Measuring xEMU Loads Through Shoulder Straps

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For years, subjects completing planetary suit testing have made qualitative comments that the pressure garment system (PGS) they are using will partially offload itself while pressurized. This is due to the Lower Torso Assembly (LTA) acting as a pressure column or spring that partially offloads the suit, especially while standing. The purpose of this effort was to improve upon the shoulder force sensing system that was developed in 2017 to help the test team understand the forces imparted into the shoulders during 1-*g* testing activities. The original system consisted of a set of square brackets and a .75-inch (1.9 cm) circular force sensor (Omega Engineering LC201-100) embedded in between them. The sensors were joined with the shoulder strap and placed at the front chest and upper back areas on each shoulder and the force transducers wiring were ran out of the spacesuit through a port hole. The large force sensors created localized pressure points for many test subjects. The new system was designed to have smaller force sensors on the shoulder strap weaving at the lower back and a custom strain gage sensor located at the front torso area of the HUT to reduce subject discomforts and to be wireless to reduce the complexity of transmitting data outside of the spacesuit. By using instrumented shoulder straps and shoulder strap brackets to measure the load, several subjects were taken through a series of movements, in both pressurized and unpressurized configurations and with multiple shoulder strap settings using the Exploration Extravehicular Mobility Unit (xEMU) government reference design spacesuit. Due to the small subject sample size and a 3D anthropometric comparison between the HUT and subjects was not done, statistical analysis was not performed on the data set. The results from this testing will be used to validate the software and hardware and will provide insights to inform the community about the benefit of the pressurized volume suit design, develop a better understanding of the expected loads carried by the subject in flight planetary applications, and help to inform the shoulder strap setting impacts to 1-G testing.

Nomenclature

ARGOS = Active Response Gravity Offload System
COTS = Commercial-Off-The-Shelf
EMU = Extravehicular Mobility Unit
EVA = Extravehicular Activity
g = gravity
HUT = Hard Upper Torso
LTA = Lower Torso Assembly
NASA = National Aeronautics and Space Administration
PGS = Pressure Garment System
SCFM = standard cubic feet per minute
VTC = vertical trunk circumference

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VTD = vertical trunk diameter
xEMU = Exploration Extravehicular Mobility Unit
xPGS = Exploration Pressure Garment Subsystem

I. Introduction

AS the National Aeronautics and Space Administration's (NASA) effort to return humans to the Moon grows rapidly, measures are being taken here on Earth to ensure the safety, preparedness, and understanding of the systems that will be used to conduct future lunar surface exploration. One of these measures include pressurized testing of Extravehicular Activity (EVA) spacesuits in ambient environments. Pressurized testing of EVA spacesuits provides a critical understanding of suit dynamics and mobility which play a vital role in training astronauts for EVAs. Therefore, it is important to develop a quantitative understanding of the subject-suit interaction.

One suit actively being used for testing is the Exploration Extravehicular Mobility Unit (xEMU) government reference design spacesuit. In a 1-*g* environment, the xEMU pressure garment, the Exploration Pressure Garment Subsystem (xPGS) can weigh approximately 180 lbs (82 kg) depending on the configuration and sizing. However, for the subject, the weight of the suit can feel dramatically lower due to the positive pressure differential internal to the suit. When pressurized, the Lower Torso Assembly (LTA) acts as a pressure column partially offloading the weight of the suit. Characterizing the amount of load being transferred to the person via their shoulder straps requires additional instrumentation.

A team of engineers at NASA Johnson Space Center designed a pilot study to evaluate suited loads during pressurized testing in the xPGS assembly. The xPGS suit architecture contains a pair of shoulder straps inside the Hard Upper Torso (HUT) which serve as the primary point of load transfer between the suit and the subject. After modifying the shoulder straps with integrated load cells, data was collected and analyzed to understand the loads experienced through static and dynamic tasks. The test series evaluated several subjects through a wide anthropometric range as they completed typical motions in an unpressurized and pressurized configuration. The goal of this study was to validate the software and hardware created to take these measurements, and help the team develop a better understanding of the expected loads carried by the subject in flight planetary applications.

