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The Embry-Riddle Aeronautical University (ERAU) Spacesuit Utilization of Innovative Technology Laboratory (S.U.I.T. Lab) is dedicated to the pursuit of advancing human spaceflight by contributing to spacesuit and operations research with experiential programs for students. A significant portion of the S.U.I.T. Lab's portfolio is dedicated to the design and execution of spacesuit range of motion (ROM) investigations using video and motion capture systems. ROM biomechanical angles were measured using these techniques in conjunction with developing protocols for both simulated extravehicular activity suits at spaceflight analogue expeditions, and on ERAU campus with Final Frontier Design (FFD) intravehicular activity pressure suits. Designing protocols ensures effective communication for the analysis of simulated spacesuit performance to a remote crew. With communication delays to Earth, a self-sufficient spacesuit diagnosis is required to provide future astronauts with immediate action to take when dealing with a malfunctioning spacesuit. The video capture methodology is designed so that any crew would be able to conduct recordings with minimal impact to their schedule and with camera resources that are standard equipment. Spaceflight mission analogues involved in this study include: Hawai'i Space Exploration Analog and Simulation (HI-SEAS Mission V, 2017); Mars Desert Research Station (MDRS Crew 188, 2018), and AMADEE-18 in Oman (2018). Video capture can be used to collaborate with several spacesuit manufacturers to offer a snapshot comparison between designs, validate and verify capabilities, and aid with the selection of the right suit for the right job. The analogue locations recorded unsuited and suited data, while the November FFD test focused on motion capture (with video capture taken for validation) of unsuited, suited unpressurized, and suited while pressurized to 3.5 psid conditions. Early results from the motion capture align with values estimated from video capture and future work will compare the accuracy of these techniques.

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Nomenclature

% Ret	=	percent retained (of range of motion)
3D	=	three-dimensional
AAS	=	Applied Aviation Sciences [Department]
BPM	=	beats per minute
EMU	=	Extravehicular Mobility Unit
ERAU	=	Embry-Riddle Aeronautical University
EVA	=	extravehicular activity
FFD	=	Final Frontier Design
FOP	=	Flight Opportunities Program
HI-SEAS	=	Hawai'i Space Exploration and Analog Simulation
IRB	=	Institutional Review Board
ISS	=	International Space Station
IVA	=	intravehicular activity
JSC	=	Johnson Space Center
MDRS	=	Mars Desert Research Station
O_2	=	oxygen
PLSS	=	Portable Life Support Systems
psid	=	pounds per square inch differential
ROM	=	range of motion
S.U.I.T. Lab	=	Spacesuit Utilization of Innovative Technology Laboratory

I. Introduction

THE Spacesuit Utilization of Innovative Technology Laboratory (S.U.I.T. Lab) at Embry-Riddle Aeronautical University (ERAU) under the Spaceflight Operations Program in the Applied Aviation Sciences (AAS) Department of the College of Aviation provides a curriculum-based experiential focused goal of teaching ERAU students about the fundamentals of spacesuit operation in relevant environments starting with intravehicular activities (IVA) within the lab and extending to analogue research in simulations with extravehicular activities (EVA). The research-focused goal of the S.U.I.T. Lab provides a testbed for industry partners to receive feedback, data, and recommendations for spacesuit design with innovative solutions while simultaneously providing ERAU with hands-on research opportunities for faculty as well as undergraduate and graduate thesis work and technology development [Kobrick, 2017].

The inspiration for this range of motion (ROM) research came from the need for investigating seated IVA ROM of an astronaut in a pressure suit, or spacesuit. The S.U.I.T. Lab defined multiple testing concepts for analyzing human performance and spacesuit efficiency based off work envelope and ROM measurements in three test configurations: unsuited; suited unpressurized; and suited while pressurized (3.5 pounds-per-square-inch-differential (psid), the minimal suit pressure in the scenario of an emergency depressurization). ROM is the full movement potential of a joint, or a human's mobility. At the end of the day, what matters most is whether or not an astronaut can reach and 'flip switches' while pressurized in an emergency.

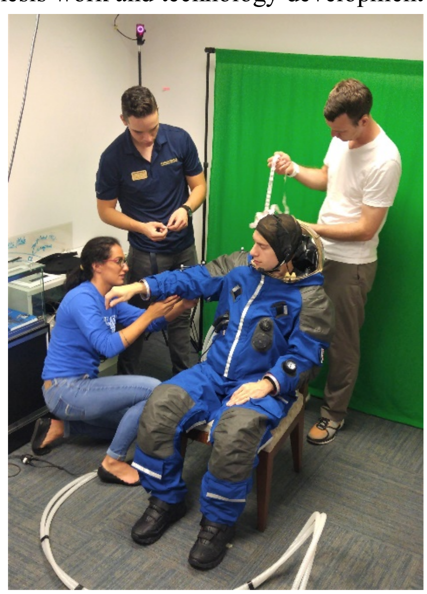

Figure 1: FFD President Theodore (Ted) Southern assists S.U.I.T. Lab technicians during Nov 2017 tests.

In the initial pursuit of creating operation-focused checklists for ROM data acquisition with motion capture in the lab, the S.U.I.T. Lab developed an experimental protocol for recording ROM of simulated spacesuits using video capture. The initial protocol was sent to an analogue crewmember in a remote Mars simulation who then used onsite equipment to record and perform the biomechanical motions provided, and sent the video files back to the S.U.I.T. Lab for post mission analysis. Using manual analysis methods similar to those used by NASA during the Apollo and Gemini eras, angular ROM metrics for unsuited and suited conditions were drawn from the videos captured in the field. This data from remote locations can be used to assess the performance of the simulated spacesuit and examine the fidelity of the suit when compared to functional EVA pressure suits. The objective is to be able to provide the protocol to any analogue mission where it can integrate seamlessly into the crew schedule and allow crews to gather baseline spacesuit performance metrics and self-diagnose ROM issues in the field. As this protocol is shared with more analogue missions around the world, the S.U.I.T. Lab can continuously update and revise the operational instructions using feedback from the crews.

The development of the video capture protocol was the primary step to developing an in-house protocol to be used with a motion capture system. The S.U.I.T. Lab is trying to establish new standards for recording three-dimensional (3D) data of spacesuits from reflective markers with OptiTrack's Motive software [OptiTrack, 2018]. 3D data can be used to calculate angular ROM metrics, specifically percent of mobility retained (% Ret). These values can act as a screen test for identifying spacesuit mobility design issues so that manufacturers can address the most significant motion deficits or unexpected coupled effects. Focusing on spacesuit assessment, these metrics can be analyzed to create an archive of resources for professionals involved in spacesuit design and testing. This work continues the partnership established with Final Frontier Design (FFD in Brooklyn, NY), who strives to commercialize their designs for human rating through qualification testing. The S.U.I.T. Lab's evolving methodologies strive to be on par with spacesuit validation techniques used by NASA Johnson Space Center (JSC). Such partnerships help define the S.U.I.T. Lab's overall mission, which includes helping detect slight design or technological oversights, leading to the improvement and advancement of spacesuit hardware for future spaceflight missions. It is the goal of the S.U.I.T. Lab to compare the accuracies of video and motion capture methods in future work to help better understand the proper use for different cases.

