropometric ranges performed a set of mobility tasks. The subjects ranged from 34th to 96th percentile in VTD, and 38th to 99th percentile in stature. The focus of these tests was to assess the suit's mobility and cycle life. As a part of the data collection, optical motion capture data was gathered from the subjects while performing tasks by placing retro-reflective markers across the spacesuit as shown in Figure 1. One of the tasks performed during the DVT testing was stepping up. For this task, the subjects were asked to step onto stackable exercise steps (Figure 2B). The subjects repeated the task increasing the step height by 2.75-inch (7 cm) increments until they could no longer perform a controlled step up without any handles or stability aids.

Figure 1. Optical Motion Capture markers Placed Across the xEMU Spacesuit.

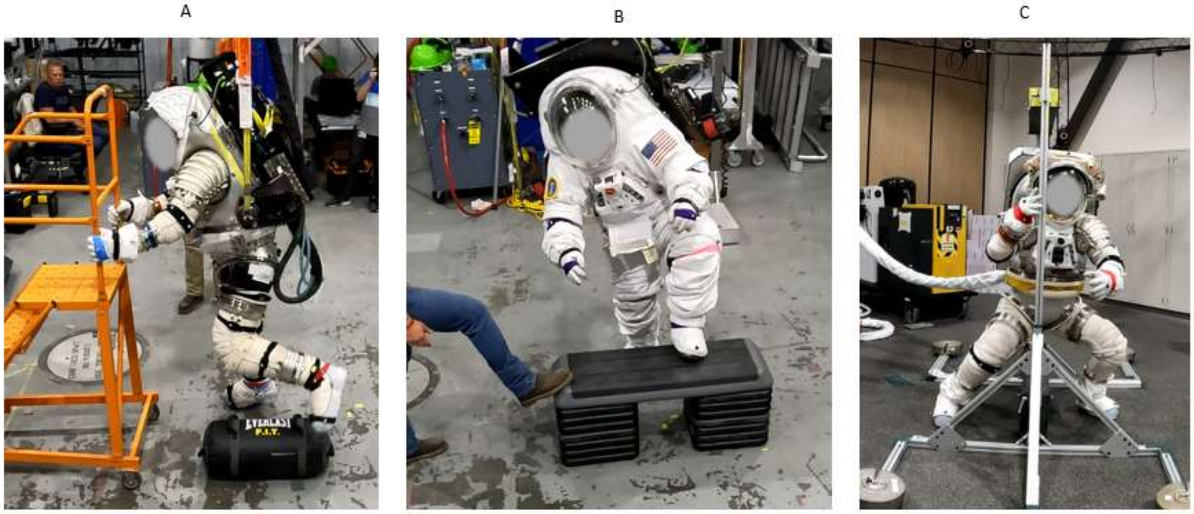

Figure 2. Subjects Performing the Side-squat-step Task (A), Front-Step-Up (B), and Hatch Translation (C). *Side-squat-step and front-step-up were performed at ARGOS with a 1/6th-g offload, while hatch translation was performed in a lab setting with no offload.*

Additional data was gathered during the DVT testing[1] for a side-step-squat over an object (Figure 2A). During this task, the subjects side-stepped over a cylindrical exercise bag with a diameter of 10.5 inches (26.67 cm), while holding onto simulated handholds.

From a separate test series, an additional set of suited data was collected to assess step height with an overhead restriction, similar to a spacecraft hatch. This test was performed in a 1-g laboratory setting without offloading using