It is important to note a similar test was conducted in 2017 in a collaboration between MIT and the NASA Space Technology Research Fellowships to analyze the interaction between humans and machines. The data from this test can be found in "Evaluation of the Mark III Spacesuit an Experimental and Computational Modeling Approach", Conor Cullinane's doctoral dissertation.[1] The Human-Suit Indexing and Load Decomposition Evaluation test series evaluated the force required to execute motions in the Mark III suit in addition to the difference in load transferred to the human operator compared to load transferred directly to the ground. The 2017 test series utilized pressure sensor arrays in the hips and feet, Inertial Measurement Units, and a force plate in addition to load cells integrated into the shoulder straps.[2] They used four subjects of similar anthropometric sizing during their study. They found the average minimum and maximum load in dynamic motions (i.e., walking and squatting) was 65 lbs (289 N) and 215 lbs (956 N), respectively.[1] Minimum and maximum load in static motions (i.e., standing) was 14 lbs (62 N) and 65 lbs (289 N), respectively.[1] This initial data set showed some potential validation to the concept of the pressurized suit supporting its own weight in certain postures which kicked of the pursuit to complete a pilot study to collect a similar data set on xPGS.

II. Hardware

To gain an accurate understanding of the loads experienced by the subject and the offloading effects of a pressurized suit, additional hardware needed to be designed. The instrumentation required force sensors, which were integrated into the shoulder straps of the suit, and a wireless system to transmit data to a location external to the suit. To complete this, a combination of commercial-off-the-shelf (COTS) and custom components were used.

A. xPGS Spacesuit Subassembly

As the pressure garment subsystem of the xEMU, the xPGS provides the necessary functions and interfaces to conduct pressurized human-in-the-loop operations when combined with a suitable gas supply system, a cooling water supply system, and a suitable communication system. The necessary supplies are provided and regulated via an umbilical attached to the hatch. Ancillary equipment includes a Liquid Cooling and Ventilation Garment to maintain subject temperature in addition to comfort gloves, undergarments, and a Valsalva device. The Integrated Communication System consists of a set of speakers and microphones inside the HUT to eliminate the need of a communication cap while ensuring adequate communication between the subject and test engineers.

The xPGS is a rear-entry planetary suit that uses a breach-lock-style disconnect at the hatch accompanied with hinges to allow the hatch to swing open and closed. The latch is located at the front of the HUT for accessibility and ease of operation. Additionally, the suit utilizes a combination of hard components such as the HUT and Brief assembly as well as soft goods components such as the hips. As shown in Figure 1, the suit assembly is complete with Extravehicular Mobility Unit (EMU) arms, legs, and Phase VI gloves. Nominal operating pressure for the xPGS is 4.3 psid (29.6 kPa) and was the operating pressure differential used in this test for the pressurized configuration. Lastly, an Environmental Protection Garment (EPG) provides thermal protection and protects suit hardware from dust and other environmental hazards. A full description of the hardware can be found in the paper by Shane McFarland, et. al. “NASA Advanced Spacesuit Pressure Garment System Status and Development Priorities 2023”.[3]

1. *Shoulder Straps*

The shoulder straps inside the HUT serve multiple purposes. Firstly, they serve to properly index the subject’s head and shoulders inside the suit’s upper torso.[4] Testing has shown to achieve optimal shoulder mobility for the rolling convolute joint, subjects should be positioned for their own shoulder to be about an inch below the scye opening. Secondly, the shoulder straps are used to uniformly distribute the weight of the suit on the subject’s upper torso, especially in a 1-*g* test in the lab. As shown in Figure 2 top, the left and right shoulder straps each have two attachment points inside the HUT: one at the front near the subject’s abdomen, and a second at the rear. The shoulder strap contains two subsections: a longer section attached to the front containing a shoulder pad draped over the length of the subject’s shoulder, and a shorter section attached to the rear. A buckle is used to join the two strap lengths together at the mid back location of the subject as seen in Figure 2 bottom. The shoulder strap setting is determined during a subject’s fit check, where the length is set