II. Background

A. NASA EVA Gaps

NASA's Integrated Extravehicular Activity Human Research Plan continues to guide S.U.I.T. Lab research. This plan identifies "EVA Gaps" or topics to be investigated and mitigated. These include the highest risks to human health and performance, providing essential countermeasures, investigation areas, and technologies for human spaceflight exploration research [HRP, 2016]. Several of these can be mapped to spacesuit mobility, design, and astronaut safety (as previously outlined in the creation of the S.U.I.T. Lab paper by Kobrick, 2017). Researchers at NASA JSC also advise the S.U.I.T. Lab on conducting multi-disciplinary cost-effective research enabling humans to perform EVAs safely, effectively, comfortably, efficiently, and on demand to enable and enhance human spaceflight exploration missions [Abercromby, 2016].

An understanding of why these spacesuit ROM restrictions exist is essential background for this body of work. EVA spacesuits are the primary pressure vessel for an astronaut when outside a vehicle or habitat. For this reason, EVA suits have many layers and rigidized parts to protect the astronaut from environmental hazards such as micrometeoroids or surface particulates. The patterning and programming of many soft body spacesuits cause these suits to have restrictions in mobility solely based on the construction of the layers. When pressurized, the softgood single axis joints of the suit will reach a neutral point that is defined by this patterning and programming. Attempting to move the suit to any other position creates a resistive force that tries to return the suit back to its neutral position. For an astronaut moving inside such a suit this resistive force can limit the mobility of their body. Over extended periods of time astronauts experience fatigue after constantly fighting the resistance the suit has when in motion. On a terrestrial mission the weight of the suit can add to this fatigue and limit mobility further. In the early development of EVA spacesuits for the Gemini missions, mobility was a secondary consideration, and pressure and thermal control took precedence. For this reason Gemini astronauts on EVA could not perform activities that were below their waist or above their shoulders [Saenger, 1970].

Moving forward, mobility on EVA has become a primary consideration of spacesuit engineers. Maximum retention of an astronaut's motion while suited can reduce fatigue and increase efficiency during EVA. Innovations in the fabrication of spacesuit assemblies lead to increases in ROM. Advanced joint designs aim to maintain a constant volume during the motion of the joint. If movement decreases the volume of the joint during motion, an increased pressure effect would cause an astronaut to apply additional forces to counteract the pressure changes. Additionally, the use of hard bearings and joints placed in biomechanically strategic locations can allow an astronaut to rotate their body without altering the volume the of the pressure garment and does not exert a resistive force on the astronaut when moving their limbs. The NASA Mark III suit implements some of these advanced joint designs, with a hybrid construction of soft and hard body components [Abercromby, 2006].

B. Range of Motion Video and Motion Capture

To analyze the mobility of simulated spacesuits from remote locations the ERAU S.U.I.T. Lab is adopting a technique used by NASA during the development phases of the Apollo A7-LB spacesuits in the 1960s. This technique utilized multi-exposure photos demonstrating the extreme ranges of each joint motion that were later analyzed to determine angular range. This method was referred to as the strobe, or movie sequence method [Jones, 1966]. The strobe method post-test analysis of still photographs was completed by printing the photographs onto transparency films, laying the photos of the two extremes of a motion on top of each other on a light table, and measuring the angle difference using a protractor. The strobe method as seen in Figure 2, also presented the final data with long photographic exposures. The method required the analyst to be familiar with the mechanics of the suit in order to properly assume locations for neutral suit positions, joint centers of rotation, and the joint segment centerlines [Aitchison, 2012]. The results of the suited and unsuited conditions were tabulated and used to calculate the percent of nude mobility retained (presented as *% Ret* in our work) by the suit for each motion.

Figure 2: NASA 1965 ROM test of Gemini spacesuit [SDASM, 2016]. Task B17 from Table 2.

Over the last 2 decades, motion capture technology has advanced rapidly and is quickly becoming a preferred method for measuring the movement of the human body. A study by NASA JSC in 2006 sought to measure the work envelope for a suited subject wearing the Mark III experimental EVA suit. Researchers were interested in the maximum reach of the suited subject and how much of the subject's work envelope lies within the subject's field of view. To gather data on work envelope and reach, the team of researchers utilized a 10-camera Vicon 612 motion capture system running Vicon iQ software [Abercromby, 2006]. A set of reflective markers across the suit, and specifically the gloves, were optically tracked by the motion capture system and interpreted as points on a 3D coordinate plane. This technology is typically used for anthropometric animation for films and video games, however NASA and the S.U.I.T. Lab is applying this advanced method for motion tracking to the biomechanical analysis of astronauts and the restrictive spacesuits they must wear. The system is highly accurate, sometimes down to the millimeter, though this comes at a price. While still very new technology, a system composed of 10 cameras can be thousands of dollars. Budgetary restraints can easily impose on the accuracy and completeness of the data collected by limiting the number of cameras, as discussed in later sections of this paper. The system also requires a large amount of space and wiring to function as intended, which can also be a restriction when operating out of a limited space or remotely. For this reason, motion capture is not always used to take measurements. Falling back to the simple video capture methods used in the past can suffice when operating in the field. NASA and the S.U.I.T. Lab have implemented an updated form of this method as well, utilizing modern day digital video cameras and digital protracting software researchers can record many biomechanical metrics quickly and with minimal resources. The exact accuracy of this method is difficult to determine, as it relies on the video quality and judgment of the analyzer, however NASA accepts the accuracy to be far less than that of an optical motion capture system [Abercromby, 2006]. When the lab conducts an analysis comparing video to motion capture, the errors and limitations will be further addressed. Despite the differences in accuracy of each method, there will be a case where one is more efficient and or effective than the other. The S.U.I.T. Lab aims to identify these cases to allow future researchers and astronauts to make informed judgments on what method of biomechanical analysis to use based on their external conditions. The OptiTrack system used in the S.U.I.T. Lab was chosen as an accurate platform with a limited budget [Kobrick, 2017]. The lab used only a four-camera system for the FFD November test, but has acquired funding for purchasing more cameras. This upgrade will address the small laboratory space issue and increase tracking accuracies by reducing data marker dropouts.

