Range of Motion (ROM) Analysis for Pressure Garments (EVA and LES) using 3D Photogrammetric Motion Capture

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Understanding work envelope (reach) and range of motion (ROM) is a critical component of pressure garment (EVA and LES) design. In comparison to methods used in the Apollo program involving the use of goniometers and 2D still photography, methods for evaluating suit ROM have significantly advanced in the past two decades with the utilization of 3D motion capture. These methods more accurately model the constraints that an EVA suit, for example, applies to nominal human ROM and reach. Current research methods for evaluating suit ROM utilize a Vicon camera system to track reflective markers placed on a subject performing a motion sequence, which are then identified as coordinatized points in a 3D space. The Aerospace Human Systems Laboratory (AHSL) at Texas A&M University has developed a new process for visualizing and analyzing ROM and reach volume envelopes utilizing a 3D photogrammetric scanning instrument. Specifically, a 10-camera scanning system is used to capture a 20-second motion sequence of a human subject at 10 images/second, resulting in 200 3D images. Coupled with supporting computer programs, any anthropometric point of interest can be landmarked on the human body or suit scan, coordinatized, automatically tracked across the motion sequence, and then plotted to analyze the subject's reach and ROM in unsuited, suited unpressurized, and suited pressurized configurations. Any decrements to performance for any size of subject in any suit size could theoretically be modelled by this method. The application of this strategy to a scanned human in an unpressurized and pressurized Russian Sokol launch and entry suit is also discussed.

Nomenclature

% Loss	=	percent loss (of range of motion)	*HRP*	=	Human Research Program
% Ret	=	percent retained (of range of motion)	*LES*	=	Launch and Entry Suit
3D	=	three-dimensional	*MCU*	=	Modular Camera Unit
AHSL	=	Aerospace Human Systems Laboratory	*mm*	=	millimeters
cm^3	=	centimeters cubed	*OBJ*	=	Wavefront 3D Object File
CSV	=	Comma-Separated Values File	*ROM*	=	range of motion
EVA	=	extravehicular activity	SOA	=	state-of-the-art

I. Introduction

WITH each generation of space suits that support NASA exploration missions, a crewmember's ability to operate spacecraft controls and maneuver in the extreme environments of space while wearing pressurized suits has become an increasingly critical factor. Multiple studies have shown that space suits that fail to accommodate adequate human fit and mobility have led to crew injuries and negatively affected the outcome of extravehicular activity (EVA) operations.[1-8] To ensure that each generation of EVA and "launch and entry suits" (LES) provide a required level of

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fit and performance, research projects continue to determine the best method for evaluating range of motion (ROM) or reach envelopes.

Recent advancements in body imaging and motion tracking are all intended to better analytically evaluate a pressure garment's fit while also ensuring optimum performance and injury reduction or elimination. The Aerospace Human Systems Laboratory (AHSL) at Texas A&M University is contributing to this engineering design research topic by developing new methods to model the ROM or reach envelopes of crewmembers which could then be correlated to performance in a particular suit design. Multiple "gaps" in space suit design and development, which have been identified by the NASA Human Research Program (HRP)[2], were used to inform this proof of concept study as well as interest from a commercial space suit company interested in integrating body scans with motion tracking at the AHSL. While the future focus of AHSL is to generate data that informs suit designers and engineers of critical suit design features that impact suit fit and mobility, this initial study focused on new proof of concept methods for computing ROM by utilizing the 3dMD full-body three-dimensional (3D) stereophotogrammetric motion capture body scanning technology. Twenty seconds of upper body human motion (e.g. arms) at 10 Hz was used to create 200 3D images. Supporting proprietary software, as well as customized software, was used to landmark and track points of interest across the motion sequence data set so that ROM and reach distance data could be generated and analyzed. This paper will discuss the current state-of-the-art (SOA) methodologies for evaluating space suit ROM, the 3dMD photogrammetric technology that the AHSL utilized, methodology developed by the AHSL for analyzing data from raw motion capture images to generate ROM data, preliminary "proof of concept" results for a subject wearing an unpressurized Russian Sokol LES suit, a discussion of the results, conclusions, and planned future work.

II. Background

One of the earliest published papers which documented the procedures for generating space suit ROM was produced by NASA during the development and testing of the Apollo and Skylab A7L and A7LB pressure suits in the late 1960s.[9] This early procedure, which was probably used for aircraft as well as Mercury and Gemini programs, involved taping paper overlays onto control panels in vehicles such as the command module and lunar excursion module, and then requiring suited subjects to draw their arc-of-reach on the paper overlays to determine if control panel switches were within reach of the crewmembers. However, in an era without the benefit of CAD models, this required physical prototype modules and control panels and continuous iteration until a defined ROM was achieved. A strobe and movie sequence study was also performed in which multi-exposure photos and movies captured the pressurized subject holding strobe lights and performing arm motions in the plane of a grid board behind the subject. Goniometers were also incorporated to perform real-time measurements of subjects holding the furthest extent of reach in various static postures. The multi-exposure photos were then printed, and the arcs created by the strobe light streaks were measured with protractors to determine the ROM of the subject in the pressurized suit.[9] Similar still photography methodologies were used to measure suit mobility as late as 1999 by Ross to evaluate the WEI and Mark III suits.[10] While useful for motion within the plane of the board, human joints do not naturally rotate perfectly within a 2D plane, so determining reach in a 2D plane is not a wholly accurate analysis of the reach constraints of the subject. 3D motion analysis was needed in order to accurately quantify human ROM in and out of a spacesuit.

The development of 3D motion capture has been a revolutionary technology. It has been applied to fashion design, animated movie production, video game design, and sports analysis industries. In these applications, 3D motion imaging can capture complex and realistic human motion and body shape and output analytical data that designers can utilize to determine the performance of their respective products. Abercromby et al.[11] conducted novel work with 3D motion capture by implementing Vicon camera systems to track the reflective markers placed on points of interest on an unsuited and suited subject in the Mark III suit. In this study, the Vicon camera system provided coordinatized point sets representing the change in location of the reflective markers. Delaunay triangulation was used as a MATLAB function to create a reach envelope based on the outer-bounded points recorded. A 2012 study conducted by Aitchison[12] compared the accuracy and reliability of the still photography (or 2D photogrammetry) method and 3D Vicon method and found that while statistically equivalent in accuracy, the two methods were difficult to compare on an equal basis due to the assumptions made by each method.