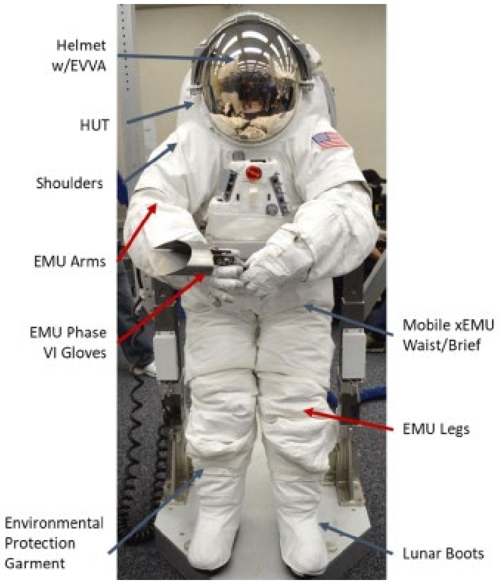

Figure 1: xPGS Suit Subsystem
Reprinted Shane McFarland, et. al. “NASA Advanced Spacesuit Pressure Garment System Status and Development Priorities 2022”[1]

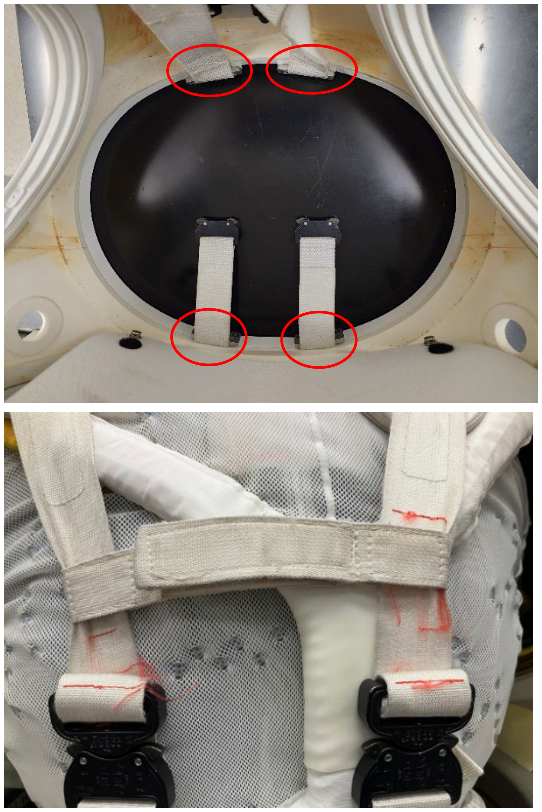

Figure 2: Interior view of the HUT from the top showcasing shoulder strap attachment points (top), shoulder strap sizing (bottom).

by the position of the top buckle which can move along the strap. The settings are denoted in 1-inch (2.54 cm) increments with red thread. Starting at 1-inch (2.54 cm), the setting becomes tighter with a higher setting number. If the buckle is set between red marks, it is assumed to be a half inch longer. For example, if the buckle is between the 3-inch (7.62 cm) and 4-inch (10.16 cm) setting, the setting would be recorded as 3.5-inch (8.89 cm). A list of shoulder strap settings used for this test can be found later in the results section of the paper. Something to note is this current shoulder strap design would not meet the self-donnable requirement.

B. Force Sensing System

The force sensing system was designed by engineers in the Anthropometry and Biomechanics Facility (ABF) at NASA Johnson Space Center. The system consisted of strain gauges placed on brackets that connect the shoulder straps to the front of the HUT and on two stainless steel tubes that go over the shoulder strap webbings at the lower back. The sensors were attached to transmitters that relayed the load data in real time to a laptop with an external access point. Based on the previously mentioned 2017 MIT study, the strain gauge locations were chosen based on those lessons learned. Having gauges in both front and back on both sides of the shoulder straps could allow for a better measurement of the total load.

1. Circular and Bracket Force Sensors

As shown in Figure 3, the circular force bracket enclosed a length of the strap webbing in between a rod and outer cylindrical cover. A force applied to the strap resulted in elongation and deformation of the external cylindrical cover. By fixing a strain gauge to a circular bracket, the resulting change in resistance of the strain gauge could be correlated to an applied force. The circular brackets were calibrated to 150 lbs (667 N) using an Instron Model 5984 load frame. The circular brackets were calibrated to 150 lbs using an Instron Model 5984 load frame. Three load cycles to 150 lbs were performed for each sensor and the sensor data from the second and third cycles were averaged and used in the sensor output voltage versus force curve fit per the laboratory standard calibrating procedures. A sample calibration plot is shown below in Figure 4. The first cycle output is higher from the 2nd and 3rd cycle due to a higher input force and strap and test fixture settling under load. Post test calibrations will have to be done if the sensor output exceeds 150 lbs (667 N) during testing. The curve fit results were programmed into the data logging software for the voltage to force conversions during testing.