C. Analogue Research

Spaceflight analogue missions on Earth are used to simulate some of the harsh conditions of living in space. The hazards of living in space include hostile environments, reduced gravity, isolated confinement, distance from Earth, and space radiation. By strategically choosing locations on Earth that are analogous to space environments with as many matching variables as possible, analogue missions provide researchers with a unique opportunity to conduct field experiments and behavioral studies in conditions that are akin to those of an actual mission in space. Popular locations are often in some of Earth's most extreme environments, including such locations as the Antarctic, Arctic, deep oceans, deserts, and volcanic regions of the planet. Crews live in minimalistic habitats with limited resources and are isolated from other people for the duration of their mission. Analogue missions may vary in length, ranging from several weeks to several months. Communications with mission support and the outside world are also delayed to mimic what would be experienced on other planets; the round-trip signal to Mars is approximately 20 minutes and is a common operational constraint to work around. When analogue crews exit their habitats to perform an EVA, they are required to wear simulated spacesuits. These spacesuits serve both a physical and behavioral purpose. The suits create a physical barrier between a crewmember and the environment and restrict their activities in the field. Though the suits are typically not pressurized and are not critical to the survival of the crew outside the habitat, wearing one shares some of the same physiopsychological effects on the crew as a real suit. To best simulate a hostile space environment, the crew should feel as though the suit is protecting them and is a necessity throughout the mission. The simulated spacesuits that are most analogous to functional EVA suits create the most realistic EVA experience for the analogue astronauts. Aspects of a spacesuit to replicate in a simulated suit might include: active cooling, weight distribution, communications, field of vision, glove dexterity, layered materials, footwear, supplies, and restricted range of motion. Different analogues have varying suit designs and prioritize different aspects of a spacesuit to simulate. Mars Desert Research Station (MDRS) suits (as seen in Figure 3) replicate the fundamental aspects of wearing a spacesuit by adding the mass of a Portable Life Support System (PLSS), inherent ROM reductions in mobility, wearing bulky gloves and heavy hiking boots, and reduced visibility from a helmet. Simulated spacesuits that reproduce these effects for analogue missions allow researchers to analyze human performance in the field without constructing fully functional EVA suits. Varied design choices in the fabrication of simulated spacesuits can lead to differences in ROM and crew performance overall. Collecting information on simulated spacesuits from multiple analogue missions identifies the commonality of spacesuit features needed to mimic an accurate EVA, both physically and mentally to increase the fidelity of the simulation. With the creation of a standardized operational protocol, the ERAU S.U.I.T. Lab aims to provide analogue missions with an efficient method for analyzing spacesuit ROM in the field using video capture that yields meaningful data which can ultimately diagnose issues in astronaut performance. For example, if shoulder mobility has been observed to have less percent retained because of externally mounted equipment, the crew could reconfigure the gear to allow more ROM to increase their efficiency in field. Many analogues prioritize different attributes of the EVA experience, to make these closer to the real thing, ROM performance needs to be considered in the simulation design process.

Figure 3: MDRS Crew 188 crewmember overlooks the Mars Desert Research Station campus in Utah, USA.

D. S.U.I.T. Lab Evolution Timeline

The S.U.I.T. Lab has been operational since January 2017 and highlights are presented in Table 1 for reference to events discussed throughout this paper.

Table 1: S.U.I.T. Lab History

2016	**Summer**	Spacesuit Operation Laboratory created with hiring of Dr. Ryan L. Kobrick by AAS Department.
	Fall	Initial motion capture system purchased. Dr. Kobrick formulating lab plans.
2017	**January**	S.U.I.T. Lab rebranded and becomes operational with Dr. Kobrick as Principal Investigator.
	April	FFD video capture test in three conditions to examine elbow ROM.
	January - May	Instructional protocol development for remote ROM analysis.
	July	HI-SEAS remote video capture test with initial instructional protocols.
	July	Initial work presented at ICES [Kobrick, 2017].
	November	FFD IRB approved video and motion capture test with 3 test subjects.
2018	**January**	MDRS Crew 188 remote video capture test with updated instructional protocols.
	February	AMADEE-18 remote video capture test with updated instructional protocols.

III. Methodology

A. Video Capture

The S.U.I.T. Lab is implementing a technique similar to the NASA strobe method utilizing updated technologies that can be implemented into spaceflight analogue missions. The motions are recorded as HD video files with current mid-range camera technology. Crews are instructed to meet desired video framing and recording requirements and are also provided a list of recommended items to prepare before recording the tests. These recommendations include general principals of videography, such as: framing, resolution, aspect ratio, lens type, lighting, blocking, providing scale items, and camera distance. The videos can then be edited down to feature each motion in the suited and unsuited conditions. Digital scales, protractors, and goniometers allow for the measurement of angles and distances within a kinematic video analysis software, such as Kinovea or DartFish©. Maximum angles are measured from the two extremes of each motion that is repeated at least three times, which can be overlaid digitally. Results are tabulated, and mobility percentage retention (% Ret) can be calculated for each motion.

This method of spacesuit analysis was chosen because of how versatile and accessible the system is to any user. With minimal setup time (estimated 20 minutes), a camera, and simple computer software, a functional analysis of angular ROM can be conducted for a spacesuit. This is ideal for remote spaceflight missions where there are limited resources available and restricted communication with support on Earth. Diagnosing spacesuit mobility problems in the field should make efficient use of time and resources to allow a crew to function independently [Newman, 1999]. Data and operational feedback from analogue missions on Earth will allow the S.U.I.T. Lab to make continuous updates to their protocol. Future versions of the protocol will be applicable to functional EVA spacesuits for use in lunar and Martian missions.

The initial tests of this protocol were conducted on campus in the S.U.I.T. Lab (Figure 4, April 2017) working directly with Final Frontier Design [Kobrick, 2017]. Elbow restriction of the FFD pressure suit were observed in the S.U.I.T. Lab. FFD President Ted Southern recognized the importance of the elbow joint in particular for IVA ROM and wanted to quantify the performance of the FFD suit in a well-documented and repeatable way by a third party, which opened the opportunity for motion capture testing in November 2017 (Figure 1). This feedback indicated that there was a need for spacesuit video capture analysis acting as the first step in understanding a spacesuit's mobility before moving on to more advanced methods of 3D motion capture. A structured protocol would be required to ensure consistency across testing multiple spacesuit designs and match biomechanical standards used across multiple industries.

