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Range of Motion Evaluation of a Final Frontier Design IVA Spacesuit using Motion Capture

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Embry-Riddle Aeronautical University's Spacesuit Utilization of Innovative Technology Laboratory (S.U.I.T. Lab) is focused on improving human performance in spaceflight by concentrating on spacesuit research for intravehicular activities (IVA) and extravehicular activities (EVA). The design and execution of range of motion (ROM) protocols in an experimental setting will provide insight on the functions and restrictions of spacesuits, aiding in current and future designs or modification. The S.U.I.T. Lab worked with Final Frontier Design (FFD) to provide a quantitative analysis protocol for seated arm mobility of their NASA Flight Opportunities Program (FOP) IVA spacesuit. The lab used reflective tracking markers on three test subjects and recorded a set of arm ROMs using OptiTrack's infrared motion capture system including: shoulder abduction/adduction; vertical and horizontal shoulder flexion/extension; and vertical and horizontal full-arm carveouts. All motions were recorded in three spacesuit conditions including: unsuited; suited unpressurized; and suited pressurized (2.5 psid). Motion capture data was edited and filtered for mobility analysis calculations. Programs were developed in MATLAB to analyze and plot angular metrics as well as three-dimensional reach envelopes. These programs allow the spacesuit manufacturer to visualize the mobility of their spacesuit design and associate qualitative mobility characteristics with quantitative results in the form of angular and volumetric data. The percentages of mobility retained between all spacesuit conditions reveal a quantifiable reduction in mobility going from unsuited to suited unpressurized to suited pressurized. Based off the performance of this investigation, FFD gathered preliminary data regarding the mobility of their NASA FOP spacesuit. Improvements to the equipment and protocol used by the lab for motion capture and analysis have been implemented since this study. Expanding from four to nine motion capture cameras, the lab has been able to capture spacesuit mobility data with far greater accuracy and completeness. Updated prescribed motion protocols instruct subjects to maintain straight arms reaching as far as comfortable and across their body in some cases, which is done to characterize shoulder mobility and is not reflective of the spacesuit's maximum mobility.

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Nomenclature

° = degree
% Ret = percent retained (of range of motion)
3D = three-dimensional
AA = abduction adduction
AAS = Applied Aviation Sciences [Department]
BPM = beats per minute
CSSS = Constellation Space Suit System
DCC = David Clark Company
EM-ACES = Enhanced Mobility Advanced Crew Escape Suit
EMU = Extravehicular Mobility Unit
ERAU = Embry-Riddle Aeronautical University
EVA = extravehicular activity
FFD = Final Frontier Design
FOP = Flight Opportunities Program
HFE = horizontal flexion extension
IMU = inertial measurement unit
IRB = Institutional Review Board
IVA = intravehicular activity
JSC = Johnson Space Center
m^3 = meters cubed
psid = pounds per square inch differential
Rep = repetition
ROM = range of motion
S.U.I.T. Lab = Spacesuit Utilization of Innovative Technology Laboratory
VFE = vertical flexion extension

I. Introduction

RESEARCH at Embry-Riddle Aeronautical University's (ERAU) Spacesuit Utilization of Innovative Technology Laboratory (S.U.I.T. Lab) is focused on improving human performance in spaceflight by concentrating on spacesuit investigations for intravehicular activities (IVA) and extravehicular activities (EVA). The design and execution of range of motion (ROM) protocols in an experimental setting provides insight on the functions and restrictions of spacesuits, aiding in current and future designs or modification. The S.U.I.T. Lab worked with Final Frontier Design (FFD) in November 2017 to provide a quantitative analysis protocol for seated arm mobility of their Stratos National Aeronautics and Space Administration (NASA) Flight Opportunities Program (FOP) IVA spacesuit (SN #008, as seen in Figure 1). This research aligns with the S.U.I.T. Lab's primary goals of providing experiential learning for students and feedback to industry.[1] This paper contains: a short recap of the previous S.U.I.T. Lab's ROM motion capture work of the FFD FOP collaboration;[2] test methodology for data collection; data processing with custom MATLAB programs to find angular metrics, reach envelopes, and percent of mobility retained; results from the FFD testing; discussion of the data; ongoing work; future work; and conclusions.

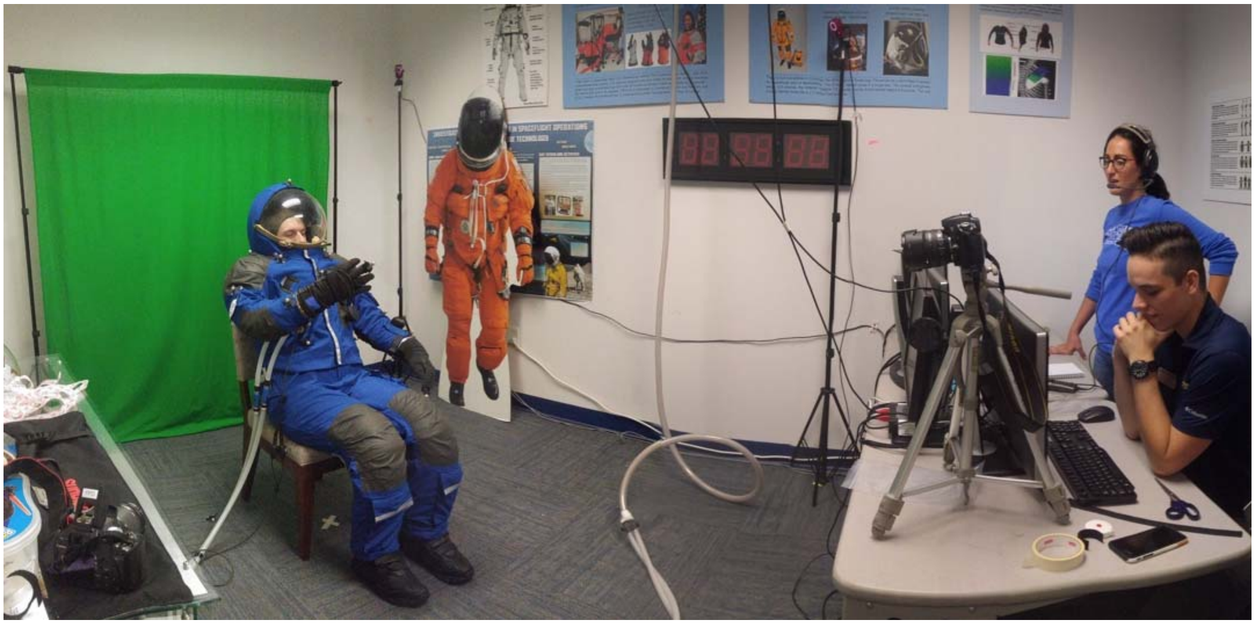

Figure 1. The original S.U.I.T. Lab location as seen in November 2017 for the FFD FOP testing. Four cameras are set up on tripods around the test subject with Peyton Schwartz as test director on a communications loop, Chase Covello as the motion capture recording technician, Ryan Kobrick recording video and taking photos, and Ted Southern as the primary spacesuit technician and safety officer.

II. Background

A. Historical Context

Motion capture has many powerful applications across a broad range of disciplines ranging from film production to injury rehabilitation. Converting three-dimensional (3D) body movement into analytical data ensures that we are recording the full scope of human or system motion. The spaceflight industry has several areas that can benefit from motion capture to address "EVA Gaps" in knowledge,[3,4] specifically for spacesuit design. For example, using standard ROM video capture techniques for spacesuits, we know how high a shoulder can lift but we are not seeing the sideways deflection that reduces the maximum lateral overhead reach. Knowledge of the 3D range of motion could directly impact how spacesuit designers fashion internal restraint strapping, auxiliary gear locations on the spacesuit, seating positioning or adjustability, or where controls are placed in spacecraft cabins.

Unrestricted shoulder mobility is an important and impossible goal of spacesuit design. The human shoulder joint allows hand placement over a wide area by acting as a crane for the hand with 11 individual degrees of freedom. Enabling an easy, wide range of motion for the shoulder is a challenge with any pressure garment or bulky ensemble. While scapular mobility is critical for donning and doffing, it is not specifically addressed in most spacesuit designs. Arm-related shoulder mobility is broken up into arm adduction-abduction, flexion-extension, and circumduction.