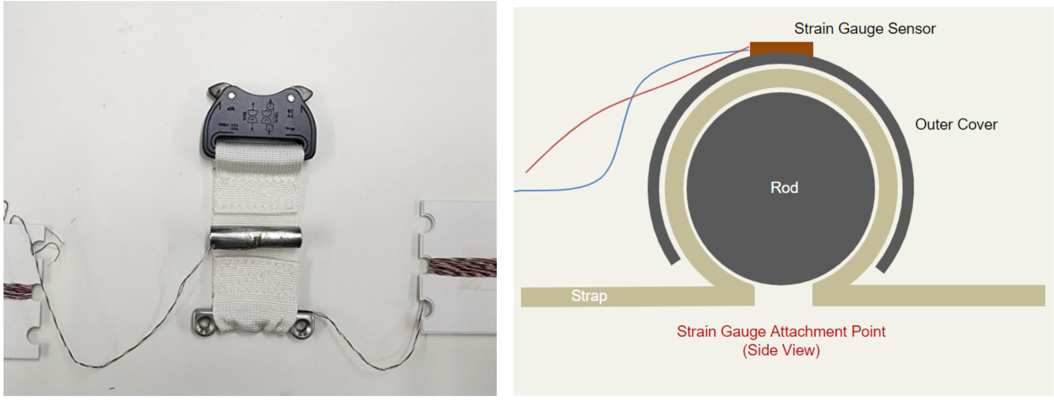

Figure 3: Shoulder strap integrated bracket force sensor and circular force sensor (left), circular force sensor side view diagram (right).

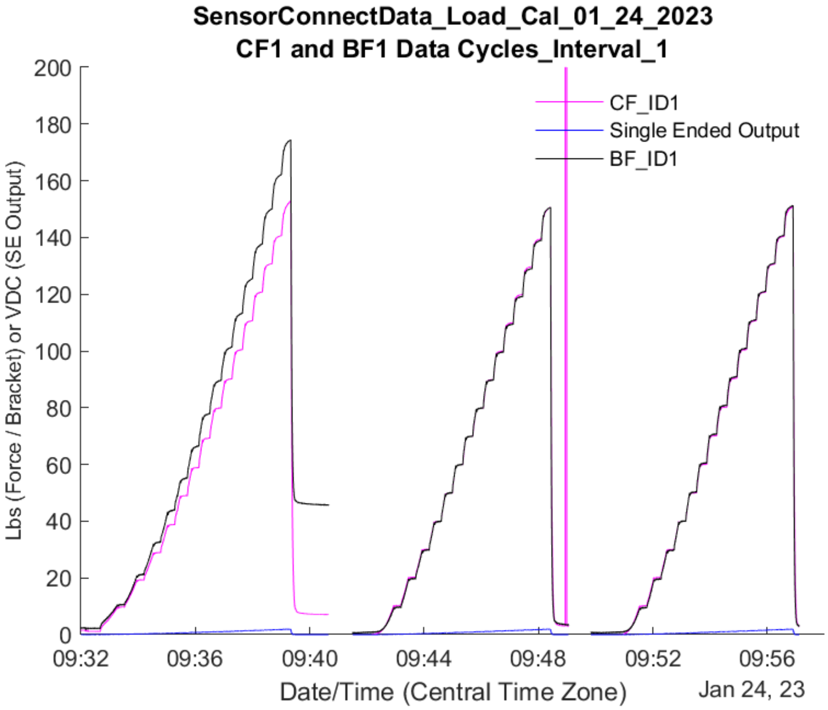

Figure 4: Sample calibration plot showing the circular force sensor (pink color), force (blue color), and bracket force sensor (black color).

Additionally, as shown in Figure 3 (left), strain gauges were placed on the top surfaces of two suit brackets that attached to the interior of the HUT. Applied forces to the straps caused these brackets to bend. The resultant changes in the strain gauge resistances were then correlated to an applied force. The procedures for calibrating and curve fitting the test data to generate the voltage to force conversions are the same as the circular force sensors above.