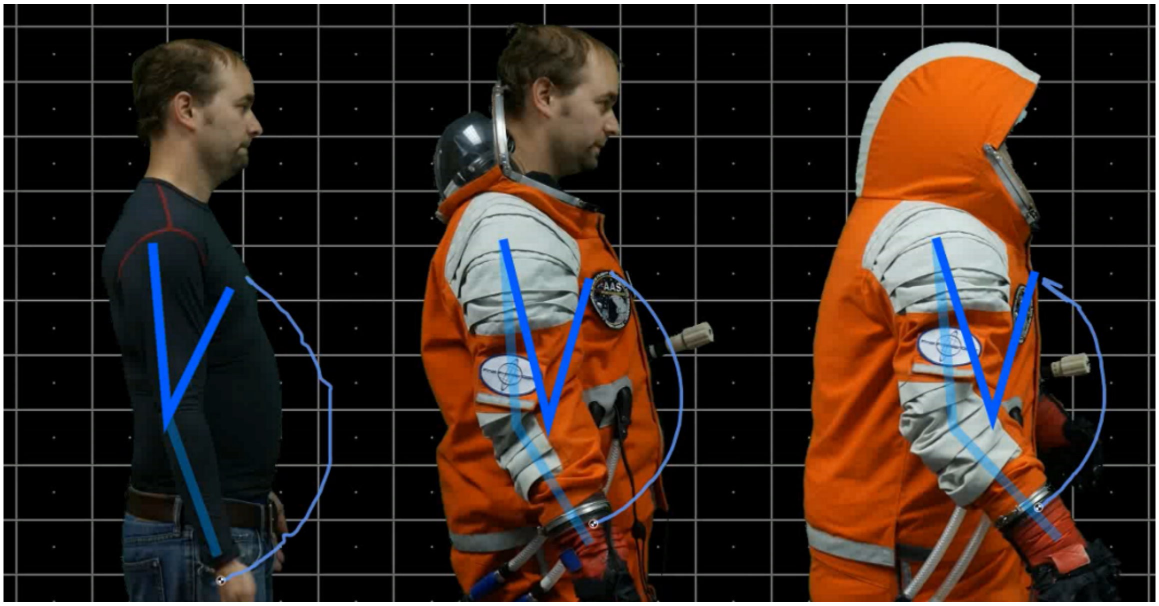

Figure 4: L to R: unsuited; suited and unpressurized; and suited and pressurized to 3.5 psid. Elbow flexion and extension angles were measured using video capture. Task B3 from Table 2. Light blue angle indicates initial angle, dark blue indicates final angle, blue arc represents path tracked.

B. A. Pilot Run with HI-SEAS

Based on the identified NASA EVA research gaps, the ERAU S.U.I.T. Lab developed multiple operational-based studies to be investigated at space mission simulations around the world, or analogue missions. Operational-based implies that these activities are budgeted into the crew's simulation timeline as a mission required task. For a long duration mission, spacesuits may be checked with a ROM protocol bi-weekly as a reoccurring task. The first version of the *Remote Video Capture Analysis of Spacesuits for Spaceflight Analogue Expeditions Protocol* was developed during the Spring 2017 semester at ERAU by Jazmyne Lones in association with the S.U.I.T. Lab as part of her independent study project. As shown in Table 2, the protocol included a set of motions to perform that are standard for conducting an anthropometric analysis [adapted from Lones, 2017]. These are motions that were identified as important for study, but not all were featured in this work. Procedures for conducting each motion were written along with a simple diagram of the intended activity. Each motion was to be performed three to five times in front of a camera by a crew member in the suited and unsuited conditions. Along with the procedure for recording each motion, a set of recommendations for video recording was provided to ensure that post analysis of the videos would be consistent across all motions.

Once completed, the first version of the protocol was sent to the Hawai'i Space Exploration and Analog Simulation (HI-SEAS) during the eight-month Mission V (January – September 2017) Mars simulation in coordination with one of the crewmembers, Joshua Ehrlich, an ERAU alumni. Ehrlich both recorded and performed the mobility tests in the "airlock" of the HI-SEAS habitat. Figure 5 shows overlaid screenshots from two of the videos returned by HI-SEAS for ROM Task B17, shoulder adduction and abduction, showing little interference for the partial movement. Previously established mission protocol at HI-SEAS restricted use of the simulated spacesuits in the habitat to the airlock room to prevent contamination concerns within the living quarters. Due to the variability between analogue conditions and limited space in the airlock, much of the set up for the testing was left to Ehrlich to decide. Ehrlich was successful in recording himself performing the desired activities (including B3, B11, B16, B17, and B18) in both testing conditions and provided the video files to the S.U.I.T. Lab post-mission. The motions performed were deemed most critical for evaluating upper-body ROM capabilities, while respecting personal time taken from the crewmember.

The HI-SEAS pilot run identified many of the biggest flaws in the protocol early on. It became evident that the protocol that was provided to HI-SEAS was not detailed enough and could be optimized to improve the overall quality of the test procedure and yielded results. A major factor contributing to the inadequacy of the initial results was the lack of an additional crewmember to assist in the recording of the mobility tests. The protocol did not specify the number of crewmembers required to complete the tests. Since Ehrlich followed the protocol on his own, he was responsible for both performing the motions accurately and meeting the video requirements. While the motions were performed as instructed, the video capture of the activities did not meet the expectations of the S.U.I.T. Lab. The video was captured in a vertically oriented aspect ratio. Due to the vertical orientation of the framing many of the motions were not fully captured because sections of the body would exit the frame during the activity. This would lead to complications during the data capture of the joint angles for all motions. At least one additional crewmember is needed to operate the camera and ensure the protocol is being followed correctly. Emphasis on writing more detailed procedures and video requirements would become the main objective for revising the protocol moving forward.

Table 2: Anthropometric motions prescribed to analogue locations.

ID	TASK TITLE
B1	Ankle Inversion/Eversion
B2	Ankle Plantar/Dorsal Flexion
B3	Elbow Flexion/Extension
B4	Elbow Supination/Pronation
B5	Hip Flexion/Backward Extension
B6	Hip Adduction/Abduction
B7	Knee Flexion/Extension
B8	Knee Internal Rotation
B9	Leg Adduction/Abduction
B10	Leg Medial/Lateral Rotation
B11	Lumbar Spine Flexion/Extension
B12	Lumbar Spine Lateral Flexion
B13	Neck Flexion/Extension
B14	Neck Lateral Flexion
B15	Neck Rotation
B16	Shoulder Flexion/Extension
B17	Shoulder Adduction/Abduction
B18	Shoulder Circumduction
B19	Shoulder Horizontal Flexion/Ext.
B20	Thumb MP Joint Flexion
B21	Thumb IP Joint Flexion
B22	Wrist Flexion/Extension
B23	Wrist Radial/Ulnar Deviation
B24	Walking/Gait

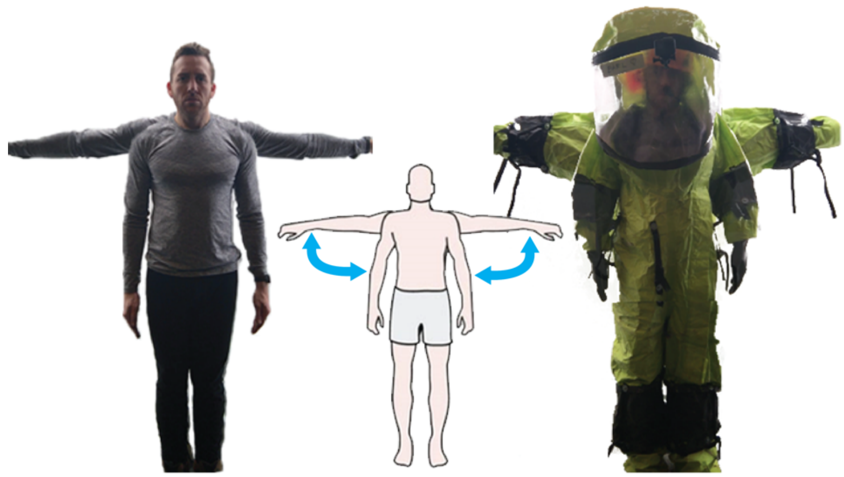

Figure 5: 2017 HI-SEAS crewmember unsuited and suited conducting remote video capture ROM Task B17 with ERAU instructional images.