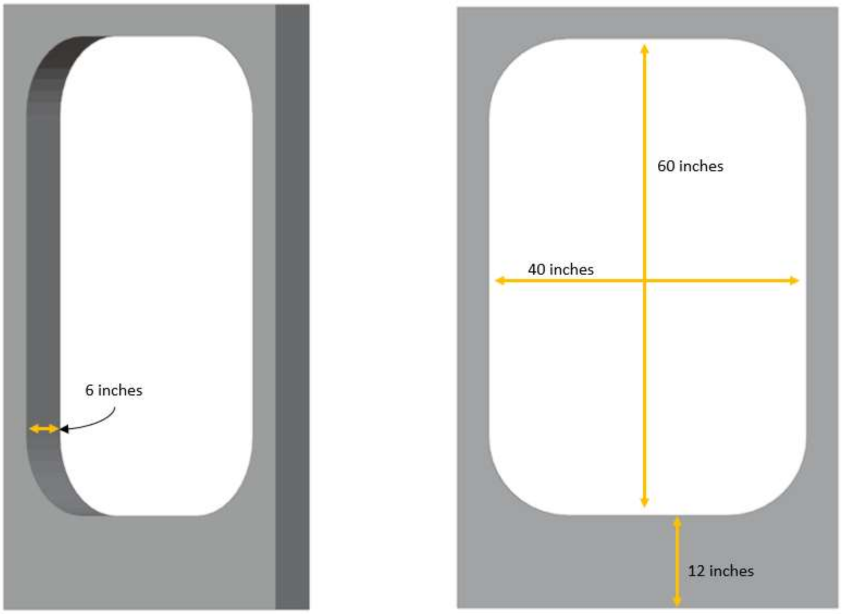

Figure 3. Hatch dimensions shown, with a 60-inch height, 40-inch width, 6-inch depth, and a 12-inch step threshold. *Step threshold heights of 12, 9, and 6 inches were evaluated during the HITL suited tests. Note that the mockup used during testing did not have curved corners.*

the xEMU spacesuit, as seen in Figure 2C. To understand the most volumetrically challenging scenario in translating through a hatch, this series involved four subjects with 4th quartile stature and VTD as the critical anthropometric dimensions. An adjustable hatch mockup was developed using foam and aluminum frames to allow for testing of various step heights and hatch overhead height combinations. The depth of the step was set to 6 inches (0.15 m) using high-density foam cutouts, based on NASA's hatch depth requirements in NASA's EHP-10028 document. The hatch width was constrained to 40 inches (1.02 m), as presented in Figure 3. These values were adapted from legacy NASA hatch design requirements from previous missions. For this test, the subjects were allowed to practice translating through the hatch two times prior to recording data to familiarize themselves with the possible techniques. The subjects were allowed to hold anywhere along the hatch frame to simulate a handle, and the hand placement was later used to understand the preferred stability aid locations for the subjects based on the hand markers.

B. Human-Suit Modeling

To assess the full range of anthropometry, the HITL data was extrapolated to perform a worst-case analysis based on VTD and stature as the critical anthropometric dimensions. Therefore, human-suit models were created using CAD of xEMU spacesuit components[2]. The proper spacesuit component sizes were used to match a 1st percentile female and a 99th percentile male in VTD and stature. The waist sizing ring was adjusted to match 1st and 99th percentile VTD. The arm and leg softgoods were also adjusted to match a 1st and 99th percentile in stature, while assuming proper suit indexing. Motion capture data was used to reproduce the test subjects' technique and kinematics for each task. The motion capture data was first labeled and gap filled in the Vicon software. The kinematics were modeled by aligning the spacesuit hard components CAD with motion capture data and calculating joint centers. The extracted values were used to adjust the joints and suit components of the extrapolated 99th percentile model to simulate the motion of a hypothetical subject with large body dimensions.

3D models of a simulated step and a simulated hatch were added to the suited model to help assess clearances between the suit and the step hardware. To understand the limitation of front step-up onto a threshold without any overhead restriction, the 1st percentile resized model was examined as the anthropometric worst-case using the front-step-up motion capture data. A similar approach was taken to assess side-stepping over a threshold with an overhead restriction, like translating through a hatch. To ensure that crew with higher stature and VTD would be capable of safely transitioning through while clearing the overhead restriction of a hatch, motion capture data was used with the 99th percentile model as the anthropometric worst-case (Figure 4). The model was then used to analyze clearance from suit to the hatch and the threshold at varying heights.

Additional analyses were performed using the models to further assess details of an ideal hatch design, such as handle placement and corner fillet radius. Table 1 provides an overview of the anthropometric worst-case identified and assessed for each design criteria, along with the specific HITL task used to adjust the human-suit model.

Figure 4. Example of xEMU Spacesuit HITL Data Extrapolated to a 99th Percentile Human-Suit Model Using Motion Capture Kinematics Data. *The suited subject is performing a side-squat-step technique to translate through a simulated hatch.*

Table 1. Overview of partial gravity design criteria and their associated data source and anthropometric worst case considered in the analysis.