EVA spacesuits often rely on shoulder bearings or scye bearings to allow arm circumduction; this motion in a traditional pressure garment is virtually impossible without a scye bearing. The bearing also enables arm flexion-extension and arm adduction-abduction with the same softgoods joint, by turning the joint about the shoulder axis. Arm adduction-abduction can be accomplished without a shoulder bearing, through a softgoods convoluted system; the convolute angle can be turned and optimized in the initial design for specific missions, for example skydiving versus a capsule.[5] Today's modern EVA suits all have shoulder scye bearings, including the Extravehicular Mobility Unit (EMU), Orlan, and Z-Suit series. Scye bearings enable an easy translation in microgravity when the body is in line with the restraint hand-holds, and enables significant shoulder mobility during operations. An exception to EVA spacesuit scye bearings is the Apollo A7L series, which used a cable restraint system to allow for arm flexion-extension as well as adduction-abduction.

Figure 2. The CSSS derived EM-ACES suit included shoulder bearings.[6]

However, IVA spacesuits generally do not have scye bearings because of their bulk, cost, and especially discomfort and potential for injury in the seat of a vehicle. During high +Gx forces (acceleration from front to back) in flight or landing, the astronaut's shoulders are pushed against the hard bearings rather than the seat, causing discomfort and potentially skeletal injury. This was found during development of the Constellation spacesuit between 2007 and 2010 (see IVA Enhanced Mobility Advanced Crew Escape Suit (EM-ACES) in Figure 2[6]) when David Clark Company (DCC) conducted a trade study of shoulder bearings versus soft joints.[7] "Testing on cadavers had convinced NASA that the first configuration of the Constellation Space Suit System (CSSS) suit could not have shoulder bearings or mid-entry closures".[6] Additionally, Tufts et al.[7] presented ROM requirements including soft shoulder joint mobility and ROM for the scye bearing. DCC then chose a cable assisted omnidirectional soft shoulder joint for the Orion IVA suit, not a scye bearing[8]. Finally, DCC presented a Link-Net all soft shoulder joint combined with an upper arm bearing, but the bearings were not chosen.[9]

This was also concluded by the Russians in early IVA suit development, specifically of their Model SI-5 suit from 1957: "The bearings caused discomfort to the wearer in the donning/doffing process, while wearing it without positive pressure in the seat equipped with the restraint system, and during parachute descent".[10] Because shoulder bearings cause discomfort and lead to possible injury to astronauts, in general vehicle systems and controls have been designed around the limited mobility of IVA spacesuits, with few, and non-critical, controls above the head, and most interfaces below the neck. This was true for early vehicles, and remains so for modern commercial crew and Orion spacecraft designs (see Figure 3).

Figure 3. Spacecraft interior designs from left to right: SpaceX Dragon;[11] Orion;[12] and Soyuz.[13]

Abercromby et al.[14] investigated reach envelope of the Mark III EVA suit, a study which guided the marker placement for this project and influenced the placement of the hand marker in future tests in the S.U.I.T. Lab. The 2006 study concluded that data would need to be collected for different anthropometry, particularly arm length of subjects. A shortcoming addressed in their work was that they were not able to identify how the spacesuit contributes to the reduction of reach envelope. This occurred because motion capture was not used to evaluate joint ranges of motion in their study, a gap that is addressed in this research. Additionally, the S.U.I.T. Lab has long term plans to develop an anthropometry-based database for each subject tested.

Prior work by Dava Newman[15] was directed towards the effort of developing a computational model for characterizing and visualizing work envelope in an EMU spacesuit using experimentally recorded torque data, and anthropometric standards. This work focused heavily on the importance of modeling a comfortable suited work envelope to aid in EVA task planning and assessment of worksites. Current work by the S.U.I.T. Lab aims to provide similar work envelope visualization and analysis methods to assist FFD in characterizing their IVA spacesuit mobility and worksites where they would be integrated.

B. S.U.I.T. Lab ROM Testing with FFD

The S.U.I.T. Lab has been expanding ROM studies both in the lab on campus and at analogue space exploration missions around the world, all of which require similar protocol updates. This paper continues the methodology developed last year for IVA ROM[2] with a focus on protocol improvement and significant effort on data analysis to be able to create unique deliverables for potential collaborators like FFD. In order to meet these objectives, the lab used reflective tracking markers on three recruited unexperienced participants (ERAU Institutional Review Board (IRB) approved) of similar physical size (height, weight, girth, and foot size), and recorded a set of arm ROM using four OptiTrack's infrared motion capture system (Flex 3 cameras, 100 frames per second, 10 millisecond latency).[16] Tests were conducted in three spacesuit conditions including: unsuited wearing a black OptiTrack motion capture suit (Velcro surface); suited unpressurized wearing the FFD FOP suit; and suited pressurized at 2.5 psid wearing the FFD FOP suit. ROM activities included: Shoulder Abduction Adduction (AA); vertical and horizontal shoulder flexion/extension (VFE and HFE); and vertical and horizontal shoulder full-arm carveouts. However, due to the limitations of the S.U.I.T. Lab's facilities at the time and the goals of the study, data from the recordings were not analyzed. The movements that were not analyzed included: Elbow V1, Elbow V2, Right Arm Full Scope, and Left Arm Full Scope. All motions are briefly described in Table 1 and shown in Figure 4.

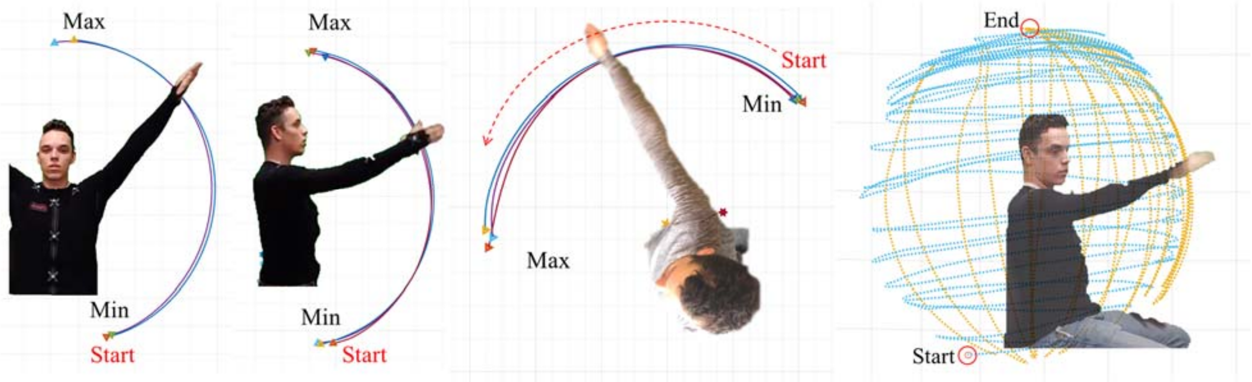

Figure 4. reach envelope range of motion activities from left to right: AA; VFE; HFE; and vertical (orange) and horizontal (blue) carveouts of the right arm. The starting positions for recordings are indicated.

Table 1. Range of motion activities and descriptions.

MOTION	DESCRIPTION
Shoulder AA (Abduction and Adduction)	Used to measure the difference in shoulder mobility when the subject would abduct and adduct their arms in both suited and unsuited configurations
Shoulder VFE (Vertical Flexion and Extension)	Used to measure the subject's ROM when they flex and extend their arms vertically
Shoulder HFE (Horizontal Flexion and Extension)	Used to measure the ROM when the subject flexed and extended their arms in and out horizontally
Right Arm: Vertical Carveout	Used to measure the ROM of the subject's right arm as they swept their arm vertically while they shifted it forward from back to front which created a shell of maximum reach
Left Arm: Vertical Carveout	Used to measure the ROM of the subject's left arm as they swept their arm vertically while they shifted it forward from back to front, creating a shell of maximum reach
Right Arm: Horizontal Carveout	Used to measure the variation of the "Vertical Carveouts" captured by the horizontal movement of the subject's right arm as they shifted upwards, creating a shell of maximum reach
Left Arm: Horizontal Carveout	Used to measure the variation of the "Vertical Carveouts" captured by the horizontal movement of the subject's left arm as they shifted upwards, creating a shell of maximum reach
Elbow V1 (Flexion and Extension)	Used to measure the ROM around the subject's elbows
Elbow V2 (Flexion and Extension – external rotation)	Used to measure the ROM of the subject's elbows when they were rotated away from the body
Right Arm: Full Scope	Used to measure a combination of several shoulder movements and elbow movements, when the subject performed a wide scope of ROM with their right arm
Left Arm: Full Scope	Used to measure a combination of several shoulder movements and elbow movements, the subject performed a wide scope of ROM with their left arm

Motions from subject 002 and 003 were cleaned and analyzed for use in the study, but subject 001 raw data was not useable. Participants were instructed, and reminded, that they should move through a range in each activity to a comfortable minimum and maximum without straining their shoulders or bending their elbows, which is done to characterize shoulder mobility and is not reflective of the spacesuit's maximum mobility. Three repetitions of key shoulder movements were completed and full-arm carveouts were instructed to be slow and steady for as much coverage as possible. Data was recorded using motion capture, photography, and video capture.