C. Final Frontier Design IVA Pressure Suit Range of Motion Testing

NASA's Human Integration Design Handbook [NASA, 2014] highlights spaceflight human system standards and has guided the lab's studies. Similar work was conducted at ERAU for the spacesuits used in multiple Project PoSSUM campaigns [Llanos, 2017] and again in the 2017 November FFD test. Understanding the limitations of astronaut's ROM is imperative and directly related to the success or failure of spaceflight missions, in particular emergency ingress or egress scenarios, cockpit layouts, and interfaces for suits. The execution of the FFD test design was composed of movements that adequately expressed the natural uses of an IVA spacesuit within an in-cabin work envelope. After data analysis, this test will help improve the future of human spaceflight for FFD by identifying potential injury points, evaluating mobility changes such as loss of reach capability, defining cockpit layouts, and finding unique human-technology interactions otherwise unseen by traditional two-dimensional video capture. S.U.I.T. Lab protocols for these tests are continuously being updated and improved with each testing opportunity.

1. Protocol Development

Before submitting the protocol to another analogue mission, the S.U.I.T. Lab was able to perform an in-house ROM test using a newly developed Final Frontier Design (FFD) pressure suit prepared for the NASA Flight Opportunities Program (FOP) in November 2017. FFD conducted a parabolic flight campaign in Florida for NASA FOP and was able to visit campus in November 2017, spending the entire day with the S.U.I.T. Lab in a full ERAU Institutional Review Board (IRB) approved study testing three subject's ROM and basic workload physiology (heart rate, respiration, skin temperature, plus more) described further below. This test used an IVA pressure suit throughout the mobility testing, therefore the subjects were seated as they would be in the scenarios for launch or entry. The testing utilized both video capture and was the pilot test of the motion capture hardware in the S.U.I.T. Lab. The motions performed were primarily focused on arm mobility since the suit being tested was for IVA, as seen in Figure

6. The S.U.I.T. Lab technicians were able to test the mobility analysis protocol with three participants of similar physical size (height, weight, girth, and foot size). Delegating tasks to different people allowed for a smoother completion of the procedure. The roles assumed were the subject, the camera and motion capture operator, and test facilitator who instructed the motions via a communication headset link. The subject would only focus on the motion of their body in the suited and unsuited conditions while adhering to the spoken instruction of the test facilitator. The camera operator ensured that the capture devices were properly logging data, for video capture this includes: proper framing, adequate lighting, high resolution, and start/stop times. The test facilitator dictated the protocol while ensuring the camera operator and the subject were meeting the requirements of the protocol to meet the safety and test standards.

Figure 6: ERAU S.U.I.T Lab ROM Task B17 test with FFD's NASA Flight Opportunities Program spacesuit. Left: video capture shoulder angles in three test conditions. Right: OptiTrack 3D data of B17 suited motion.

Multiple participants during the execution of the protocol greatly improved the efficiency of the testing and quality of the results. At least two crewmembers are required to complete the protocol effectively, as the test facilitator and camera operator roles could be combined if there is a shortage of available crew. While the testing was a success, executing the protocol still exposed some operational ambiguities. The procedure for performing each motion along with their respective diagrams were causing confusion in the proper execution of the intended motion. For example, the procedure did not specify the length of pauses between the repetitions of the motions nor did it emphasize the importance of certain keywords that ensure a clear understanding of the motion. Revisions to the procedure for each motion required a full rework of phrasing and bolding of keywords and numbers.

2. Motion Capture

Motive, an optical motion capture software developed by OptiTrack, was used to record and gather 3D data for all mobility tests in the S.U.I.T. Lab. A motion capture specialist controlled the OptiTrack cameras and software, while monitoring the quality of the tracked markers throughout the testing. General test operations were all under the guidance of the team's Principal Investigator, Dr. Ryan Kobrick, and FFD President Ted Southern. This upheld the experimental safety standards of the IRB while ensuring productive test execution. The team utilized four Flex 3 cameras stationed around the lab to create a 3D capture volume in which the test subject performed the motions. In each trial performed by the three test subjects, tracking markers were placed on major joints of the body for the Flex 3 cameras to track using infrared light emitted from each camera. The markers were placed on a Velcro vest for unsuited motions and directly on the FFD suit during suited motions. The placement of the marker set was guided by the OptiTrack website and previous research on the accuracy of low cost motion capture systems [Carse, 2013]. The Motive application has the ability to record each test (as seen in Figure 6), label the markers for identification, smooth the recordings, and export X, Y, and Z, coordinate data for use in external software where 3D trigonometric analysis methods are applied.

3. *S.U.I.T. Lab FFD Test Day*

The three test subjects (one shown in Figure 7 in the pressurized FFD suit) completed the following seated ROM movements under direction from the S.U.I.T. Lab technician's operational checklist: motions from Table 1 including B3, B12, B16, B17, and B18; and recommended arm motions from NASA JSC [electronic mail communications with lab] including "Full Arm Vertical Oscillations", "Full Arm Horizontal Oscillations", and "Full Scope Arm Carve Out", which could only be analyzed using motion capture. The last three examined the entire arm reach volume, essentially painting a cloud of data points in the work envelope. These motions were selected to remain consistent with previous tests and to make sure that all three test subjects could be evaluated in the one-day test window provided by FFD. The FFD November test included the following projects involving Spaceflight Operations (College of Aviation) and Aerospace Physiology (College of Arts and Sciences) students working and volunteering in the S.U.I.T. Lab, and their work is helping set a baseline for future IVA tests within the lab. Physiology results were insightful to workload and effort and will be covered in future publications (including Kobrick, 2018).

- Motion capture: four-camera OptiTrack [OptiTrack, 2018] data acquisition system, although additional cameras are recommended to prevent marker occlusions caused by the inability to capture certain motion angles. More cameras will be purchased.
- Videography: Position mounted cameras in locations that provide framing which is parallel to the plane of motion in which the movements occur. This allows for video capture for comparative analysis.
- Thermal scan: skin temperature measurement for muscle movement. This provides an estimate of kilocalories or the metabolic activity expended.
- Oximetry: allows the determination of oxygen saturation on the hemoglobin in the capillary bed as well as the heart rate in beats per minute. The reading of heart rate in beats per minute (BPM), and oxygen (O_2) saturation indicating level of effort.
- Zephyr bioharness: heart rate, heart rate variability, respiration, 3-axis accelerometer. Used to calculate subject's workload and highlight moments of physical stress.
- NASA-TLX: NASA Task Load Index [Hart, 1986] is the most common measure of subjective workload reported in the literature. Perceived workload is divided into six sub scales: Mental, physical and temporal demands, performance, effort and frustration.
- Outreach: GoPro time elapsed for additional views. Videos helped show examples to remote study locations. Photos posted to social media with permission.