Design Criteria	HITL Task Analyzed	Anthropometric Worst-Case Percentile Stature and VTD Evaluated
Step Platform Height	Front-step-up	1st
Hatch Step Threshold Height	Hatch translation	99th
	Side-step-squat	1st
Hatch Step Threshold Depth	Side-step-squat	1st
Hatch Stability Aid (Handles)	Hatch translation	99th
	Side-step-squat	1st

III. Results

A. Step Platform Height with no Overhead Restriction

During the xEMU DVT series, which took place in the ARGOS 1/6th-g offloaded environment, the subjects performed a front-step-up onto a set of stacked exercise steps. The subjects repeated the task while increasing the number of steps stacked until they felt they had maximized their controlled and comfortable step height. The motion capture data from the two subjects with the smallest stature and VTD across the subject group were then used with the resized 1st percentile human-suit model. The 1st percentile human-suit modeling allowed for observing the worst-case step height needed, assuming that taller subjects could step as high. Since the subjects were limited by the increments based on the height of each exercise step added, the data provided a conservative estimate of the suited person's capability, which was deemed appropriate to analyze for requirement development.

During the DVT testing[4], the subjects achieved a front step height range of 17.1 inches to 30.1 inches (43.4 to 76.5 cm). These measurements were from the floor to the tip of the boot marker which is not the lowest point of the boot. Therefore, it is important to account for the thickness of the boot sole, estimated to be 2 inches (5 cm). Since the smallest subject was of 38th percentile stature and 33rd percentile VTD, the step height was parametrically scaled down for a hypothetical 1st percentile suited crewmember. The joint angles from the motion capture data were extracted and projected to the 1st percentile model. The 1st percentile human-suit model achieved a 12.5-inch step height, as shown in Figure 5. It is assumed that the crewmembers would have a stability aid available for balance when performing a step-up task, which could increase achievable step heights. The subjects may have also been limited in the amount of torso roll since the ARGOS offload gimbal has a roll limit.

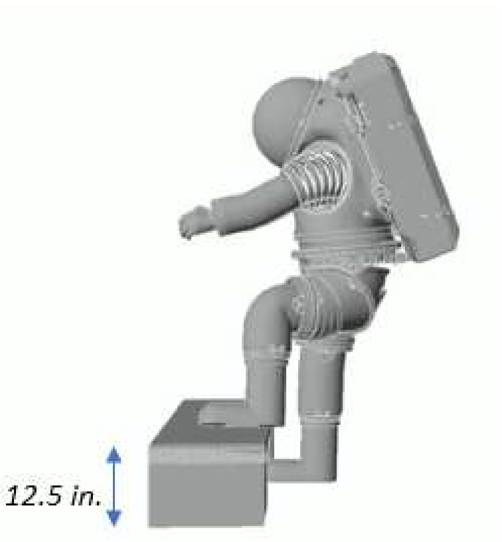

Figure 5. 1st Percentile resized xEMU Human-suit model Performing a Step Up. *Kinematic data captured from xEMU DVT series used to create a static step-up posture.*

B. Step Threshold with an Overhead Restriction

A hatch opening on the lunar surface needs to be properly sized to allow a 99th percentile suited crewmember to translate through while wearing a spacesuit. The bottom threshold needs to allow the shortest crew members to transfer through without needing to hop or jump over the threshold. A set of HITL tests was performed using a simulated hatch and the xEMU suit without offloading to understand the kinematics of a suited human ingressing/egressing through a hatch with a fixed dimension of 60-inch height and 40-inch width. Previous HITL tests and preliminary modeling showed that a side-step-squat technique would work best for translating through a hatch while clearing the overhead obstacle[3], with a step-forward technique not allowing taller subjects to clear the overhead restriction. It is expected that this may be dependent on waist and hip flexion in the suit while stepping across. The preliminary modeling of 1st percentile subjects showed that they can clear the 60-inch overhead restriction without an issue while side-stepping over a 12-inch threshold, as seen in Figure 6. However, the 99th percentile model showed uncertainty in the top clearance based on the assumed technique due to limited reference data, considering the modeled clearance analysis was done in static postures, potentially leading to overly conservative estimates. Thus, the focus of the suited testing was to understand whether a 99th percentile crewmember could translate through without excessive bending or stress on their body by updating the model with dynamic data using appropriate suit and hatch volumetric mockup hardware.