Motion capture data was edited and filtered for mobility analysis calculations. MATLAB code was developed to analyze and plot the 3D data while yielding metrics for percent of mobility retained between all spacesuit conditions for all activities. This analysis allows the spacesuit manufacturer to visualize the mobility of their spacesuit design and associate qualitative characteristics with quantitative results in the form of angular and volumetric data.

III. Methodology

A. Overview

MATLAB was chosen as an analysis tool for this ROM research due to its proficiency with matrices and plot creation. MATLAB is also one of the programming tools introduced to ERAU students in technical degree programs. Before advancing on the MATLAB code to analyze the 3D motion capture data, it was important to ensure all files were free of tracking gaps on critical markers in OptiTrack's Motive software. As this analysis is focused on arm mobility, the critical markers included those on the wrists, shoulders, and chest. Other markers, such as those on the elbows and fingertips, were deemed too unreliable to provide accurate and consistent tracking data. For this reason, this arm mobility analysis focuses heavily on the range of motion for the shoulders. Figure 5 shows the layout of all markers during this series of testing. The RWristOut, LWristOut, RShoulder, LShoulder, RChest, and LChest markers highlighted were fully edited and cleared of tracking gaps on all recordings for subjects 002 and 003. Tracking data from subject 001 was omitted from the analysis due to

Figure 5. motion capture marker layout of a suited pressurized subject.

a myriad of tracking issues and gaps in the data, which were too severe to edit. Errors may have occurred from learning how to affix markers with adhesive to the suit with some falling off, and also from the lack of lab space to have a proper capture volume with the minimal four cameras (below the recommendation by OptiTrack, which motivated the upgrade to nine cameras in future projects as discussed in Section VI. Ongoing Work). Once edited, the tracking data was exported as an .xls file, where every marker is tabulated with their X, Y, and Z coordinates for every recording frame. From here the .xls data is imported into the MATLAB analysis programs developed by undergraduate research assistants of the S.U.I.T. Lab. It should be noted that the X-Y-Z frame of reference for the data collected uses the coordinate system set during the calibration of Motive (values are in meters). This origin is set with a right angle triangle comprising of tracking markers on the floor by the front of the test subject chair, with Z perpendicular and positive towards the technician desks, X parallel and positive to the right (from technician point of view), and Y set as vertical positive upwards. The MATLAB code swaps Z and Y in this work as seen in the resultant plots.

The motions recorded can be divided into two types: angular and volumetric. A ROM Angular Analysis Program was developed by Fornito, and a Reach Envelope Volumetric Analysis Program was developed by Lopac. The Angular Analysis Program exported plots and angles measured for each angular motion recorded during the testing, as well as the percent retained (% Ret) from unsuited to suited unpressurized and to suited pressurized. The volumetric analysis program exports plots and volumes measured for the combined horizontal and vertical carveout motions, as well as the % Ret from unsuited to suited unpressurized and to suited pressurized.

B. ROM Angular Analysis Program

The MATLAB Angular Analysis Program determined what type of ROM the subject had performed based on its corresponding plane from the .xls file. The program then determined how many repetitions (Rep) the test subject performed. MATLAB's *findpeaks* function from the signal processing toolbox was used to locate the local maxima for Figure 6 abduction (during AA) or extension (during VFE/HFE). As shown in there are five local maxima points on the left wrist X coordinate. The first value was always the minimum value because of the test protocols, unless specified. The second peak value was the maximum abduction value; therefore, it distinguished the first repetition from the others. The same process can be used for HFE for the X coordinate and VFE for the Y coordinate. Occasionally *findpeaks* would identify peaks incorrectly and input parameter adjustments were necessary to correctly identify minimums and maximums of motion.

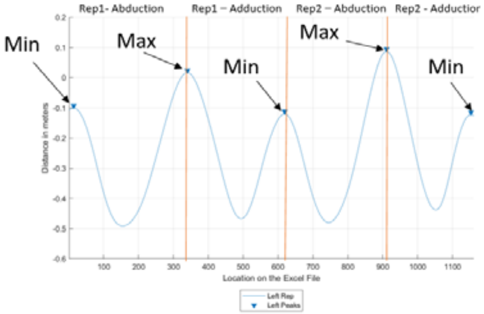

Figure 6. Visual output of MATLAB data used to find maxima in subject's motion.

Once the frames had been gathered the next step was to collect the corresponding coordinate values and the origin point. The origin point was calculated as the average distance between the shoulder and chest coordinate points. The reason to find the average point was to approximate the location of the shoulder joint where the motions originate, which would be internal to the body between these markers and estimated based on industry advice. A problem that had occurred for chest and shoulder points was a loss of tracking; to solve the issue the last known frame of the marker would be its replacement coordinate value. The shoulder and chest coordinate points used for analysis were taken from the first repetition when the wrist was at a minimum value. In other words, repetition one and two both used the same shoulder and chest points. This standard was emplaced assuming the resting seated position was the same across all repetitions. This may be amended in future programs to update the shoulder rotation location as the subject moves and this will be possible with the smoother data seen on the nine camera system. The approximate deflection or deviation of this shoulder origin estimation was measured to be 5 centimeters.

After all the key coordinates were gathered, the next phase was to find the angle per repetition and the average angle per test condition between the two vectors. Vector *u* was the maximum extension or abduction points subtracted by the shoulder origin points. The same was done for vector *v* except the pointer was the minimum extension or adduction points. To calculate angle theta (θ) take the *arctan2* of the dot product and the norm of the cross product:

$$X = \ Dot\ Product = u \cdot v = u_1 v_1 + u_2 v_2$$
$$Y = Norm\ of\ the\ Cross\ Product = \ \big||u|\big|\big||v|\big|$$
$$\theta = \ \ arctan2(Y, X)$$

The function *arctan2* is a two-argument arctangent that has a range of $[-\pi, \pi]$ for vectors positioned in a unit circle. The program also calculated the % Ret using the maximum angles for all conditions. To visualize the motion the program generates subplots for each subject’s motion, for all conditions. % Ret is simply calculated as follows, where “Condition” represents suited, suited unpressurized, or suited pressurized:

$$\% \, Ret = 1 - \frac{(Condition\ A - Condition\ B)}{Condition\ A}$$

C. Reach Envelope Volumetric Analysis Program

Using the raw .xls data from the Horizontal and Vertical Oscillations (a.k.a. carveouts) movements for each arm, the MATLAB Reach Envelope Volumetric Analysis Program is able to estimate the shape and volume of the area carved out by the recorded subject for all test conditions. “Volume” for this research is loosely defined solely for % Ret comparisons, but future work will investigate internal boundaries and maximum reach surface area (see Section VII). The RWristOut marker data from the Horizontal Right and Vertical Right Oscillation files are combined into one matrix to represent the total ROM for the right arm, and the same is done for the left arm using the LWristOut marker data with its corresponding files. The shoulder points are considered fixed (as previously discussed) and extracted from when each arm is resting down at the side of the body.

An example of the unprocessed wrist marker data, and the single shoulder points can be seen in Figure 7 (top). Using this data, a reach envelope can be created for each arm using MATLAB’s *alphashape* function. Points which are not on the outermost bounds are not considered in the creation of the shape mesh, similarly to how convex hull algorithms work. A*lphashape* creates a shape mesh using the Delaunay triangulation algorithm, which connects points to their proximal neighbors based on a specified radius. Running *alphashape* for an arm matrix (all wrist data and a single shoulder point), results in a solid shape representing the maximum ROM reach enabled by the shoulder joint while the arm is fully extended (Figure 7 bottom). The volume of this shape can then be calculated and stored by the program.

The % Ret from unsuited to suited unpressurized and unsuited to suited pressurized can be calculated using the volumes for each arm. After all conditions have been analyzed, a subplot is created to view the test conditions side by side for a test subject. The viewpoint of the plots can also be rotated to view the range of motion from front, top, side (left or right), and isometric vantages. The exported plots can be used by the spacesuit manufacturer or vehicle designers to easily understand reach envelope and restrictions the spacesuit imposes on the wearer specifically on shoulder mobility.