The instrumentation and methodology used to capture and analyze ROM data in previous studies is different than those used in studies done recently by Kobrick et al.,[13,14] where a four-camera OptiTrack motion capture system was utilized. The OptiTrack motion capture system utilizes infrared cameras recording at 100 Hz to track IR-reflective markers externally attached with tape or Velcro to points of interest on the subject. Upon capturing motion of the subject, the camera system records the position of these points as a data set of XYZ coordinates that can be exported and processed in supporting programs (e.g. MATLAB) to evaluate relevant ROM parameters. As reported by Kobrick, ongoing work is being done to increase the camera system to nine cameras to improve the retention of tracked markers and increase the capture space in which mobility is observable. Important results generated from tracking these markers include angular ROM and volumetric reach envelope data.

The Anthropometry and Biomechanics Facility (ABF) at NASA JSC is currently evaluating computational photogrammetry techniques to collect motion data and generate reach volume comparisons. A comparison of scan data between traditional laser scanners and a static 3dMD scanning system showed that the 3dMD system provided unique capabilities that warranted its use in human-suit interaction studies as a complimentary analysis tool.[15] However, this study was not holistic as the static 3dMD scanner configuration was not able to capture and analyze dynamic ranges of posture and motion. In order to overcome the disadvantages of either 2D images or 3D static poses, the AHSL utilizes a 3dMD motion capture system capable of scanning human subjects (unsuited, unpressurized suited, and pressurized suited) in motion.

III. Methodology

A. The 3dMD Motion Capture System: Hardware and Software

This study utilized the 3dMD motion capture stereo photogrammetric scanning system comprised of an array of cameras on surrounding towers or "islands". AHSL operates two tower/camera configurations: one for full body and one for focused hand imaging. A hand imaging study, which was completed and published in 2019, confirmed the accuracy of the system to 1mm.[16] The study reported here used the full body configuration. Each configuration uses a different composition of towers and cameras. For full body scans, the 3dMD motion capture system utilizes 6 mobile towers or islands with ten modular camera units (MCUs) that are focused around a defined capture space (the zebra board), as shown in Figure 1. Each MCU (Figure 2) contains three cameras; one color camera generates the texture images and two black and white cameras generate the surface information. Each MCU also contains a speckle projector which supports digital image correlations between in-plane and out-of-plane displacements. Each mobile tower contains two LED panels to control the lighting level during scans (Figure 3).

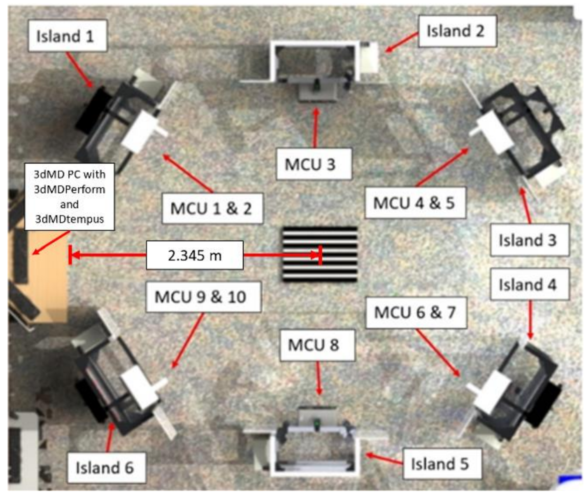

Figure 1: CAD of the 3dMD full body scanner configuration with 6 towers/islands and 10 MCUs.

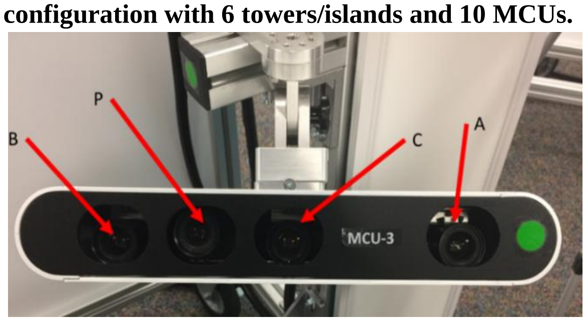

Figure 2: 3dMD motion capture MCU composed of two black and white cameras (A & B), one color camera (C), and a speckle pattern projector (P).

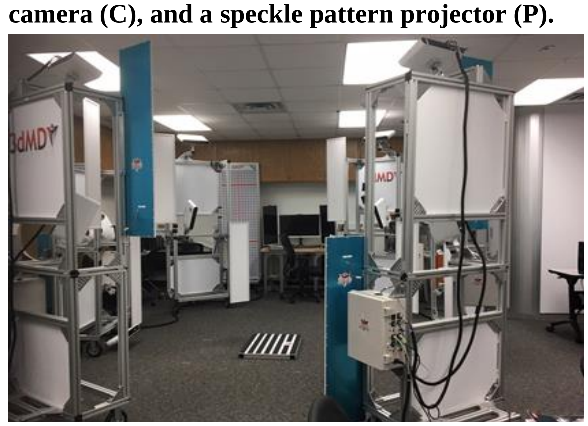

Figure 3: 3dMD full-body motion scanning towers with cameras and LED panels (blue)

The 3dMD motion capture system utilizes active stereophotogrammetry to create 3D models of the scanned subject. Stereophotogrammetry measures the 3D coordinates of an object by capturing an image from multiple camera positions. Some scanning systems determine geometry information solely based on existing surface detail, which is considered passive stereophotogrammetry. In the case of the 3dMD motion capture system, existing surface detail is supplemented with a projected speckle pattern on the subject. Utilizing the distortion of this supplemental pattern in the resulting camera images (active stereophotogrammetry) generates more discernable geometry data of the object.

The analytical software used in this study is summarized in Table 1. Proprietary algorithms developed by 3dMD (3dMDperform software) create a 3D mesh from the overlap of images from different camera views. The result is a 3D object model for every instance (or frame) of a motion sequence, which can be displayed as a wireframe mesh, a monochromatic surface, or a surface with full-color texture. After performing a scan and creating the 200-frame sequence of 3D surface meshes, the sequence was played back on

3dMDtempus software. 3dMDtempus allows the operator to view each 3D surface mesh frame by frame. 3dMDtempus also allows the operator to view the solid surface with or without overlaid texture as well as the respective surface mesh.