Using the motion capture data gathered throughout the tests, all four subject kinematics were extrapolated to a 99th percentile hypothetical subject in the model. The subjects transitioned through the hatch by lifting their left leg across the hatch in a side-step motion, then lowering their torso below the overhead restriction, and tilting outwards while pulling their right leg over the threshold, as shown in Figure 7. Although all subjects generally used a similar approach, minor changes in techniques were seen across the attempts, such as more splayed hips and knees with a deeper squat.

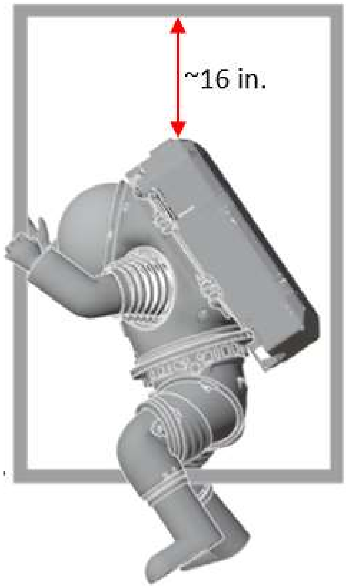

Figure 6. 1st Percentile resized xEMU Human-suit model Transitioning through a 60x40 inch hatch, with a 12-inch step threshold. *Kinematic data captured from xEMU DVT series used to create a dynamic side-squat-step through model.*

Table 2. Subjective feedback gathered from subjects performing hatch translation.

Threshold Height (in.)	Hatch Opening (in.)	Subject ID	Difficulty Rating (scale 1 -5, 1-easy 5-cannot do it
12	60	A	2
		B	2
		C	2
		D	1

The results from the HITL test applied to the 99th percentile model showed the modeled kinematics from three of the four subjects cleared a 60-inch overhead restriction while stepping over a 12-inch step. The modeled case that did not clear the hatch had a 2.2-inch overlap between the PLSS and overhead restriction. The subjective feedback and difficulty ratings gathered across all subjects, presented in Table 2, indicated that clearing the step threshold required minimum effort. It is also expected that lifting the leg across the threshold in lunar gravity will be easier than in 1-g. Additional test cases were performed by the subjects by adjusting the hatch mockup, using a 9-inch (0.23 meters) threshold, bringing the overhead restriction height to 69 inches (1.75 meters) from the floor, and a 6-inch (0.15 meters) high

Figure 7. 99th Percentile resized xEMU Human-suit model transitioning through a 60x40-inch Hatch, with a 12-inch step threshold. *Kinematic data captured from xEMU spacesuit hatch evaluation test series were used to create a dynamic human-suit model.*

threshold with 66-inch (1.68 meters) high overhead height from the floor. Although the subjective feedback from the test subjects showed these cases to be more challenging, subjects successfully completed the hatch translation. Positive clearance was observed with the 99th percentile model in the 9-inch threshold, 69-inch overhead height as well. When analyzing the 99th percentile model with a 6-inch threshold and a 66-inch overhead height, large negative clearance values were seen. Therefore, requirement recommendations include a 12-inch (0.3 m) maximum step threshold for a 60x40 inch (1.52x1.02 meters) hatch to reduce excessive effort by crew across the anthropometric range while transitioning through a hatch. Similarly, a minimum 69-inch overhead restriction height from the floor was recommended to reduce risk of overhead contact for tall crew members, with the assumption that astronauts will be trained to perform the successful technique.

C. Step Threshold Depth.

Although the hatch suited testing verified that large male subjects could clear a step threshold with a 6-inch depth, a modeling analysis was performed using a resized 1st percentile human-suit model to verify their capability in clearing the 6-inch depth step at a 12-inch height. Kinematic data from the xEMU DVT[5] side-step-squat task done by a small female were used in the resized xEMU model for a 1st percentile female in VTD and stature. Once the motion was reproduced in the model, CAD of the hatch was overlayed onto the model.