Figure 7: Spaceflight Operations ERAU undergraduate student participating as a test subject in S.U.I.T. Lab ROM test with FFD's NASA FOP spacesuit.

D. Updated Protocol for MDRS and AMADEE-18

In preparation for the Mars Desert Research Station (MDRS) Crew 188 and AMADEE-18 analogue missions in February 2018, the S.U.I.T. Lab developed an updated version of the *Remote Video Capture Analysis of Spacesuits for Spaceflight Analogue Expeditions Protocol*. The Principal Investigator of the S.U.I.T. Lab, Dr. Ryan L. Kobrick, was the mission commander of MDRS Crew 188. Though he was present for the recording of the mobility testing, he did not participate in the execution of the procedures to keep the operation unbiased (as seen in Figure 8). Kobrick observed operations and noted the interpretation of the protocol by the crew. Version 4 was sent to MDRS and results along with feedback from the crew were sent back before the start of AMADEE-18. This allowed for a slightly revised version 5 to be developed in time for the AMADEE mission.

Version 5 included six main sections: List of Suggested Items, Framing Requirements, Recording Requirements, Range of Motion Instructions, Steps for Recording, and Data Logging. The list of suggested items mainly included things that were essential to the functionality of the test, such as: main camera, tripods, a scale item, blocking tape, and a monochromatic backdrop. The framing and recording requirements were split into two separate sections unlike previous versions of the protocol. This was to emphasize the importance of each separately. Proper framing is one of the most essential elements to a successful test. Occlusion of the test subject or errors in the alignment of the camera can lead to inconsistent or irrelevant videos. Recording the video properly factors into the post analysis phase of the experiment that does not currently occur in the field. High resolutions and adequate camera settings are key to a detailed analysis of the simulated spacesuit performance. The analyst must be able to identify the points of rotation on the subject as well as features of the spacesuit that may be hindering performance. The Range of Motion Instructions section of the protocol was redesigned to provide a detailed description for the steps of each motion while emphasizing key steps and numbers. This was suggested by Crew 188 of MDRS after performing their tests. The Steps for Recording section reiterates the key factors of the previous sections in a single procedure for conducting the entire test from preparing the materials, through recording the motions for each condition, and ending with file saving and sending. The steps include descriptive reminders for meeting the test requirements and implements recursive steps to ensure the crews are constantly reminded of the test requirements for each video they record. Finally, a Data Logging section was implemented in version 5 after the MDRS crew suggested a section of the protocol used for making suggestions. Along with a box for suggestions, a table of metrics recorded throughout the test was added and was intended to be used by the crew to keep information organized and ensure they were capturing all the requested data. The table included: Names of Crew, Simulated Suit Description, Camera Description, Location Description, Lighting Conditions, Height of Camera, Distance to Subject, and Size of Scale Item.

Figure 8: MDRS Crew 188 test subject carrying out ROM Task B11 in SUIT 1. SUIT 2 PLSS is seen on left shelf.

Both MDRS and AMADEE provided good data, and supportive feedback to improve the efficiency and fidelity of the protocol. Future versions of the protocol will benefit from their contributions and the S.U.I.T. Lab will continue to provide updates to these analogues as the project develops.

IV. Results

A. Analogue Mission Video Capture ROM

Angles measured from the videos collected are computed using a digital protractor in the free to use program Kinovea [Kinovea, 2018]. The protractor tool is accurate to 1 degree. Angles were recorded for the motions B3, B11, B16, and B17 from Table 2 for all analogues with the exception of HI-SEAS (Only motions B3 and B16 provided useable data, lessons learned were applied to the revised versions of the protocol). ROM data was recorded for the suited and unsuited conditions with a different subject at each analogue, only one subject participated per analogue. MDRS Crew 188 provided tests for two suit variants, yielding an extra set of data. Motions B11 and B16 are divided into flexion and extension angles. After review of the videos it was determined that motions B3 and B17 do not induce extension and abduction respectively. This is because the procedure only has the subject move their arm in the counterclockwise direction from the neutral position. Extending the motion in the clockwise direction from the neutral position would account for both types of motion. For this reason, B3 and B17 only demonstrate elbow flexion and shoulder adduction respectively. In future versions of the procedure this issue will be addressed, and all motions should yield a pair of angles. Table 3 below displays the angular data collected from each analogue for the unsuited and suited conditions for all motions tested along with the percentage of angular ROM retained (% Ret) by each suit for each motion. The suits measured at the analogue locations are shown in Figure 9, the angles shown are averages of the 3 repetitions performed for each motion. For these preliminary studies, the suits are worn by different subjects. Future studies could track the same participant(s) through a series of different analogues and simulated spacesuits. This percentage is calculated by dividing the ROM achieved while suited by the ROM achieved while unsuited.

Table 3: Summary of ROM data collected during analogue missions

	HI-SEAS Mission V			MDRS Crew 188					AMADEE-18		
Motion #	**No suit (°)**	**Suit (°)**	**% Ret.**	**No suit (°)**	**SUIT 1 (°)**	**% Ret.**	**SUIT 2 (°)**	**% Ret.**	**No suit (°)**	**SUIT (°)**	**% Ret.**
B3 Elbow F/E	141	125	**89**	138	145	**105**	135	**98**	148	110	**74**
B11 Lumbar Spine F/E	---	---	**---**	137	122	**89**	114	**83**	126	83	**66**
	---	---	**---**	55	45	**82**	34	**62**	23	20	**87**
B16 Shoulder F/E	175	174	**99**	176	157	**89**	143	**81**	172	102	**59**
	65	66	**102**	75	40	**53**	39	**52**	58	37	**64**
B17 Shoulder A/A	81*	68*	**84***	176	138	**78**	133	**76**	176	61	**35**

*HI-SEAS B17 motion was later modified for follow-on simulations

Figure 9: From Left to Right: HI-SEAS HAZMAT suit [Wilson, 2015]; MDRS one-piece exo-suits (SUIT 2) [photo courtesy of Renee Garifi]; and AMADEE-18 Aouda.X suit [ÖWF, 2018].