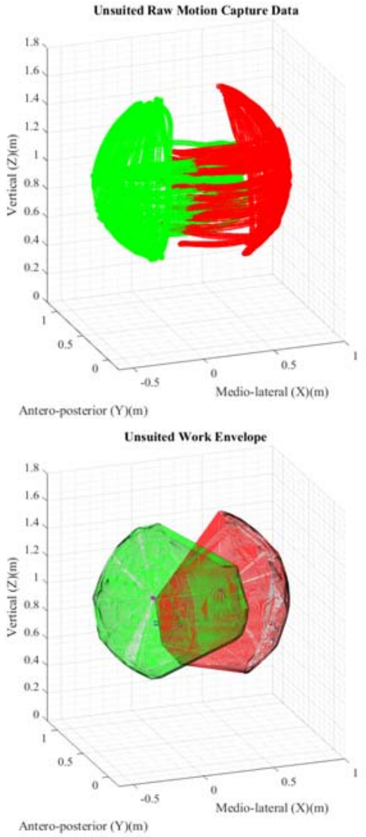

Figure 7. Subject 003 raw data (top) converted to alpha shapes (bottom).

IV. Results

A. ROM Angular Data

The outputs of the custom MATLAB programs are summarized in the following tables with accompanying figures. The data output from the angular analysis in Table 2 shows the angles for each motion, arm, and test condition per subject with averages across all repetitions. The accuracy of the angles calculated in these tables was verified as a sanity check by using a physical protractor on the outputted plots which were equally scaled and rotated to view the principle movement from the normal plane. The % Ret values in Table 3 are calculated using the maximum angles achieved for each arm in every test condition. Some recordings did not complete three full repetitions, thus averaging only two measured angles. A higher number of repetitions per motion could produce more statistically relevant averages; however, the S.U.I.T. Lab was being cautious not to overly fatigue the subjects with excessive motion while suited. Figure 8 is the mediolateral view subplot for the shoulder AA movement across all three test conditions for subject 002 (Note: this view is not the orthogonal view of the AA angle calculation as the subject is not perfectly aligned to the X-Z plane). The lines drawn in this figure are the true movement of the subject’s wrists, recorded in 3D by the infrared cameras of the motion capture system. Every motion recording has front, top, side, and isometric plots which can be made available upon request. VFE and HFE example plots are shown in Section V for further discussion.

Table 2. Angular results for shoulder AA, VFE, and HFE showing average angles.

MOTION	ARM	TEST CONDITION	SUBJ. 002 (°)	SUBJ. 003 (°)
AA	Left	Unsuited	160.7	156.4
	Left	Suited Unpressurized	105.0	113.0
	Left	Suited Pressurized (2.5 psid)	69.6	85.5
	Right	Unsuited	153.9	155.3
	Right	Suited Unpressurized	94.2	99.5
	Right	Suited Pressurized (2.5 psid)	73.7	88.8
VFE	Left	Unsuited	148.8	150.5
	Left	Suited Unpressurized	83.2	121.2
	Left	Suited Pressurized (2.5 psid)	51.2	93.1
	Right	Unsuited	149.8	144.2
	Right	Suited Unpressurized	83.6	109.0
	Right	Suited Pressurized (2.5 psid)	53.3	90.6
HFE	Left	Unsuited	134.1	113.3
	Left	Suited Unpressurized	74.1	79.0
	Left	Suited Pressurized (2.5 psid)	31.1	53.6
	Right	Unsuited	134.0	114.9
	Right	Suited Unpressurized	74.9	79.0
	Right	Suited Pressurized (2.5 psid)	33.4	61.2

Table 3. Percent Retained (% Ret) for subject 002 for shoulder AA, VFE, and HFE using maximum angles.

MOTION	ARM	% Ret: Unsuited to Suited Unpressurized		% Ret: Unsuited to Suited Pressurized		% Ret: Suited Unpressurized to Suited Pressurized	
		SUBJ. 002	SUBJ. 003	SUBJ. 002	SUBJ. 003	SUBJ. 002	SUBJ. 003
AA	Left	68.9	73.8	43.9	56.7	63.7	76.9
	Right	64.9	66.3	47.9	60.5	73.8	91.3
VFE	Left	54.9	83.5	34.8	63.5	63.3	76.0
	Right	54.7	75.6	38.0	63.0	69.5	83.4
HFE	Left	56.0	75.2	23.9	51.2	42.6	68.0
	Right	54.6	72.1	25.7	59.2	47.0	82.1

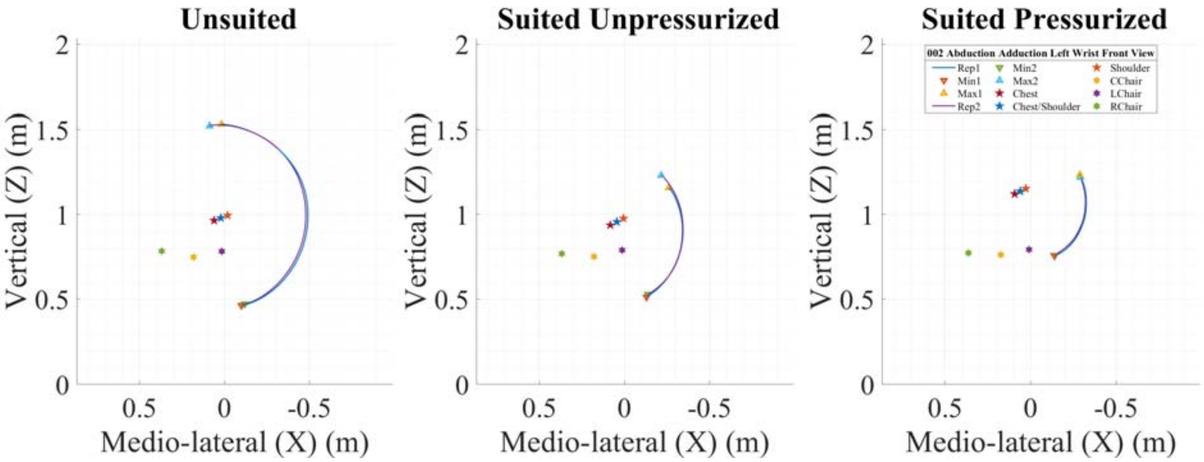

Figure 8. Shoulder Abduction Adduction (AA) mediolateral view for subject 002's left wrist marker.

B. Reach Envelope Volumetric Data

The results of the 3D volumetric analysis in Table 4 show the left and right arm alpha shapes representing volumetric reach envelope in meters cubed (m^3).

Table 5 shows the % Ret of relative reach volume for each subject between every test condition. In future tests calculating total volume will require updates to the MATLAB code to produce an overlapping alpha shape in the analysis to show cross-reach volume. An example of overlapping shapes can be seen in Figure 10 and Figure 12 (front and top views) where subject 003 has a shared volume within their unsuited reach envelope. This is not the case for subject 002 as seen in Figure 9 and Figure 11 (front and top views). Additional left side views are provided in Figure 13 (subject 002) and Figure 14 (subject 003). Right side and isometric views are available upon request.

Table 4. Reach envelope volume for each arm of subject 002 and 003.

SUBJECT	ARM	Unsuited (m^3)	Suited Unpressurized (m^3)	Suited Pressurized (m^3)
002	Left	0.23	0.06	0.02
	Right	0.22	0.06	0.03
003	Left	0.25	0.07	0.03
	Right	0.33	0.10	0.04

Table 5. Percent Retained (% Ret) for each arm of subject 002 and 003.