The result showed slight interference (0.6 inches) when bringing the trail leg through the hatch, as presented in Figure 8. However, considering the overhead restriction does not limit a 1st percentile crewmember's motion, there is likely flexibility for smaller subjects to adjust their technique and clear the threshold by allowing them to stay more upright. Therefore, it was deemed acceptable to recommend a 6-inch depth at the 12-inches threshold height. Due to the limited HITL data regarding the performance of a 1st percentile subject, no conclusions could be made regarding a step depth greater than 6 inches.

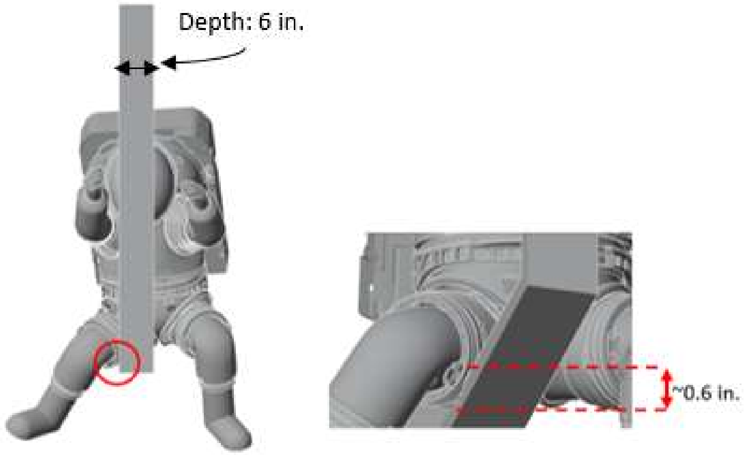

Figure 8. Side-step-squat motion kinematics extrapolated to 1st percentile model, with a 12-inch threshold hatch. *Slight interference (0.6 inches) was observed between the suit and the hatch within the model.*

D. Hatch Corner Radius

An additional analysis was performed using a beveled hatch to understand the maximum possible radius a hatch can have while providing sufficient space for the suited crew to transfer through without occlusion. 9.8 and 19.7 inch (25 and 50 cm) bevel radii were assessed using both the 1st percentile and 99th percentile models. An initial review of the 1st percentile model showed no issues, considering they would be closer to the front of the hatch to hold onto the stability aids while transiting through the hatch. The 99th percentile model showed possible interference with the hardware with a 9.8-inch (25 cm) inside corner radius hatch, depending on the technique used. Therefore, based on the modeled results, the 99th percentile suited crewmember may be very close to the edge of the hatch, although no restrictions were apparent, as shown in Figure 9.

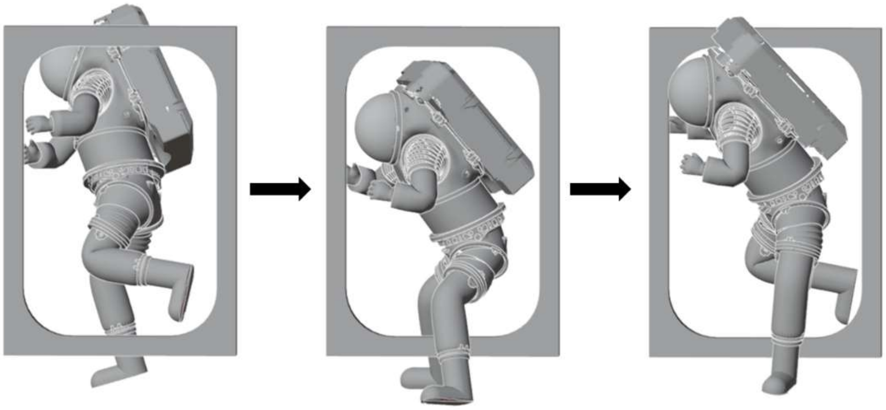

Figure 9. 99th Percentile xEMU model transitioning through a 60x40 in. hatch with a radius of 9.8 inches (25 cm).

E. Stability Aid Handle Considerations

Providing handles in an accessible location has been proven to be a key aspect of safely stepping onto or over a threshold. An analysis was performed using the motion capture kinematic data with the 1st percentile and 99th percentile extrapolated human-suit models to estimate a proper handle location range accessible across the anthropometric range on the hatch structure.