What becomes immediately apparent by looking at these results are the differences in ROM restrictions between each simulated spacesuit. These differences stem from the construction and fit of the simulated spacesuits. The HI-SEAS suit that was tested during Mission V is a modified HAZMAT suit and fits extremely loose around the wearer. The loose fit causes problems for the video capture method, it can lead to uncertainty in the location of the joints on the body, making the analysts job more difficult. The baggy suit easily warps to adjust to the wearers movement, thus demonstrating high percentage retention for ROM. The HI-SEAS simulated spacesuit retained about 89% of the user's original mobility for motion B3 and about 100% for motion B16. MDRS simulated spacesuits also retain a relatively high percentage of unsuited mobility for all motions. The MDRS suits are traditional flight jumpsuits combined with a simulated PLSS backpack attached to the bulbous helmet. The restrictions in ROM for the MDRS suits stem from the tight fit of the flight suits, and the bulk of the PLSS on the back. Motion B3 indicated higher mobility when suited in SUIT 1 making it an outlier among the other suits which maintained the trend of restricting mobility. This may indicate that the subject did not reach their maximum ROM during the unsuited recordings and that the MDRS flight suits may not be very restrictive at all. In future versions of the protocol further emphasis on moving to the subject's maximum ability while maintaining the correct posture will be needed to reduce the possibility for inconsistency in future data. While both suits tested by Crew 188 at MDRS showed similar ROM, SUIT 2 was slightly more restrictive due to the increased size and elongated shape of the PLSS. Additionally, the subject testing suit mobility for MDRS proved to be more flexible than other subjects tested across all three analogue missions. The physiological differences between the crew members testing the suits must also factor into the direct comparison of simulated spacesuits from a variety of analogue missions. The differences in flexibility, arm length, and muscle mass are just some of the physiological aspects that may vary across the subjects, causing inconsistencies. Testing different suits with the same subject would be the most accurate representation of the limitations that these suits impose on ROM.

The most restrictive and perhaps most interesting simulated spacesuit was that of AMADEE-18. The Aouda.X suit is designed to create the most accurate terrestrial EVA experience for analogue astronauts on Earth. Simulated spacesuit designs typically operate without pressurization to reduce the cost of the suit and increase the safety of the analogue astronauts. However, pressurization is one of the key elements of a functional spacesuit, and is a contributor to the limitations in ROM for astronauts along with the structure of the suit. To simulate pressurization the Aouda.X suit utilizes an inner exoskeleton composed of springs and elastic bands to provide resistance to the user's movement (see Figure 10 for internal view). The exoskeleton attempts to simulate ROM limitations astronauts experience when operating the Extravehicular Mobility Unit (EMU) that is currently used on the International Space Station (ISS) when astronauts go outside the station on EVA [Groemer, 2012]. While the exoskeleton is the main source of ROM limitations, the many additional layers above the exoskeleton combined with the weight of the PLSS and chest pack create additional limitations in the movement of the user. Across all four motions tested the Aouda.X is about 20% more restrictive than the second MDRS suit that was tested. Motion B17 showed the most significant drop in mobility, the ROM for the adduction of the shoulders dropped from 176 degrees unsuited to 61 degrees suited. Here the exoskeleton is clearly performing its function, only 35% of the subject's unsuited ROM is retained, as they can barely reach above their head.

Figure 10: Internal view of the Aouda.X suit at AMADEE-18 showing the shoulder joint of the exoskeleton [ÖWF, 2016].

Figure 11: Unsuited and suited visual difference between neutral position for shoulder adduction B17 test for the AMADEE-18 Aouda.X suit.

The B17 motion also revealed a noteworthy characteristic of the Aouda.X exoskeleton. The neutral position of the arm when suited does not lie at the side of the body as it does when unsuited. Rather, the arms are suspended 24 degrees away from vertical and do not make contact with the sides of the body (see Figure 11). The drastic reduction in mobility for B17 when compared to the other motions is likely due to the shift in the neutral position of the arms. When performing the motion suited the arms are at a new neutral that is already 24 degrees extended from the unsuited neutral position, this significantly reduces the angle between the maximum adduction of the shoulder and the neutral position. The authors were unaware that this may occur and the protocol was constructed to measure from wherever the natural neutral point of the suit lied. While this is a trait quantitatively observed with the FFD FOP suit, and qualitatively with the EMU and Apollo A7-L spacesuits, it may signify an issue in spacesuit design overall. The S.U.I.T. Lab will continue to investigate these neutral points and determine the proper way to accommodate them in future results. On planetary EVAs, an astronaut should have the fullest mobility possible in the shoulders. During training here on Earth, shoulder injuries are still commonplace from use of the current NASA EMU [Anderson, 2014]. While the extended neutral position aids in comfort when performing tasks directly in front of an astronaut, when reaching for components on the body of the suit, such as suit controls, an astronaut may struggle to hold the position required to complete the task. Extended reach above the head should be targeted by suit designers as well. Astronauts will someday need to be able scale vertical ladders or rock walls in the future of planetary exploration. From a suit designer's perspective, reaching above the head or having the arms closer to natural neutral hanging arm position are conflicting goals. The human shoulder is an incredibly complex joint with multiple points of rotation. For example, to reach above the shoulder level, we use our clavicle and rotate at the sternum. Designing these motions into a traditional pressure garment is not simple but needs further attention.

In summary, the numerical results of these preliminary tests will aid in future versions of the test protocol and provide the participating analogue missions with relevant feedback about the design and function of their simulated spacesuits. The goal of this initiative is to increase the fidelity of analogue EVA operations by guiding the design of simulated spacesuit's ROM to match actual prototypes, or previous Apollo suits as a baseline. The experiential results of these tests have provided the students at the S.U.I.T Lab with an understanding of crewed operations in the field and operational protocol design. The lab aims to continually refine their methods in order to develop a standardized protocol for the video analysis of simulated spacesuits in remote locations that can be applied to analogue missions on Earth or planetary missions to the Moon or Mars.

B. FFD Range of Motion Data Interpretation

The full November 2017 test with FFD included three test subjects who had similar height, weight, girth, and foot size measurements within specification of the FFD maximum allowable dimensions for a size medium spacesuit. ROM Task B17 is shown in Figure 6 with a screenshot of the data in motion on OptiTrack's Motive software. Figure 6 illustrates the angle differences in each of the three testing conditions from a basic video capture measurement technique conducted by Nicholas Lopac, Lead Technician of the S.U.I.T. Lab. Unsuited, the test subject had full range of shoulder motion showing 160 degrees between the fingertip marker and resting position; the Velcro suit fits close to the body keeping the tracked markers consistent in position with respect to the actual movement. Immediate movement restriction was observed during the suited unpressurized test, with maximum movement at 91 degrees from resting position. The maximum angle measured while pressurized for the B17 task was 90°, only a slight 1° difference from the unpressurized condition. These measurements were taken using the video capture method previously discussed to measure the angle between the maximum and minimum positions of the arms across the targeted joints. Comparatively, the data captured in a 3D volume by a motion capture camera system can be used to track points on the subject with a much higher degree of accuracy and illustrate the volumetric properties of the subject's work envelope [Abercromby, 2006].

Due to the S.U.I.T. Lab having only four cameras in their motion capture system, inconsistencies in tracked points were prominent for certain markers during the FFD November test. OptiTrack recommends the use of eight cameras for this application with a minimum of six (per technical support communications). Mainly markers placed on the fingers and outer arms encountered tracking errors due to occlusion from the cameras during the movement of the subject. Loss of tracking does not allow for a continuously marked point in the Motive recording software, thus a method for patching lost data was needed to continue with a numerical analysis of the recorded motions.