2. *RF Transmitter, Receiver, and Data Logging Software*

To accurately interpret data during testing, it was important to design a system capable of relaying data wirelessly in real time. A COTS radio-frequency transmitter, SG-Link-200-OEM by Microstrain, operating at a transmit power of 10 dbM was used to transmit test data outside the spacesuit. The transmitter was powered by a 3.7V rechargeable lithium ion battery. The transmitter and battery were housed in a 3D printed plastic case and mounted inside the HUT. Each of the two force sensors on the left and right shoulder straps had a corresponding transmitter and battery resulting in four total sets of batteries and transmitters. A COTS receiver, WSDA-200-USB by Microstrain, was used to coordinate the transmission of data between all four nodes and the receiver. The receiver was connected to a laptop via USB and was used to configure and setup each of the nodes.

Within the data logging software, SensorConnect, the linear correlation values between force input and strain gauge output found during calibration of the force sensors were used to convert the strain gauge millivolts outputs to forces. When testing was completed, the data was exported as a .csv file and a custom MATLAB script was run to segment and plot each task.

II. Test Plan

The objectives of the test series were to quantify the offloading effects of a pressurized planetary suit, characterize subject-suit interaction based on changes in indexing, and evaluate the differences in loads between static and dynamic tasks. A test plan was created to provide adequate data sets to draw conclusions for each of the stated objectives. Figure 5 shows a summary of the tasks performed. The shoulder straps' "well-fitted" setting was determined at the subject's previous fit check as their nominal shoulder strap setting which is approximately 1-inch below the scye opening. The "tight" and "loose" setting was approximately 1-inch from the "well-fitted" baseline. Figure 6 shows an example of the settings for one subject. Table 2 lists the shoulder strap setting for each subject.

IV. Discussion

The goal of this project was to develop and validate a small portable force sensing system that can help the test team understand the forces imparted into the body as a function of suit sizing, suit posture, and tasks. The results of the testing indicated that the system developed can meet the technical requirements. In addition, this device provides insight on how the LTA offloads some of the weight of the spacesuit when pressurized. It should be noted that the offload recorded was specific to the xEMU spacesuit design, and it would be expected that pressurized offload would change depending on the spacesuit architecture and mobility joints.

Figure :□ Percent Suit Weight Offloaded Compared to Vent Pressure

Weight offloads during the static standing stance at vent and nominal pressures are shown in Table 4 and the data shows the following trends. Subjects were carrying most of the suit weights during vent pressure and at nominal pressure with the tight strap setting while the looser strap setting resulted in the LTA supporting the most weight. The reason tighter shoulder straps result in higher load is it forces the subject to push against the straps when fully standing; therefore, resulting in more load through the shoulders. A visual representation of this load distribution can be seen in Figure 8 which displays the percent of the suit weight that is offloaded when pressurized to 4.3 psid as compared to vent pressure using the values from Table 4. Simplifying the data further, in the loose, nominal and tight shoulder strap configuration, the average percent of the suit weight that was offloaded while standing as compared to the force in the shoulders while at vent pressure was 65%, 51%, and 26%, respectively. However, the standard deviation was 16%, 12% and 20%, respectively.

To understand the load differences, subjects with the same strap settings were examined. Since the subjects were wearing the same small HUT and short Brief, one of the contributing factors is how well they fit volumetrically inside the spacesuit. Subjects 2 and 5 used the same strap settings for the testing but there were differences between them regarding their vertical trunk diameters and circumferences. The differences for the left and right vertical trunk diameters are 4.5 in (11.4 cm) and 3.9 in (10 cm) and the differences for the left and right circumferences are 8.5 in (21.6 cm) and 7.7 in (19.5 cm), respectively. Subject 2 has a tighter suit fit than subject 5 and the volumetric differences between them and the spacesuit could have contributed to the disparity in load. Looking at the nominal percent offload, they also go in the same order as vertical trunk circumference subject 2, 4, 3, 5, 1. In addition, depending on the shoulder strap configuration and the strength of the test subject, the subject could have lifted the spacesuit and put additional loads (manloads) into the spacesuit itself. A three-dimensional analysis using body scan data and CAD models of the spacesuit will have to be performed to understand the anthropometric and spacesuit parameters that can affect shoulder loads. The 3D volumetric analysis was not done for this study.