The kinematic data from the hatch evaluation test with large male subjects was used with the 99th percentile model. The result showed the highest hand position to be 56 inches from the floor to the center of the hand. Similarly, the kinematic data from the xEMU DVT side-squat-step task was used to assess the 1st percentile female model.

The result showed that a 1st percentile female is likely to hold the handle 40 inches above the ground to the center of the hand, as shown in Figure 10. Therefore, an initial range of 40 to 56 inches from the floor with a potential buffer was recommended as the appropriate stability aid placement for hatch transfer.

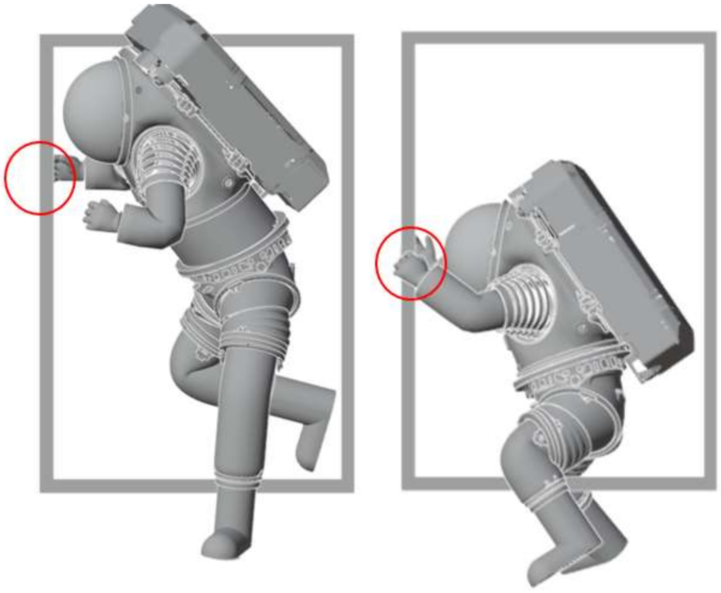

Figure 10. 1st Percentile (Right) and 99th Percentile (Left) Modeled Hand Placements.

IV. Discussion and Assumptions

The results from the HITL tests with the xEMU spacesuit and the human-suit modeling analyses were used as inputs to NASA's partial gravity EVA requirements regarding hatch and step design. Due to the limited number of HITL runs, data from various tests were used with a focus on tasks with similar techniques, such as the use of side-step-squat for hatch evaluation modeling. These requirements are levied across various programs under the Artemis campaign, including Human Landing System (HLS) and habitats, to ensure the safety of suited crewmembers when performing EVAs on the lunar surface without the need for excessive physical stress or hard postures. Differences in suit architecture, joint mobility, size, and boot thickness across other spacesuits can lead to differences in clearance ability across the discussed cases. The addition of tools and the complete Environmental Protection Garment (EPG) over the suit are not expected to change the results. This is considering other subjects have performed a similar motion in other xEMU test series with the EPG and toolbelt on. The EPG is designed to minimally impact hip mobility. The toolbelt has shown minimal interference with a leg lifting motion and does not have a significant impact on the CG of the suit-human system. However, the addition of tool holsters to legs may have negative impacts to the translation. Additionally, given that the tests performed did not use 1st percentile or 99th percentile subjects and the subjects were not specifically instructed to maximize their clearance for extrapolation purposes, there may be discrepancies in body adjustments and technique when performed by actual 1st and 99th percentile subjects.

Based on the analysis done for step platform height, kinematic data gathered using motion capture markers during xEMU DVT series in the ARGOS 1/6th-g offloaded environment were used with an extrapolated 1st percentile human-suit model. The analysis showed a maximum step height of 12 inches is acceptable for both front-step-up and side-step-up onto a step in a controlled motion, with the 1st percentile human-suit model showing a 16-inch clearance from the overhead restriction. Since the test setup used to assess the front-step-up did not involve any stability aids for the subjects, it is assumed that subjects will achieve a 12-inch step height safely, especially if stability aids are provided on the side of the hardware.