Table 1: Software used for Proof of Concept ROM Study

3dMDperform	3dMD Proprietary to generate 3D images from 10 MCUs (30 cameras) http://www.3dmd.com/
3dMDtempus	3dMD Proprietary software to view each individual frame
3dMDvultus	3dMD Proprietary for anthropometric calculations based on selected points and planes: distance, circumference, surface area, etc.
MATLAB	AHSL Customized to generate ROM from 200 3D images

A supporting software program, 3dMDvultus, allows users to perform any relevant anthropometric measurements and analyses on generated models, and also to landmark and track any points of interest relevant to ROM analysis. All required anthropometric measurements are available to 1 mm accuracy, including total volume, volume segments, and surface area. This anthropometric product has an inherent advantage over reflective target strategies as it enables the capture of the complete 3D shape of the human subject as it moves through specific motions and postures and this motion/surface shape can be correlated to the captured motions.

For the purposes of this technology study, two volunteer subjects were scanned. Subject #1 was a large male in the upper anthropometric Caucasian quartile and subject #2 was selected to fit a loaned Sokol suit. Subject #2 was a female in the second quartile, Caucasian.

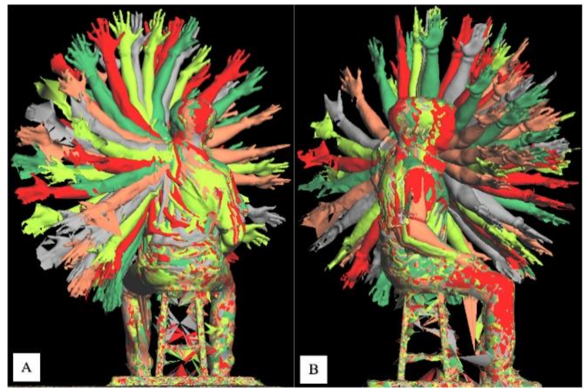

Figure 4: Compiled motion sequence frames of left arm motion in 3dMDvultus.

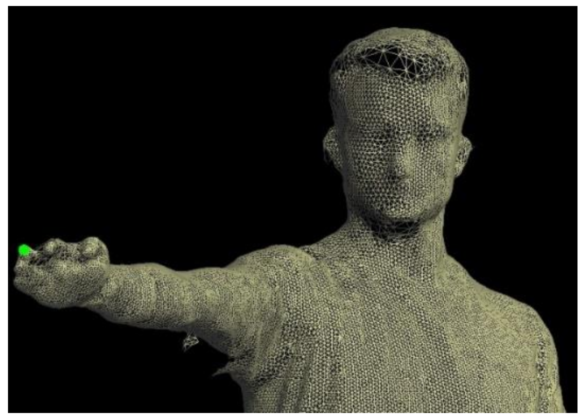

Figure 5: 3dMD Mesh pattern with manually introduced landmark on fingertip in 3dMDvultus.

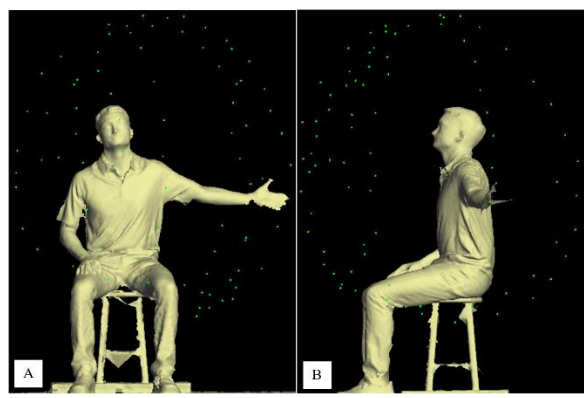

Figure 6: Left arm motion with manually selected fingertip landmarks registered to a single body image in 3dMDvultus A) Front view B) Left view.

B. Proof of Concept: Landmark Placement and Coordinization with Seated Unsuited Subject

Subject #1 was placed in a sitting position and instructed to move arms randomly in the following sequences: (1) left arm and then (2) right arm. For each of these sequences, a full 20 second scan generated 200 frames of motion. Upon exporting the raw OBJ file set from the 3dMD motion capture system (3dMDperform) to the 3dMDvultus computer, each OBJ is opened into the 3D environment (Figure 4). For each motion sequence, the operator isolated each frame in the set and placed a digital landmark on the farthest fingertip of the hand (usually the middle fingertip), as shown in Figure 5 as a green dot. In reality, this green landmark was placed within the significantly magnified mesh, so that the landmark could not be seen on the Figure by the human eye without artificial enlargement. The actual landmark is only a few pixels wide. Since some frames of the motion sequence may have noise or incomplete surfaces on or around the captured fingertip, the operator must be able to estimate location, but this is on the order of a few hundredths of a mm. For every landmark placed on the image, a set of XYZ coordinates are generated and a workspace table in the 3dMDvultus application is populated with these coordinate values. These points are coordinatized with respect to the same reference point (the subject), and all frames are aligned to this reference point so that the coordinate system is consistent across frames. Figure 6 shows the compiled landmarks with a single body reference frame for the motion.

Once all frames have an individual landmark representing the fingertip, the table containing the landmark coordinate data is exported as a CSV file into MATLAB. The MATLAB alphaShape function is used to create an enclosed volume using the outer-bound points of the inputted data file. This data is discussed later in the Results section.

C. Proof of Concept for Unpressurized Russian Sokol Suit

The AHSL acquired a Russian Sokol suit on loan from Mr. Art Dula, shown in Figure 7. Although these suits are generally custom made for each crew member, the history of this suit is currently unknown. Based on the size, it could be classified as "small" by NASA anthropometrics. A volunteer subject of appropriate height and arm length was used to evaluate the methodology previously developed for the unsuited crew member. Because the AHSL did not have the capability to pressurize test the Sokol suit, this evaluation was limited to testing only unsuited and suited-unpressurized configurations. At the time of this experiment, no formal motion path had been established to ensure that the distribution of the fingertip was even across the hemisphere-like shape of the subject's reach envelope. Instead, the subject was instructed that arms were to be kept straight during all motion, and to move in all possible directions at an even speed, covering the hemispherical envelope within 20 seconds.