SUBJECT	ARM	% Ret: Unsuited to Suited Unpressurized	% Ret: Unsuited to Suited Pressurized	% Ret: Suited Unpressurized to Suited Pressurized
002	Left	26.1	8.7	33.3
	Right	27.3	13.6	50.0
003	Left	28.0	12.0	42.9
	Right	30.3	12.1	40

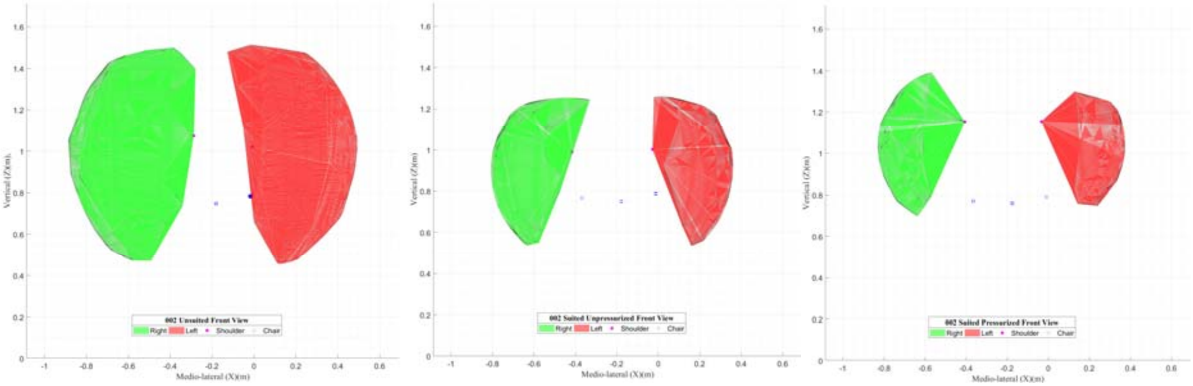

Figure 9. Subject 002 front view of reach envelope.

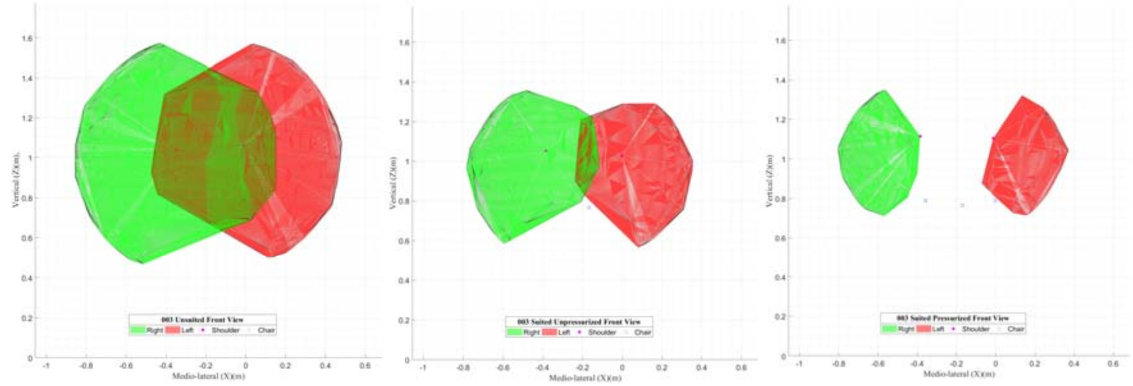

Figure 10. Subject 003 front view of reach envelope.

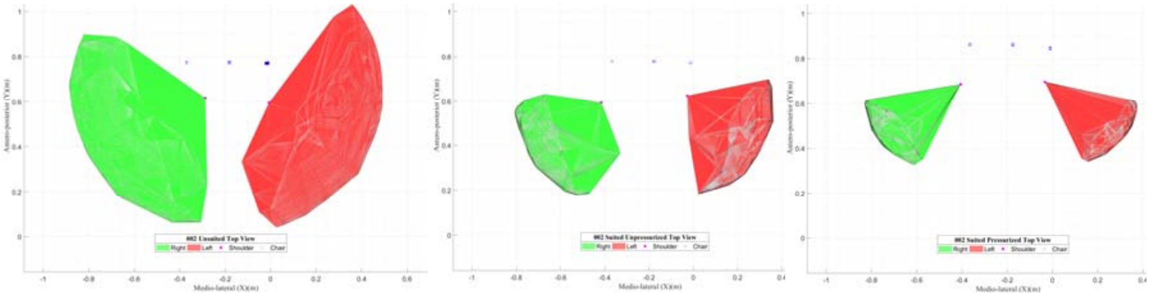

Figure 11. **Subject 002 top view of reach envelope.**

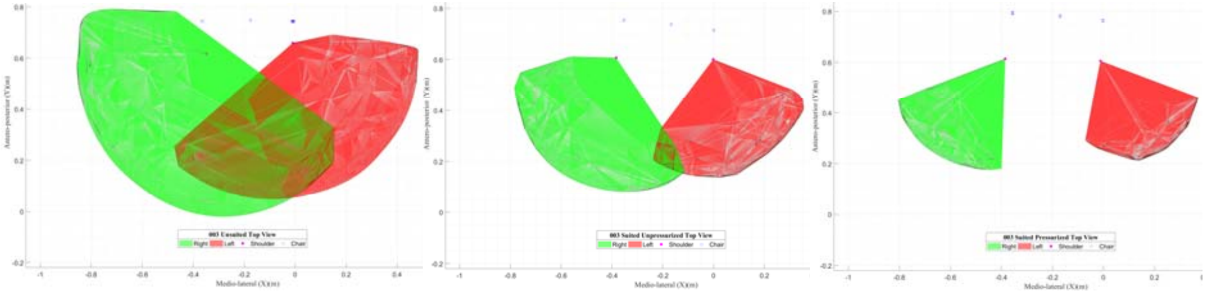

Figure 12. **Subject 003 top view of reach envelope.**

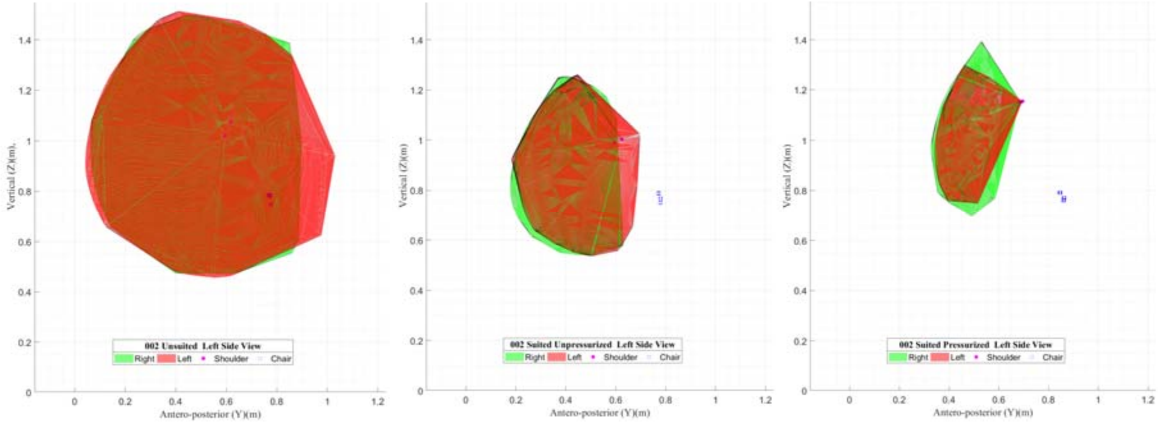

Figure 13. **Subject 002 left side view of reach envelope.**

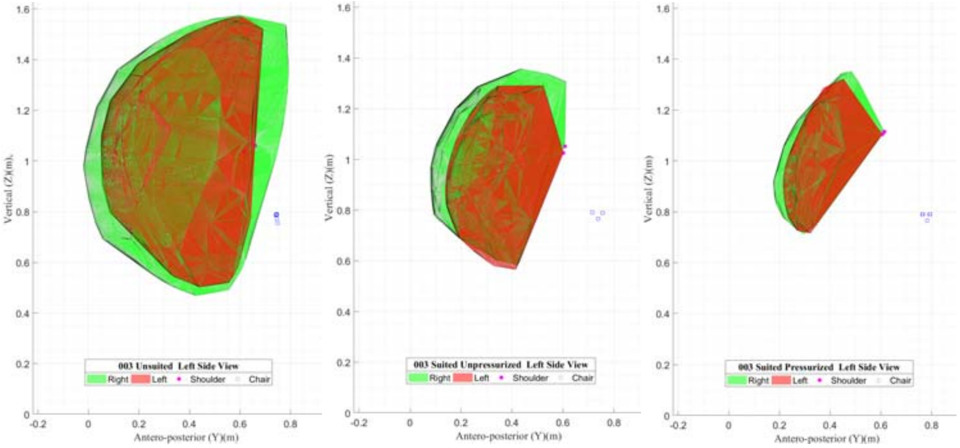

Figure 14. **Subject 003 left side view of reach envelope.**

V. Discussion

A. Angular ROM Observations

The lines drawn in all angular figures are the true movement of the subject's wrists unsuited or wrist/cuff interface location on the spacesuit recorded in 3D by the infrared cameras of the motion capture system. A noticeable occurrence in the angular figures was the change in position for the shoulder and chest points. This was most likely caused by the pressurization of the suit lifting the subject higher from their unpressurized seated position due to a lack of restraints. Since all three test subjects were the same anthropometric sizes, the suit sizing was nearly identical, but each subject was properly adjusted during the donning process by FFD. It is important to reiterate that these test subjects had no previous spacesuit experience and the resultant data shows significant differences in ROM and reach envelopes. These differences can be attributed to how closely protocols were followed more than spacesuit fit. The results presented are the accurate quantifiable measurements, and indicate reach, but do not represent the spacesuit's ultimate capability for this subject size, but do provide a solid methodology for future analysis. Valuable lessons have already been applied to the next S.U.I.T. Lab project that can be used to create a model of spacesuit reach envelopes.