When creating hardware for step threshold height with an overhead restriction, a hatch width of 40 inches and step depth of 6 inches were assumed during testing. This test series used the xEMU spacesuit in a 1-g non-offloaded environment, and other gravitational environments may yield different techniques and perceived difficulties. Handholds were not provided, however subjects were able to hold onto the hardware to simulate a stability aid. It is also assumed that the surface height is the same on both sides of the hatch, considering differences in the surface elevation can introduce variance in technique and stability. The analyses done regarding hatch design indicated that a fixed hatch with a 60-inch height, 40-inch width, and up to a 6-inch depth is sufficient to allow for crew across the NASA required anthropometric range to transfer through on the lunar surface, with a 72-inch overhead clearance from the ground. The HITL testing highlighted the importance of crew training to utilize a side-squat-step technique similar to what was observed to ensure successful hatch ingress/egress on the lunar surface. Additional analysis concerning curved hatch corners was done using the modeled data. This assessment showed that having a hatch corner radius of 9.8 inches (25 cm) is acceptable across the anthropometric range and does not introduce additional restrictions.

All subjects used the stability aid to maintain balance during this task. Based on the test results, stability aids on both sides of the hatch opening were additionally included in the requirement and placed at least 40 to 56 inches from the ground. These values were gathered from evaluating the hand placements during testing, with the data extrapolated to 1st and 99th percentile subjects using the human-suit model.

V. Forward Work

Additional analysis and testing are beneficial to understanding how the subjects can perform step-up and hatch transfer while carrying tools or payloads. Specifically, HITL testing can be performed with more mature hardware mockups to provide greater confidence to the extrapolated values. It is expected that operational concepts need to be assessed when training for the ingress/egress of large hardware from the various rovers and landers within the Artemis campaign. Similarly, the performance of other partial gravity EVA tasks, such as pulling another suited crewmember into the vehicle cabin through a hatch in an incapacitated crew rescue (ICR) case, requires further testing to understand potential unique kinematic challenges. All the tests analyzed were performed with the xEMU suit with a 4.3 psi pressure. Performing the tasks in other spacesuits and at higher pressures may require further testing to ensure no excessive stress or technique challenges are introduced to the crew across the anthropometric range. It could be beneficial to gather metabolic rate data, along with a more detailed questionnaire, in future testing to better understand human performance and the physiological effort associated during the different types of hatch types and translation tasks.

VI. Conclusion

With the high cost of pressurized suit testing, human-suit modeling has shown to be useful for providing valuable data to programs across the Artemis campaign. Motion capture data from various HITL tests using the xEMU spacesuit were gathered and applied to a human-suit model created from xEMU components in a 3D computer graphics software. The application of kinematic data from motion capture onto the resized suit model allowed for analysis of step height and hatch dimension requirements across the complete anthropometric range, as required by NASA. The resized 1st percentile model reposed using the motion capture data showed that a step height of 12 inches is accessible to all crewmembers, especially when stability aids are provided. The combination of this data with a reposed 99th percentile human-suit model helped assure that taller crewmembers can clear a 12-inch threshold while transitioning through a hatch with an overhead restriction of 72 inches above the ground. Additional quick review analyses using the model helped reduce the need for further HITL testing while providing further insight into ideal stability aid placements for ingress/egress of crew members through a hatch on the lunar surface.

References

[1]McFarland, S., Campbell, D., and Rhodes, R., "NASA Advanced Space Suit Pressure Garment System Status and Development Priorities 2023." In: 52nd International Conference on Environmental Systems. 2023.

[2]Jarvis, S., Vu, L., Benson, E., and Rajulu, S., "Development of Human-Spacesuit Interaction Models." In: 48th International Conference on Environmental Systems. 2019.

[3]Hernandez, Y., Sabahi, S. P., Kim, H., Vu, L., Newby, N., (2024, August 25-29). “Defining Work Limit and Capabilities for Spacesuit Wearers in Lunar Exploration Tasks”. In: 22nd International Ergonomics Association. 2024.

[4]Rhodes, R., Flaspohler, C., and McFarland, S., "Testing Fit, Mobility, and Comfort of the Exploration Pressure Garment Subsystem (xPGS)." In: 52nd International Conference on Environmental Systems. 2023.

[5]Flaspohler, C., and Rhodes, R., "Exploration Extravehicular Mobility Unit Pressure Garment System (xPGS) Cycle Testing Overview and Results." In: 52nd International Conference on Environmental Systems. 2023.