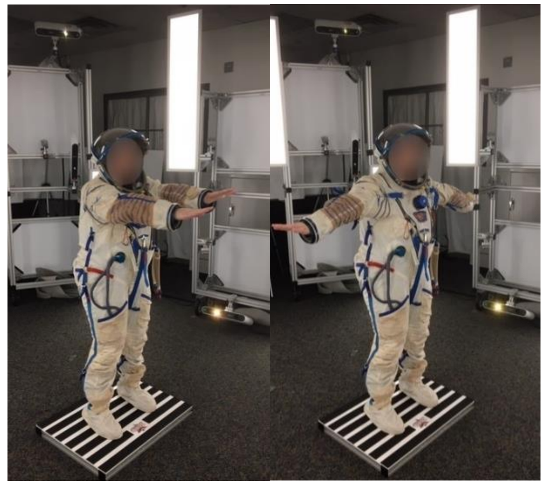

Figure 7: Subject in loaned Russian Sokol LES, compliments of Mr. Art Dula.

IV. Results

A. Seated-Unsuited Subject

Figure 8 shows the motion paths of the fingertips for left and right arm motion captured for a seated and unsuited subject. Each motion sequence was generated at 10 Hz for 20 seconds, producing 200 total 3D images. This data was saved as a set of 200 separate OBJ files, which were post-processed and analyzed in supporting software to generate reach volumes and ROM data. Although the fingertip was landmarked for this data set, the same file could be used to establish any landmark, including the palm.

After all files were processed, a reach envelope was generated as shown in Figures 9 – 11. The X, Y, and Z axes are shown in millimeters (mm). In addition to generating data for ROM using the fingertip, it is possible to measure any anthropometric feature of interest, including arm length, shoulder breadth, sitting height, circumference at any body point, etc.

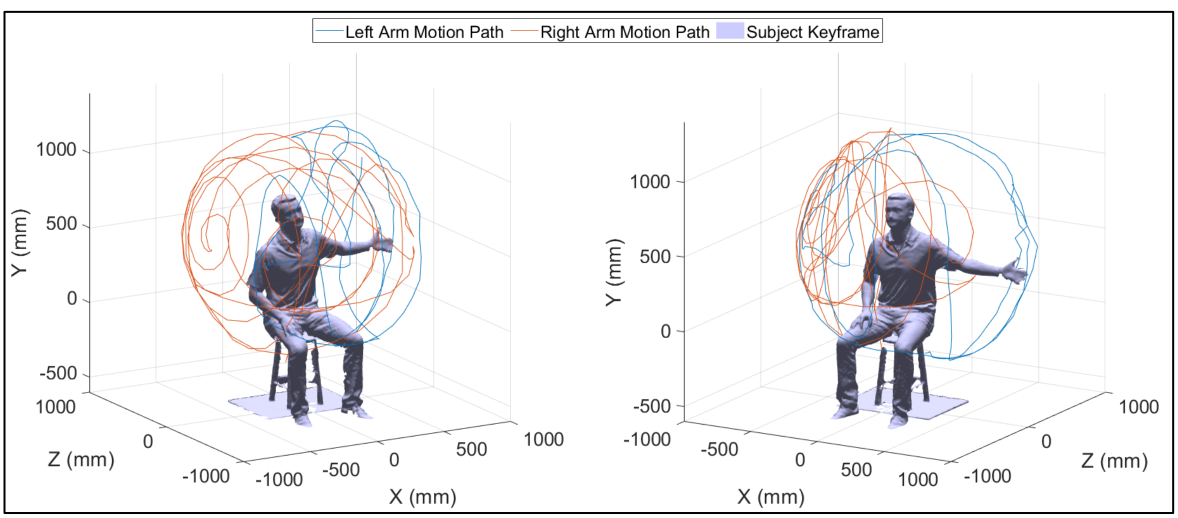

Figure 8: Motion paths of seated-unsuited subject for reach envelope generation.

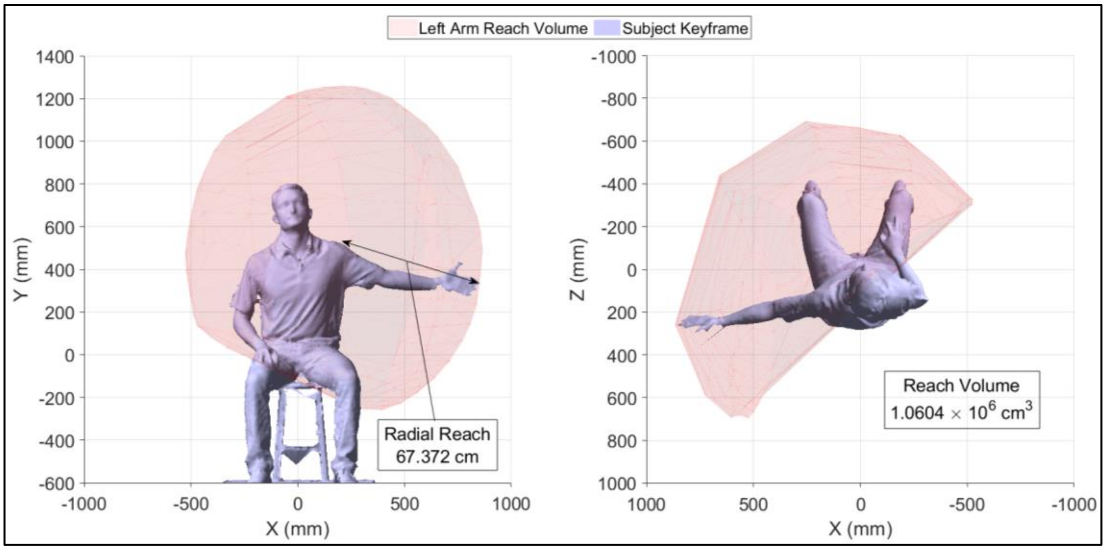

Figure 9: Left arm reach volume (front and top views) with radial and volumetric data.