Figure 15 displays the anteroposterior (side view) to scale subplot of the shoulder AA movement for subject 002. The side view visualizes the sway or deviations from a subject's perfect linear motion that may be anticiapted in a standard video capture frame of reference facing the test subject. By using actual 3D data in motion capture, the slant of the body can be measured and actual angles orthogonal to the AA motion were obtained with vector math. Additionally, it can be seen that the arm is pushed forward of the natural shoulder rotation point with the shoulder of the spacesuit sitting higher when pressurized.

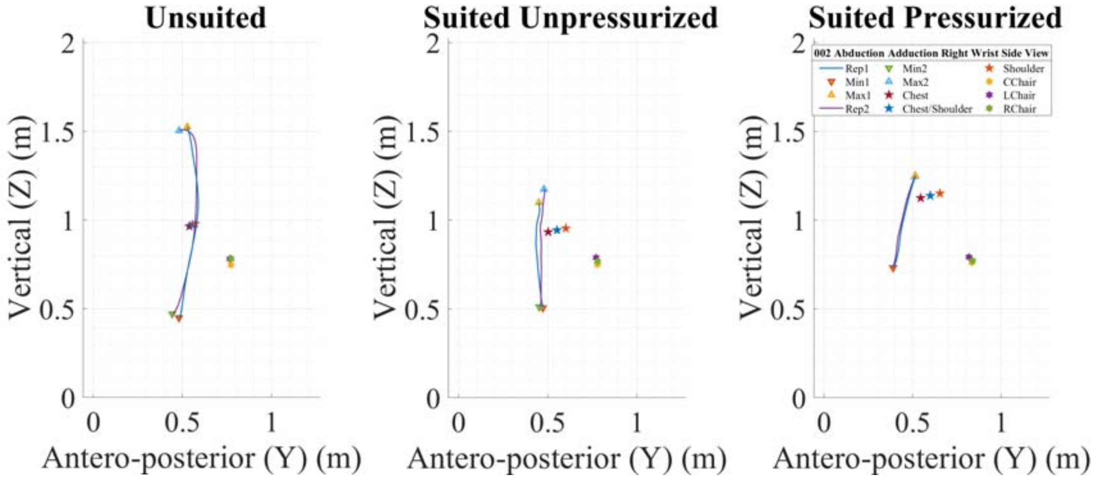

Figure 15. Shoulder AA anteroposterior side view for subject 002's right wrist marker.

A noticeable and expected occurrence with the angular results was the decrease in angle size as the spacesuit is donned and pressurized. For example, as shown in Table 2, the average AA angle for subject 002's left arm was 160.7° for unsuited, 105.0° for suited unpressurized, and 69.6° for suited pressurized. Table 3 shows the % Ret values as the spacesuit is donned, and then pressurized. The sharpest decrease in mobility is the transition from unsuited to wearing the suit pressurized. The effect of pressurization had the most effect (lowest % Ret) in the anteroposterior plane of motion during the HFE motion.

The two motions that skewed the consistency of the results subject 002 were VFE and HFE. In Table 3, the % Ret for VFE was 34.8% (left) and 38.0% (right) from unsuited to suited pressurized. Figure 16 displays the low percentages caused by the subject bending their arms. This figure also shows VFE of subject 002's right side, where the hand should not be close to shoulder and chest points; however, for the suited pressurized the maximum extension was too close to the rotation point. Additionally, it can be seen from the unsuited to suited unpressurized plots that the arm length from the shoulder is shorter. To justify the claim that the subject bent their arm, the recorded footage of Motive (and videos recorded for every test) were reviewed and displayed that the subject had indeed bent both their arms for that particular motion. Therefore, the % Ret considered unsuited (no bent arms) and suited pressurized (bent arms) resulting in a lower % Ret. Further investigation is needed to see if subjects were bending their arms due to unclear protocols, or because the suit influenced joint angle.

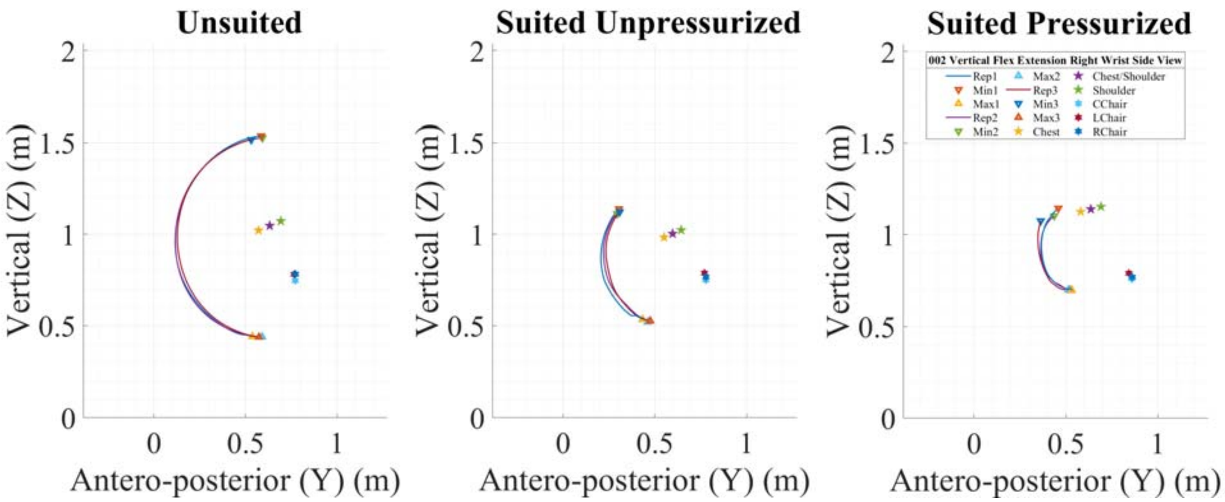

Figure 16. Shoulder VFE anteroposterior side view for subject 002's right wrist marker.

In Table 3, the % Ret for HFE was 23.9% (left) and 25.7% (right) from unsuited to suited pressurized. The cause for the lower % Ret was not because of bent arms as in the VFE case, but likely from the restricted mobility of the suit. As shown in Figure 17, the unsuited condition minimum points were further behind the shoulder and chest points compared to suited pressurized. Possible attributing factors for why this happened to subject 002 and not subject 003 (reviewing Table 2 right arm values, subject 002's HFE was 134° and 003 was only 115°) could be difference in strength and/or how well the suit was adjusted to the subjects. The main differences between the data collected for both subjects is likely due to misinterpretation of the motion instructions.

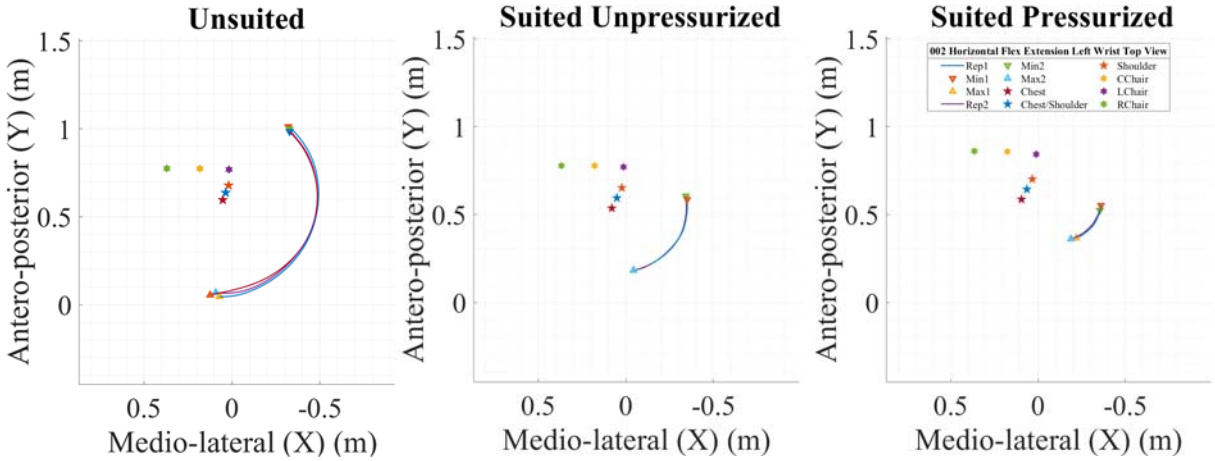

Figure 17. Shoulder HFE top view for subject 002's left wrist marker.