Within each task during the nominal pressure dynamic trials, the following average and peak total shoulder force trends were noticed between the different shoulder strap configurations. The data for the tasks are shown in Tables 5 through 13. For the majority of test subjects, the highest average and peak total shoulder forces were generated with the tight strap configuration and the lowest with the loose strap configuration. Subject 5 was the anomaly and did not follow the trend for the walking, squatting, standing, and kneeling tasks. Subject 5's average and peak total shoulder forces were slightly higher with the loose strap configuration. The average total shoulder force was within 3 lbs (13.3 N) and the peak total shoulder force was between 6 lbs (26.6 N) – 16 lbs (71.1 N) for the nominal and loose strap configurations. It is theorized the nominal shoulder strap setting may have slipped during their testing for subject 5 to cause this anomaly in the data. It has been noted during other tests that the shoulder straps can slip around 0.5-inches. Since the difference between nominal and loose for subject 5 was only 0.5-inch versus a full inch for other subjects, there is a higher chance this error occurred. Subjects 2 and 5 could not achieve the full 1-inch for the loose configuration so their data might be affected.

Another trend seen was the highest average total shoulder forces ranked by tasks in descending order are shrugging, walking, standing, squatting, and kneeling. The highest average total shoulder force was 261 lbs during the shrugging task and the lowest was 134 lbs during the kneeling task. The highest and lowest average total shoulder forces were done by subject 2. The highest peak total shoulder forces ranked by task in descending order are shrugging, squatting, walking, kneeling, and standing. The highest peak shoulder force value was 447 lbs during the shrugging task and the lowest peak shoulder force value was 198 lbs by during the standing task. The highest and lowest peaks total shoulder forces were done by subject 2. It is not surprising that subject 2 had the highest average and peak total shoulder force values. The subject fit snugly inside the small HUT and brief and with a tight shoulder strap configuration, the subject could be carrying more of the suit weight and having higher imparted shoulder loads during the dynamic tasks. In addition, shrugging was expected to generate higher peak forces due to the suit being a static length and subject's capability to impart additional tensile load into the shoulder straps.

Potential sources of error include the suit sizing, relative to the subject, variations of the placement of the nominal shoulder strap length, shoulder strap slippage during data collection, subject technique, and posture. In addition, any technician support given, or support staff used, especially during the kneeling task, could skew those data results. For this study, a 3D anthropometric comparison between the HUT and subjects was not done which would give better insight to how the subject interacts with the internal geometry of the suit. Further analysis and testing would be required to better understand why subject variance and standard deviation differed so widely from across subjects.

V. Conclusion

In summary, the test team was able to develop and validate a force sensing system that is portable and can be used to acquire test data for different test environments and suit architectures. The ability to view the data real time provides quantitative data to engineers to help with the following: sizing of spacesuits for astronauts and test subjects and understanding the weight relieving properties of the spacesuit as a function of pressure. In addition, this data showed the xEMU spacesuit configuration will support some of its own weight while pressurized with varying results depending on the shoulder strap settings and body posture. The pressurized suit supporting some of its own load has potential implications for decreasing the overall load a subject has to support, including in partial gravity environments where the weight of the suit will be decreased, but the pressure offload will remain the same. Future work includes collecting data from more test subjects, increase the durability of the sensor design, including a 3D anthropometric analysis to understand how human-suit interactions are affecting data, and testing at different pressures to understand how that affects the offload will help to further validate the design. In addition, this setup could potentially be used to characterize and compare shoulder loads for different suit configurations and designs. This could also be utilized in different environments, such as the Active Response Gravity Offload System (ARGOS), with a simulated lunar gravity of 1/6-*g*. If used in the ARGOS environment, a simulated PLSS mass could also be incorporated.

VI. References

[1] Cullinane, Conor. (2018). *Evaluation of the Mark III Spacesuit An Experimental and Computational Modeling Approach.* [Doctoral dissertation, Massachusetts Institute of Technology]. DSpace@MIT, https://dspace.mit.edu/handle/1721.1/117896

[2] Cullinane, Conor. "Test Readiness Review Board, Human-Suit Indexing And Load Decomposition Evaluation." 2017.

[3] McFarland, S., Campbell II, D., and Rhodes, R., "NASA Advanced Spacesuit Pressure Garment System Status and Development Priorities 2022." *51st International Conference on Environmental Systems,* 2022.

[4] Meginnis, I., Rhodes, R., Watters, J., McFarland, S., and Cox, D., "NASA Advanced Spacesuit xEMU Development – Shoulder Assembly." *51st International Conference on Environmental Systems,* 2022.