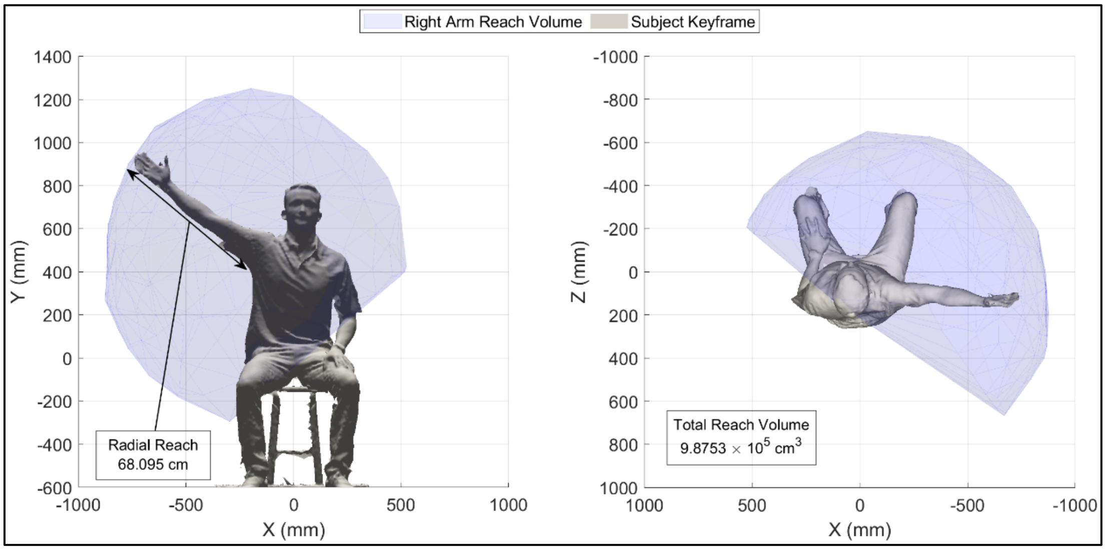

Figure 10: Right arm reach volume (front and top views) with radial and volumetric data.

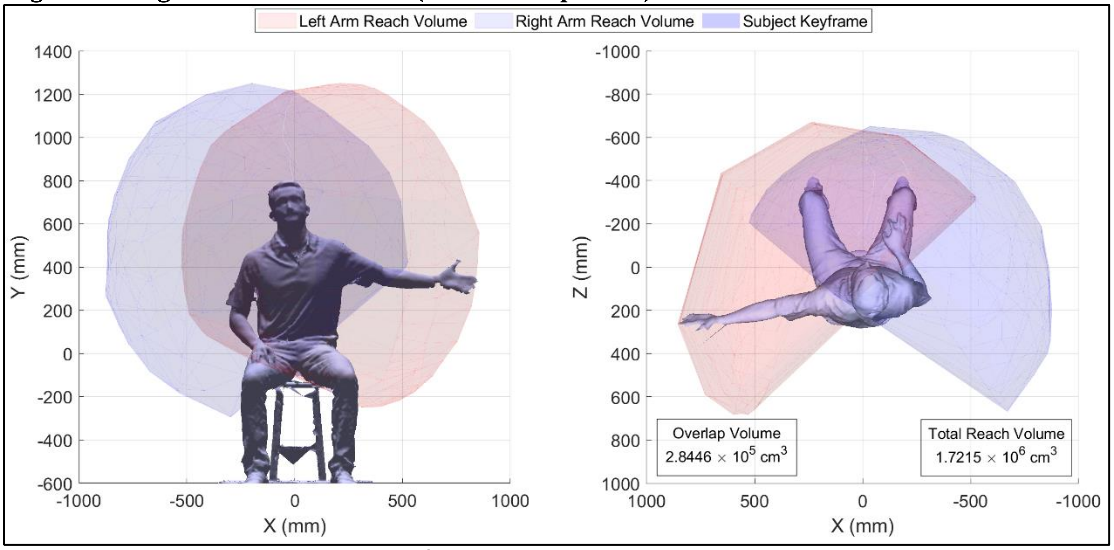

Figure 11: Combined reach volume (front and top views) with total reach and overlap volumetric data.

B. Comparison of ROM for Unsuited and Unpressurized Sokol-Suited Subject

Figures 12 – 15 illustrate the motion path of a Sokol-suited subject and the comparison of unsuited vs. suited-unpressurized configurations of the subject for right and left arm motion and simultaneous two-arm motion. In order to facilitate computation and to "smooth" angular transit paths, a custom-written code was developed in MATLAB to calculate volume.

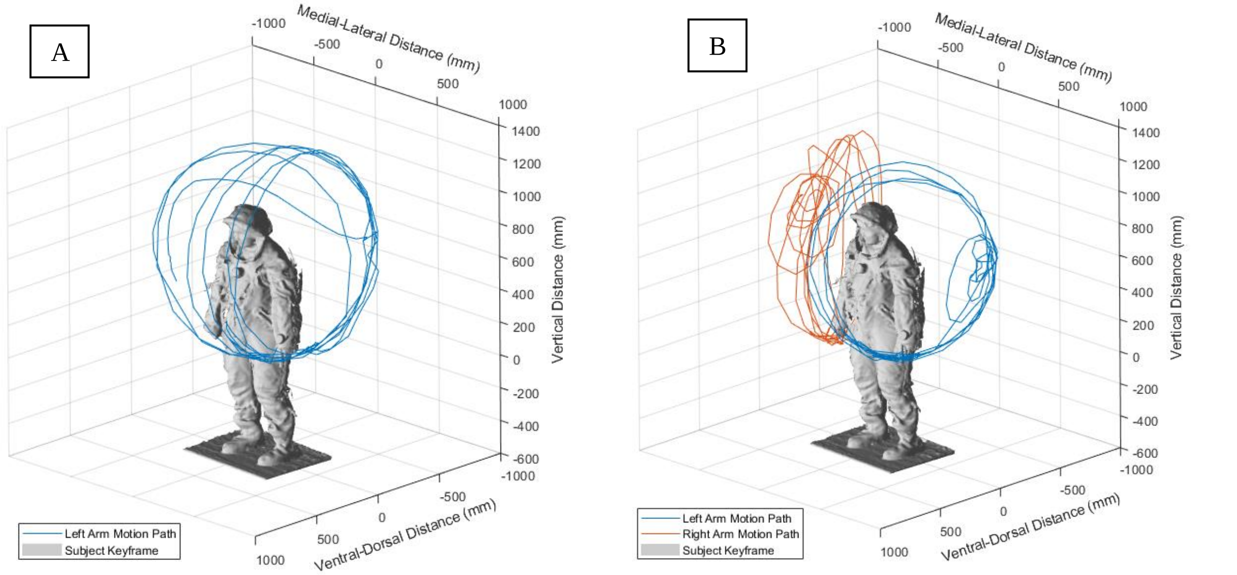

Figure 12: Motion paths followed for reach envelope generation A) Left arm motion and B) Two-arm motion.