Analyzing results in the % Ret Table 3 shows that the right arm was more dominant than the left arm in 11 out of the 18 conditions. Furthermore, unsuited to suited pressurized and suited unpressurized to suited pressurized right arm percentage was greater than the left arm 11 out of the 12 % Ret conditions. The left arm was dominant under the % Ret for unsuited to suited unpressurized in all 6 % Ret conditions. The results may be caused by arm dominance, adjustments of the suit for each subject, other factors, or a combination of factors.

B. Volumetric Reach Envelope Observations

The exported plots of the Reach Envelope Volumetric Analysis Program represent the overall reach envelope of each subject's performance. These plots are visual representations of where a subject can reach in 3D space across all test conditions, with unbent arms. Similar reach envelope plots featured in work by Abercromby et al.[14] were used to plan the layout of control surfaces for the Science Crew Operations and Utility Test (SCOUT) vehicle based upon the reach envelope of Mark III EVA suit. The methods used by the S.U.I.T. Lab for plotting reach envelope can be applied to the design of new launch vehicles that would integrate IVA suits like the FFD FOP suit. The plots provide an understanding of the maximum reach of the subjects in both the unpressurized and pressurized suit conditions. Distances from the body or chair can be measured using the plots to understand the maximum distance any control surfaces or safety equipment can placed inside the vehicle.

The plots for both subject 002 and 003 reflect a reduction of mobility prominently in the posterior, vertical, and cross body areas. Both subjects saw difficulty in reaching above their heads and across their body while keeping their arms fully extended. In Figure 10, Figure 12, and Figure 14 subject 003 has a prominent area of their unsuited reach envelope that is shared by both arms. After donning the suit, they lose a significant amount of this shared volume. After pressurizing the suit this shared volume no longer exists for the straight arm protocol. While the subjects may be able to retain some of this shared volume by bending the elbows, they were instructed to keep their arms straight in order to isolate shoulder mobility and only move within their comfort level without straining. The reduction of volume in the reach envelope appears to be larger than expected, which is reflected by the % Ret values in Table 5. This may be due to the creation of the alpha shape in the program by extending the maximum reach points directly to the shoulder points. The shapes created may reflect an over estimation in the reach envelope volumes of the subjects. Despite this, the plots still visualize an accurate representation of the maximum outward reach and % Ret indicates potential loss across conditions. An attempt to capture the inner bounds of the reach envelope would be needed to yield a more accurate and quantifiable representation of the reach volume (see section VII. Future Work).

C. General Observations

The common trend throughout all of the data collected for both subjects was the degradation of shoulder mobility for the subjects in the FFD spacesuit as it was worn unpressurized and then pressurized. This trend has been quantified in the tables of data collected in the results section above with reductions in angular ROM and reach envelopes. The plots exported from the analysis can also provide qualitative insights into the performance of the FFD spacesuit. Both lateral and vertical motion of the arms were significantly restricted. There was particularly more restriction when reaching across the front of the body, above the head, and towards the rear as illustrated by the reach envelope plots for both suited test conditions. The restrictions in these particular areas of the reach envelope are supported by the results of the angular ROM analysis and their accompanying plots. The desired motions in the vertical and mediolateral planes correlate with movements that are achieved by adding shoulder bearings in IVA spacesuits as previously discussed in background (Section II.A). The results reinforce the trade space of increased ROM versus the potential shoulder injuries (or worse), which may remain a design challenge for launch, entry and abort suits. The differences in the angular and reach envelope results between both subjects can be attributed to physical differences between the subjects and their individual interpretations of the test procedures as addressed in the next section.

D. Inconsistencies

After recording the FFD FOP tests, several issues developed that prompted the S.U.I.T. Lab team to reassess certain factors of the test. One of these factors was the protocol for running the test. The preliminary nature of the protocol led to some inconsistencies between the three test subjects. One of these inconsistencies was the different ways that each subject performed HFE and carveout movements. When subject 002 performed HFE and carveouts, they would swing their arm all the way behind as far as their reach would allow. However, subject 003 did not reach their arms all the way backwards. This caused the data to be partially skewed. The other discrepancy that occurred between subject 002 and 003 was how far they crossed the central line in front of each subject during the horizontal and vertical carveout motions. When performing the horizontal and vertical carveouts, it is important that each subject moves their arms all the way across their chest in order to determine their maximum reach. Subject 003 successfully crossed all the way over to their maximum reach during the carveout motions. However, due to a lack of specification in the test protocol, subject 002 did not reach their maximum and instead ended their movements when their arms were extended straight out in front. These lessons learned have already been applied to ongoing work as discussed in Section VI. The lab has observed with new test projects that research subjects with more spacesuit experience do tend to have less apparent errors, with virtually no re-takes needed during motion capture.

VI. Ongoing Work

The FFD FOP suit investigation was a critical indicator for the performance changes that would be required for both the motion capture system and protocols in order to reduce data editing and to improve repeatable movements. The S.U.I.T. Lab has proactively addressed these challenges to strengthen capacities for ongoing work.

The motion capture system only included four OptiTrack motion capture cameras during the FFD test, but with a new total of nine cameras (see Figure 18), the lab has been able to capture spacesuit mobility data with far greater accuracy and completeness. The positioning of the cameras was upgraded to a higher camera frame that wraps around the room. With a higher vantage point and more cameras, the functional capture volume continues to improve as well as the quality of the recordings. This includes less occlusions that previously led to markers requiring relabeling during a lengthy editing process. Recently the lab has not seen loss of marker tracking from sudden subject motions or stuttering. Additionally, the hand-arm extremes are being fully captured in the lab's small volume without going "off the grid". Marker swaps have also been eliminated, where previously it was possible for the system to swap a tracked marker if it overlapped with another (if each marker did not have a sufficient number of cameras tracking it).

A quantitative example of the motion capture improvement in the S.U.I.T. Lab's recent tests is the retention of tracked markers. When a marker is lost during tracking, Motive eventually relocates it but as a new marker with a new identifier. During the FFD test 18 reflective markers were placed on the subject, but due to these tracking losses, the number of independent markers recorded by Motive during a horizontal carveout test climbed from 18 to 246. In a recent test of similar motion with the upgraded system using 17 reflective markers, only 29 independent markers were generated by Motive from occlusions or losses. The tracking maintains an order of magnitude of improvement with very little editing required after data recording.

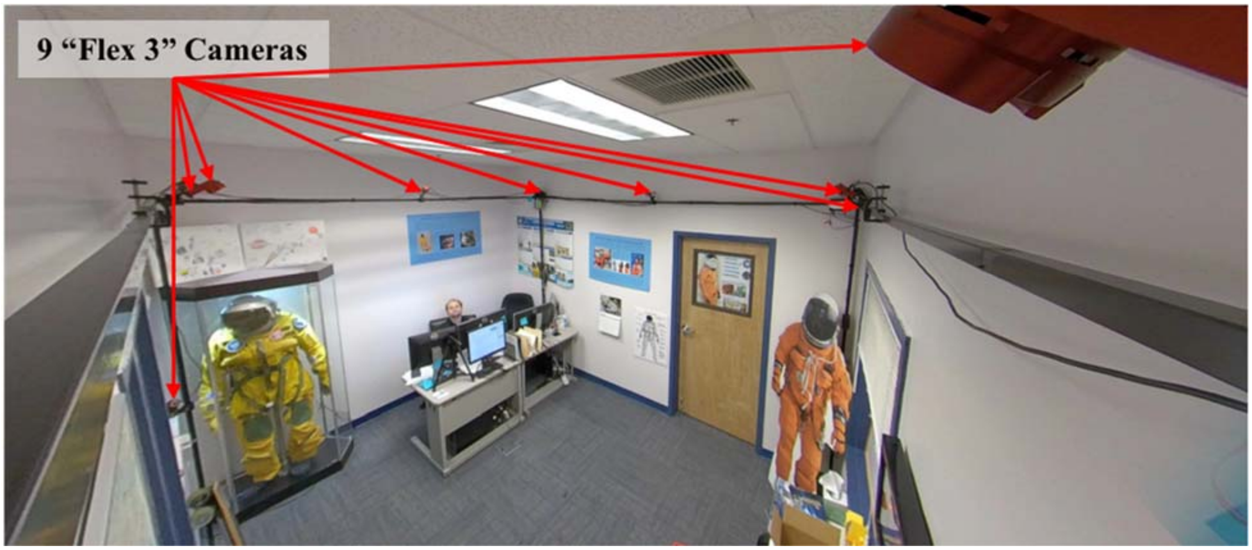

Figure 18. The new S.U.I.T. Lab location is similar in size, but a frame was built to accommodate the new nine camera system.