The motion capture recordings were perforated by breaks (as seen in Figure 12) in the tracking data. These were caused by the movements of the test subject and the limitations of the capture volume. If less than two cameras can see a particular marker, the connection is lost and a gap forms in the tracking trajectories for the marker. If the marker is blocked for long enough, the tracking data will be fragmented and will require extra editing to fix. Fixing these gaps is critical for determining the usability of the data. The fragments of data for a marker are grouped under the same label to connect the data and to determine the gap size and location. Motive is equipped with data editing tools, including a system that fills trajectory gaps. The software provides estimates for the missing data and uses them to fill the spaces. This method works well for smaller gap sizes. However, the larger the trajectory gap, the more inaccurate the replacement data becomes. For some markers, the information was too fragmented and was deemed un-usable. A prime example was the markers attached to the fingertips of the subjects. As the subjects performed sweeping motions up and down with arms outstretched, the fingertip points would be lost as they passed outside the capture volume of the cameras. This was a result of the limitations of the available space and the number of cameras. The solution was to utilize the wrist markers as the outermost points for tracing out sweeping and flexing movements to calculate joint angles.

To repair the fragmented data, the frames on either side of the break are highlighted and then filled using one of the several estimates that the Motive OptiTrack software provides. Once the gaps are effectively patched, an editing tool is used to smooth out the trajectories graphs. This is to clean up the data even more and to fix wobbling markers. After the necessary markers were labeled and smoothened to patch inconsistencies in the recordings, a numerical analysis of the data was able to begin.

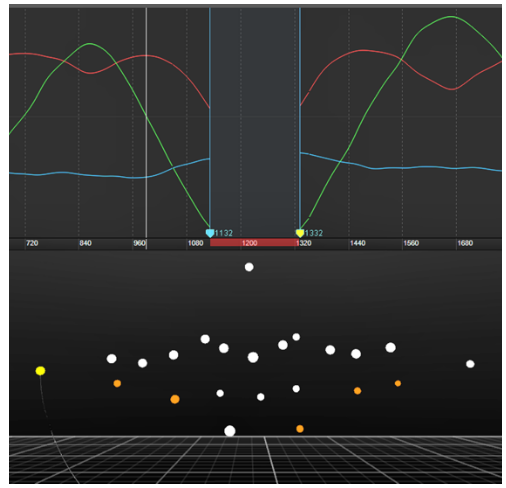

Figure 12: Trajectory gap in data due to limited capture volume in lab from the right hand marker, highlighted in yellow [screenshot: OptiTrack Motive software].

The S.U.I.T. Lab recruited a number of ERAU Aerospace Engineering (College of Engineering) undergraduate students at ERAU to assist in extracting spacesuit ROM angle information of the unsuited, suited unpressurized, and suited pressurized conditions. Engineering students at ERAU are introduced to MATLAB as it is the college's preferred coding language for scientific analysis. Thus the lab would aim to develop analytical code in MATLAB to digest the 3D data exported by Motive and return ROM joint angles akin to those provided by the video capture method. While the creation of this analytical program is still in progress and not final, students were able to develop an initial program for measuring the joint angle of the subject for the shoulder adduction motion B17 of the FFD testing (as described above 160, 91, and 90 degrees). The students were provided with a single swath of data from the unsuited testing condition from subject 002. The experimental code was able to analyze the maximum and minimum locations of the arm throughout the motion and calculate the angle between those locations and the point of rotation at the shoulder joint. The MATLAB analysis yielded a preliminary joint angle of 163.95 degrees for ROM in the adduction of the shoulder during motion B17 (subject 002, unsuited condition), which was within 4 degrees of Lopac's video capture analysis. This pilot code and data will be used to further calibrate the accuracy of the program and is the first step in supporting the further development of MATLAB applications that can analyze other motions across multiple subject conditions. As the lab's method for 3D analysis of ROM develops over time a comparison between video and motion capture of spacesuit ROM will be made to determine the best use cases for each method, and their relative accuracies. The 3D motion capture ROM results will be released to FFD and included in future publications.

V. Future Plans

The S.U.I.T. Lab has put in extensive work to form insights into astronaut performance with limited ROM in order to help improve the spacesuit design process. In lieu of suit limitations, the lab is dedicated to developing operational standards and protocols for IVA and EVA that design tasks around limited mobility and cockpit layout. Sharing these insights with the industry and other researchers is the continued goal of this work. Using video capture and 3D motion capture of ROM angles, the team has demonstrated the ability to extract pilot spacesuit mobility data through the development of thorough experimental protocols. The lab will continue to verify ROM measurement methods to the methods and historical data from NASA as it works towards conducting a comparison of video versus motion capture techniques. The next step for the S.U.I.T. Lab is upgrading equipment and executing off-site experiments with the portable equipment in the lab. Recording 3D ROM videos with, at minimum, two more Flex 3 cameras (6 total), will reduce the amount of marker occlusions and inconsistencies by covering more of the capture volume with available tracking zones. The lab received funding to purchase four more cameras from ERAU, which will lead to faster and more accurate data analysis. Condensing the lab equipment allows the S.U.I.T. Lab team to travel to industry partners, creating more testing opportunities and catalyzes the overall productiveness of companies involved in the development and manufacturing division of the human spaceflight industry. The S.U.I.T. Lab will further compare the accuracy of video capture to motion capture to understand the strengths and weaknesses of each in different spaceflight operations. It is the desire of the S.U.I.T. Lab to perform new tests with a variety of spacesuits, both simulated at analogue missions, and functional with industry partners.

VI. Conclusion

This work builds on the history of spacesuit development and benchmarking and applies decades of research to spacesuit mobility and human performance. An operational protocol for spacesuit performance analysis that can be followed independently would be essential for long duration planetary missions so that a crew can diagnose problems in real time or capture key motion data to send back to Earth. When terrestrial operations increase in complexity and scope crews may not have the time to work with a support team on Earth to diagnose problems with EVA spacesuits. Allowing a crew to function autonomously can lead to efficiencies in the crew schedule, especially when communications to Mars can be delayed by 20 minutes or more. With advancements in video capture technology and artificial intelligence, the ROM analysis could be processed in real time and provide instant feedback to the crew regarding the performance of the suit. The importance of writing detailed and comprehensive operational protocol comes down to the overall safety and success of a crew during a mission. If procedures are to be followed without the aid of a technician or mission controller, they must be tested to be infallible. Students in the Spaceflight Operations Program at ERAU that support the S.U.I.T. Lab in the creation of this protocol are able to observe the effects of their own work using some of the highest fidelity analogue spaceflight missions on Earth and spaceflight ready hardware in the lab. A cause and effect model for experiential learning will improve the student's abilities to think critically and write detailed procedures for human spaceflight operations. Continued involvement with more operations, engineering, and physiology students exposes the lab to a wider range of skills and experience that can benefit both the ERAU and human spaceflight communities. The S.U.I.T. Lab is open to collaboration with investigators around the planet and the sharing of our *Remote Video Capture Analysis of Spacesuits for Spaceflight Analogue Expeditions Protocol*. The S.U.I.T. Lab continues to support spaceflight research by partnering with industry leaders and innovators, such as Final Frontier Design, while providing students a truly "gloves-on" experience.

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