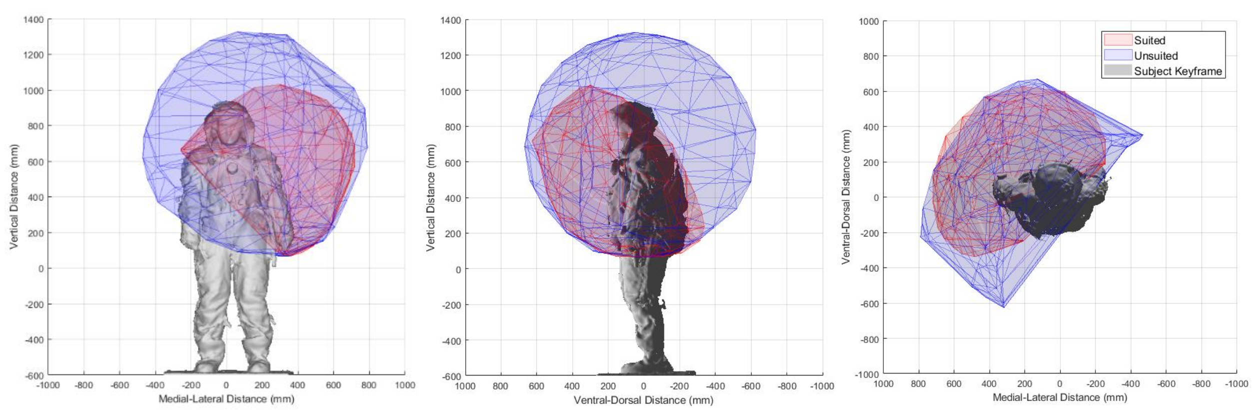

Figure 13: Unsuited vs. unpressurized suited reach volume comparison for left arm motion.

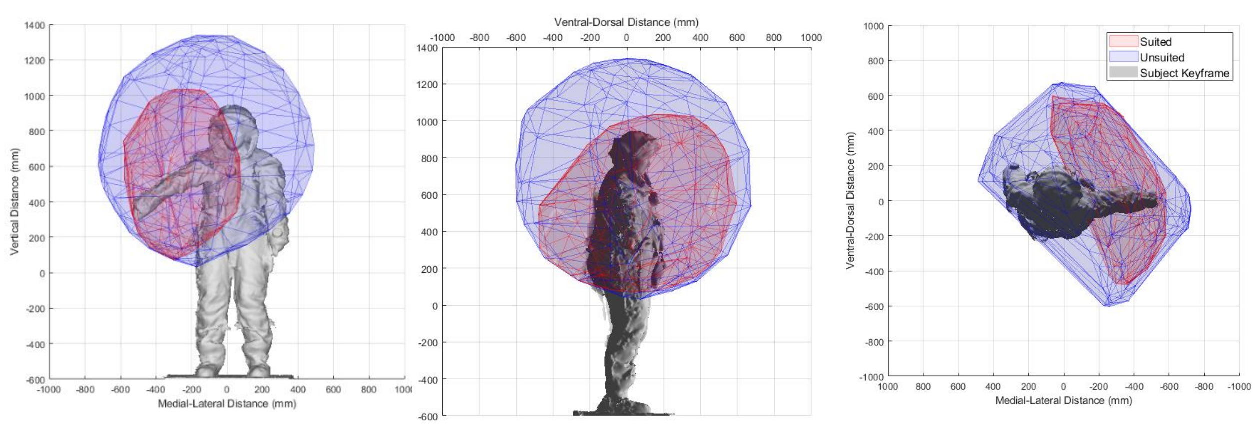

Figure 14: Unsuited vs. unpressurized suited reach volume comparison for right arm motion.

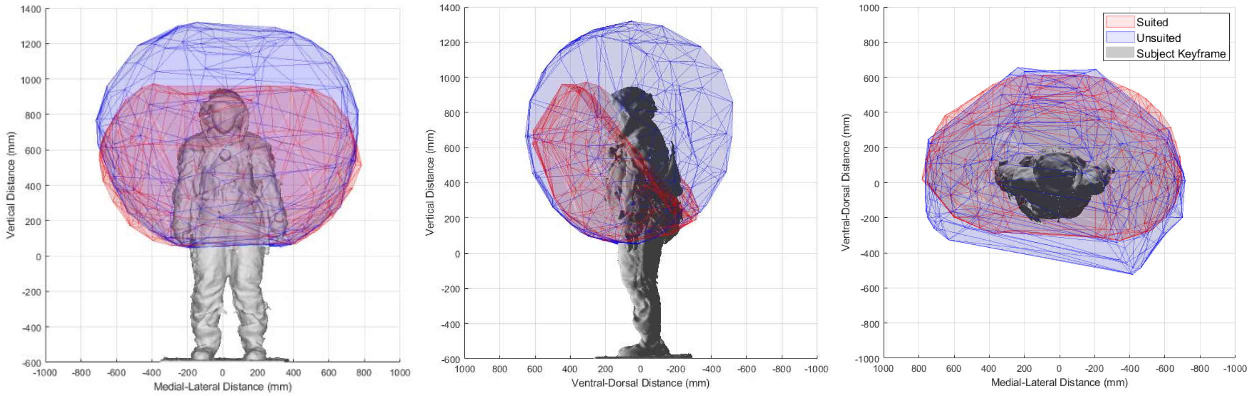

Figure 15: Unsuited vs. suited reach volume comparison for two-arm motion.

The volume calculated in the customized MATLAB script, given in meters cubed (m^3), is shown in Table 2. Also shown is the difference between unsuited and suited reach volumes, the percentage of relative reach volume retained (% Ret), and corresponding percentage reach volume loss (% Loss).

Table 2: ROM Volume for each arm motion in unsuited and unpressurized Sokol-suited configuration.