The other major issue that required improvement was the protocol that dictated how the FFD FOP ROM test was to be carried out. This early form of the test protocol was very sparse with regards to the way in which the recordings were to be carried out. Having been written by the researchers who would conduct the test, certain exhaustive details pertaining to how each movement should be done and how the test subjects were instructed to perform the tasks were left out. Because of this, the instructions that each subject received and subsequently the movements that they performed were slightly different. This caused some differences in the recorded data of certain movements between each subject. In order to address this problem, the protocols have been revised and test procedures have been upgraded. Current protocols include step by step checklists to dictate how each section of every test should be conducted. Training procedures are now in place in order to educate each subject on how to perform every movement so as to eliminate discrepancies from person to person. Contingencies are now in place so that a recording will be redone if the subject or environment strays from the established conditions of each test. These changes continue to improve the fidelity and efficiency of each new ROM spacesuit test. Protocol changes also included the removal of elbow motions, splitting the HFE into two motions with left and right arms in separate takes, and VFE starting at a minimum versus a maximum location. In the Fall of 2018, one of the team projects in the ERAU course CSO 395b (Spacesuits & Human Spaceflight Operations) focused on protocol observation and recommendations to the S.U.I.T. Lab. Their demo videos led to a new set of videos, recorded as tutorials, which can be provided to test subjects in advance of sessions as training. Training saves time and minimizes operational human errors or misunderstandings in motions, yielding cleaner recorded data. On a test day, it would be ideal that the subjects have zero learning curve on motions.

Additionally, the S.U.I.T. Lab is using a more simplified marker layout for current tests. The marker layout used for testing the FFD FOP suit was overly complex, with redundant markers, which often times fell off the spacesuit or were occluded from the tracking cameras. The current marker layout was inspired by the motion capture studies done by Abercromby et al.[14] while assessing the reach envelope of the Mark III spacesuit at NASA. Most notably this layout includes markers that are on the back of the palm rather than on the wrists. Tracking these markers represents where the subject can grasp items.

VII. Future Work

The S.U.I.T. Lab has planned several features to incorporate within the MATLAB analysis programs to enhance usability, research output, and lab procedures. The lab plans to combine the ROM Angular Analysis Program and the Reach Envelope Volumetric Analysis Program with a graphical user interface (GUI). The GUI shall allow the user to efficiently operate the code rather than through the editor or console. To improve research output, the lab is in the process of developing an extension to the current reach envelope program to calculate the unknown intersection of two arm envelopes. Identifying the intersection will provide additional insights into the total reach envelope of subjects and where they can reach the most. An addition to the code, and a potential improvement for lab procedures, would be to implement live data from Motive into MATLAB using plugins from OptiTrack. Live data can help prevent any mistakes or inconsistencies in the motions, visualize carveouts in real time, and allow subjects to understand their range of motion instantaneously. Furthermore, the lab plans to implement recordings of internal reach allowing for the omission of the shoulder points from the reach envelope volumetric analysis. Internal boundary of reach will further the lab's investigation into volumetric reach and work envelopes by including the subject range of mobility near the suit rather than solely how far away a subject can reach. This would be critical to verify that an astronaut can reach safety equipment or valves on the suit surface. This will improve the fidelity of reach envelope results by creating a more accurate volumetric representation of overall boundaries in the exported data and plots. Incorporating tasks with astronaut strength and torque could be added to compare the reach envelope to the work envelope, i.e. the work envelope is where you can actually "actuate" versus just reach.

Inherent in any code is the use of approximations to fill gaps, such as in a volume. The lab would like to statistically address the level of uncertainty that occurs during the process so that recorded data has a quantified variability that can be used as a safety factor for reach. For example, a switch may need to be designed 5% closer to account for error tolerances. Additionally, a range of test subjects are needed to account for differences in anthropometry. As the protocol and data reduction is further refined with the recommendations addressed, a study could be run to collect a large spectrum of body type data with students across ERAU campus. Recruiting near identical body-type subjects for the FFD FOP test was effortless and the S.U.I.T. Lab has been fortunate to have a continuous stream of volunteers, all waiting for their chance to don a spacesuit. It would be recommended that this database starts with common standards that are used by NASA for their spacesuit system sizing.

A database has the potential to be used for commercial spaceflight applications for scientist astronauts who may want to know what volume they can safely operate in. This scientific work envelope could be characterized by whether they are wearing a spacesuit, the seat type, if restraints are worn, and other spacecraft neighboring systems. Analogous to this practice, ZERO-G's Weightless Lab program divides (or sells) ten square feet of in-flight test area for equipment and operations. Alternatively, database information could be created for flight providers based on their cabin configurations.

It is recommended that future seated testing include a stable chair platform bolted to a base or the floor with a five- or six-point harness. In ongoing work, the S.U.I.T. Lab has used a basic restraint across the lap, but further investment will be needed to build or purchase a test platform. Ideally the test chairs would be as similar to the flight provider's equipment as possible with a common baseplate, for spaceflight relevance. Chairs that would be ideal targets would include both suborbital and orbital configurations for the variety of potential space explorers.

Future work in the S.U.I.T. Lab may include inertial measurement unit (IMU) devices for both IVA and EVA studies as previously mentioned. One commercially available garment being tested is the Rokoko suit.[17] IMUs could track body angles inside the suit while motion capture tracks the spacesuit's exterior. The differential joint angles could be indicative of energy expenditure losses or potential locations for injuries.[18,19]

Further analysis could be conducted with a range of spacesuit operating pressures. By investigating the % Ret of mobility versus pressure, critical differences may be found that suggest an ideal operation pressure, but additionally indicate if ROM will be gained/loss if the spacesuit is adjusted for independent scenarios.

A stretch goal for the S.U.I.T. Lab would be gain access to a current Sokol spacesuit or previous NASA IVA suits, to conduct baseline measurements while comparing ROM to system requirements. This baseline could then be used to compare next generation suits to see how they measure up against historical data. The S.U.I.T. Lab continues to work with partners to test FFD spacesuits, but ERAU would greatly benefit from purchasing their own FFD suit.

VIII. Conclusion

The aim of this study was to collect quantitative and qualitative insights focused on shoulder mobility of the FFD FOP spacesuit. Using motion capture hardware and software, raw 3D data was recorded for a variety of shoulder motions targeting specific human body reference planes and maximum reach envelopes. After these recordings were saved and edited for data gaps they were ready for analysis. Two separate MATLAB programs were created to produce results for angular ROM and reach envelopes. The programs were successful in outputting quantitative data in the form of angles, relative volumes, and % Ret while also exporting the recorded mobility tests visually into informative plots. The programs developed for this study will serve many future analyses by the S.U.I.T. Lab and are undergoing continuous improvements. This study was the first attempt by the S.U.I.T. Lab in developing mobility procedures, motion capture protocols, and motion capture analysis software. Angular ROM data collected revealed the degradation of mobility on specific planes of motion, and their plots show the deflection of the arms while in motion. The reach envelopes created outlined how far a subject could reach and in what direction across all test conditions. These results from this preliminary test have provided FFD with information regarding the mobility of their spacesuit that they would have been unable to collect without the solutions for mobility analysis developed by the S.U.I.T. Lab. This is a service that can be replicated for other spacesuits, with applications in spacesuit design, vehicle layout, human performance, and safety analysis. With current work and future plans to upgrade the capabilities of the S.U.I.T. Lab, this research will continue to evolve into a more robust system for analyzing spacesuit mobility.

IX. Acknowledgements

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Figure 19. Multiple views of the test subject overlaid during shoulder AA.

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