Arm Motion	Unsuited (m^3)	Suited (m^3)	Delta (m^3)	% Ret	% Loss
Left Arm	.724	.285	.438	39%	61%
Right Arm	.762	.247	.515	32%	68%
Both Arms	1.11	.471	.641	42%	58%

V. Discussion

The purpose of this proof of concept evaluation was to demonstrate the capability to generate accurate ROM and reach data using the 3dMD full body motion capture system and to be able to correlate that data with 3D body scans and other anthropometric data. A systematic scan (20 seconds/200 images) and a ROM generation procedure were developed for an unsuited-seated subject. The resulting procedures were then applied to a suited subject in an unpressurized Russian Sokol Suit for the purposes of comparing suited versus unsuited ROM as proof of concept. The procedures which were developed did demonstrate the capability to make these measurements. A unique capability of the 3dMD motion capture system is the ability to capture the complete highly accurate (to 1mm) surface detail of the scanned subject. The software-generated mesh provides planes and vertices which can be digitally marked, eliminating the need for externally attached reflectors. This allows not only landmark tracking on any surface, but also provides the anthropometric data of the subject at each instant of a motion sequence (e.g. point to point measurements, selected volume/circumference measurements, and surface area). An objective of the scan and data processing was also to determine if this information could be graphically illustrated and numerically calculated using procedures developed for this purpose using the 3dMD system and software. We were able to do this with the addition of a customized MATLAB code.

An advantage of 3dMD motion capture is that reach volumes generated by the recorded motion sequences give a complete picture of the 3D mobility of the subject, including external contact points between the suit and the subject (for example, arm contacting chest in cross reach). The data collected for the Sokol suit evaluation was particularly instructive. It should be noted that it was not possible to specifically select a subject for the Sokol suit based on anthropometric data from the subject and known dimensions and CAD models of the suit since this suit was custom made for an unknown person. Instead, a subject who appeared to be of the correct height and arm length was scanned without the suit and then with the unpressurized suit. It was assumed that the suit would result in degradation of the ROM, simply because the sizing was not optimized, and the data verified this assumption.

Every orthogonal view in Figures 12-15, as well as the data presented in Table 2 demonstrated that this particular Russian Sokol suit on this subject imposed a noticeable decrement to arm mobility and reach. In this case, what appeared to be a well-fitting suit, even unpressurized, created a ROM decrement of 61% in the left arm, 68% in the right arm, and 58% using both arms. Front and side views for left and right arm motion show part of this decrement is due to the subject's inability to effectively reach over the head and across the body with the suit donned. Top and side views show that another part of this decrement is due to limitations in reaching behind the back. Considering the small and constrained fit of the Sokol suit and the fact that the suit was not designed and manufactured to fit the subject for maximum mobility retention, these results are expected. This technique could be used in the future to evaluate and rank suit prototypes or help identify critical points in suit prototypes that limit subject mobility. Additionally, in a more controlled experimental setting, subjects would be suited in what would be considered “optimal fitting” suits and then evaluated for ROM. With suits that allow for adjustments on a single subject, motion scans could provide rapid assessments of the relationships between those adjustments and ROM. The 3D 3dMD digital images can also be exported as an OBJ file directly into spacecraft or EVA suit CAD designs. IR camera systems (such as Vicon, OptiTrack, etc.) do not possess these capabilities. Despite the advantages of the 3dMD system and the promising proof of concept data, several areas were identified for future optimization: (1) increase in statistical sample size for each scan session, (2) subject motion path optimization, and (3) automatic landmark tracking.

A. Increase in Scan Sample Size.

There were some inconsistencies in the reach envelopes that are worth noting. An example of this can be seen in the top view of the right arm, unsuited reach volume, shown in Figure 14. Generated reach volumes are expected to show smooth curves along the boundary of reach, as this indicates an absence of obvious obstructions or constraints that would hinder the subject’s motion along a joint. This smooth curvature was expected along the front right boundary of the blue reach volume, but a linearly shaped boundary exists. If this existed as part of the suited reach volume, one could deduce that the space suit played a part in this hindrance to motion, but since the reach volume is for the unsuited motion of the subject, the likely cause of this is due to a large gap in data points existing within the region containing the long linear segments. This means that the subject likely did not move the hand in that region of their full reach envelope and so Delaunay triangulation linked the two closest points on either side of that region with straight lines to fill the gaps in the data field. The root cause of this problem may lay in the instructions given by the operators to the subject on the motion path to follow. If more adequate and concise instructions were given as to where the subject should reach their arms during the captured motion sequences, then data point gaps like the ones that exist in Figure 14 would be minimized and potentially redundant data points would be eliminated. Conversely, it could be that there was not enough time in the 20 second data capture to cover the envelope.

A slightly different anomaly exists in the top view of two-arm motion, as seen in Figure 15, which involves the same root cause. According to the figure, suited radial reach from the shoulder joints is shown as being greater in front-right and front-left boundary regions of the reach envelope than unsuited, which would be unrealistic. One can also see that the unsuited boundaries in these regions are straight lines extending from the front of the boundaries to the respective left and right sides of the envelope boundaries. If this experiment were repeated so that the subject was better instructed to reach in every quadrant of their possible reach, then these boundaries might appear more curve-shaped, and would likely extend as far as, if not slightly further than, the curved suited reach volume boundary. These reported calculations were based on a single set of scans at 10 HZ, generating 200 3D images. A more statistically robust assessment could be generated by several methods: (1) capturing multiple 20 second scans of full motion, generating 200 3D images in each scan session or (2) upgrading the MCUs to higher data rates (e.g. more 3D images per second). Another useful strategy would be to break motion sequences into multiple segmented sequences so that subjects can move more slowly to ensure that every area of reach is captured during scanning.

B. Motion Path Optimization

The data shown in Table 2 indicates certain inconsistent characteristics of each motion sequence. While the unsuited reach volume was larger in right arm motion than in left arm motion, the unpressurized suited reach volume was larger in left arm motion than in right arm motion by roughly the same margin. This led to the 7% difference in % Ret between left and right arm motion. Possible causes could be inconsistent motion paths followed for each arm, which could have prevented data points from being selected that would have provided a more holistic representation of the reach volumes calculated. The two-arm motion volume data is interesting, as this motion retained the most amount of mobility (42% Ret) in unpressurized suited configuration. This could be due to the assumption made that the subject would have overlapping reach between the two arms in motion, so Delaunay triangulation was performed to create a reach volume connecting all data points for both arms, as opposed to two separate reach volumes for each arm in the motion sequence. Therefore, Delaunay triangulation created regions, such as those behind the back, which are interpolated between the two arms in motion. Based on the full body motion capture images, it was determined that the subject, while unsuited, moved both arms cross body. However, when suited the subject kept each arm in its own hemisphere so that there was no cross-reach motion.

In order to provide consistent ROM data from subject to subject and within experimental data sets, a systematic motion path will be implemented in the future. This will minimize large gaps in the resulting landmark data and subsequently prevent the Delaunay triangulation algorithm from assuming long linearized segments of the reach envelope that is known to be inaccurate. Potential motion paths to be implemented for future experiments may involve those used by Abercromby[11] and Kobrick[14], shown in Figure 16. The literature does not suggest that any one motion path is objectively the best motion path. Rather, the priority of the motion path is that the resulting field of data points of the landmark tracked across the motion path be dense enough to provide a clear "arc of reach" with minimal gaps that would, under Delaunay triangulation, generate long linear segments in the arc. Additionally, for longer and slower motions being captured and analyzed, multiple twenty second motion sequences can be captured in succession and post-processed together to ensure accurate reach volume generation.

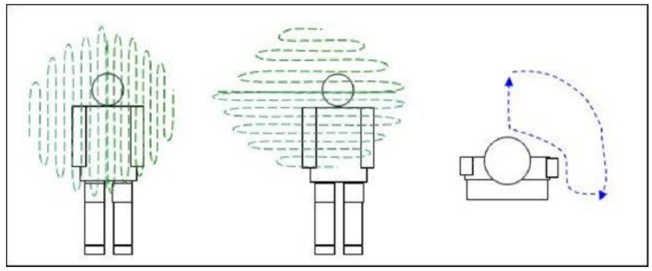

Figure 16: Right hand motions during reach envelope data collection protocol (Abercromby[11]).

C. Automatic Landmark Tracking

Another opportunity for improvement is automating digital landmark tracking. In this proof of concept study, landmarks were manually selected on an expanded mesh image in the 3dMDvultus software. A landmark was placed by the operator on each of the 200 frames in a motion sequence. Approximately two hours was required from the point that the raw object data set was processed in 3dMDperform to the point that a reach volume was generated in MATLAB. One underlying reason for manually placing digital landmarks was to ensure the accuracy and integrity of the computed volumes as compared to unproven or uncertified algorithms applied to 3dMD data. Although this time investment is relatively modest, since no additional time was required to edit raw data, the AHSL is attempting to shorten and automate this process by evaluating various "automatic registration and tracking" algorithms. One concept of automatic registration is to place landmarks on a single, highly-detailed "template scan" and utilize affine transformation principles to translate, rotate, scale, and shear vertices in the 3D mesh of the template so that it accurately matches a "target" scan. This registration would then be applied to each of the 200 frames in a motion sequence, resulting in 200 transformed templates; and the landmarks of these transformed templates would be tracked across the motion sequence to generate an accurate motion path of the landmark. This methodology has been demonstrated by Marin[17] with the Functional Automatic Registration Method (FARM) for 3D human models. Figure 17 shows an example from this study of how a template mesh is transformed to raw scan data in various poses and how the landmarks of the template register to the target meshes to indicate the location of head, hands, feet, and other body points. According to Marin, this methodology is robust, even when using scan data with topological gluing, missing parts, or surface noise. In the case of spacesuit mobility evaluation, the motion path of the landmarks from the transformed templates would be analyzed for various ROM data, including reach envelopes.

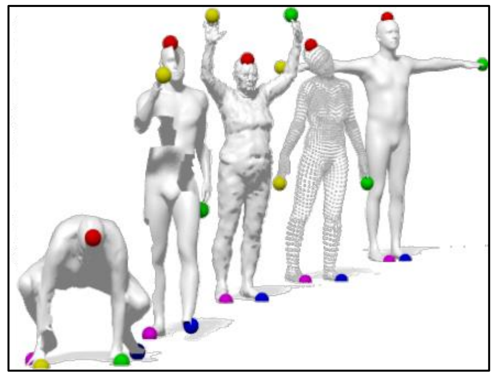

Figure 17: Landmark stability under mesh perturbation (Marin[16]).

VI. Conclusion

The focus of this proof of concept study was to demonstrate technology and corresponding methodology for performing space suit ROM and mobility evaluations using 3dMD 3D active stereophotogrammetric scanning. Compared to IR-camera systems that track reflective markers attached to points of interest on a subject, 3D photogrammetry systems create a complete 3D image of the subject, any point of which can be tracked over a motion sequence. This capability was demonstrated with the 3dMD by scanning the left, right, and two-arm motion of an unsuited subject and then a subject in an unpressurized Russian Sokol suit. The fingertip of the subject was digitally landmarked and tracked across a twenty second motion sequence captured at 10 Hz, and the resulting coordinatized data set was plotted as a 3D reach envelope. The volume of this envelope and additional anthropometric data were calculated for ROM analysis and illustrated in relationship to the subject. For the "proof of concept" test with a Russian Sokol suit, reach volume data was calculated and indicated a clear degradation in mobility of the subject.

A 20 second/200 image sequence results in some angular tracks because of the velocity of movement of the subject and missing some of the volume sectors. Smoothing of these angular tracks can be accomplished by (1) the addition of MCUs, (2) by increasing the camera image rate (3) by dividing the ROM into quadrants, each measured within the 20 second scan or (4) optimizing the motion path. The AHSL will be pursuing all of these options as it begins to work with commercial space suit developers. Because the scans are anchored to a keyframe (the subject), more than one scan can be combined for a total ROM and a predetermined path will provide more consistent and complete data.

As stated in the 2019 NASA HRP report, it is necessary that standard methods be developed for rigorous assessment of suit fit in order to verify xEMU requirements for future Artemis mission needs. Initial work done by Abercromby et al.[18] has proposed a standard methodology to characterize and compare existing and future space suits under realistic spaceflight conditions. Utilization of 3D photogrammetric motion capture with a full body digital human mesh has the potential to help fill multiple EVA gaps related to fit and mobility that have been identified by the NASA Human Research Program (HRP).[2,15]

Acknowledgments

This project is funded and made possible by the Texas A&M Chancellor's Research Initiative (CRI) and the Aerospace Human Systems Laboratory, directed by Professor Bonnie J. Dunbar, Ph.D. Special gratitude is also given to Mr. Arthur Dula for loaning his Sokol suit to AHSL and to 3dMD for their assistance with this project.

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