In-Suit Sensor Systems for Characterizing Human-Space Suit Interaction

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Although the U.S. has studied space suit performance for decades, relatively little is known about how the astronaut moves and interacts within the space suit. We propose the use of in-suit sensor systems to characterize this interaction and present our results using pressure sensors and inertial measurement units (IMUs) inside the David Clark Mobility Mock-Up and the Mark III space suit from NASA's Advanced Space Suit Lab at the Johnson Space Center. A network of 12 low-pressure sensors are distributed over the arm to measure the pressure between the arm and the suit soft goods. A high-pressure sensor mat is used to detect the pressure between the shoulder and the suit hard upper torso (HUT). Finally, we place three IMUs inside directly on the person's lower arm, upper arm and torso, with three corresponding IMUs outside on the space suit to measure joint angles. We perform two human subject experiments with 5 movement tasks focusing on upper body motions. The 5 motions include 3 isolated joint movements (elbow flexion/extension, shoulder flexion/extension, and shoulder abduction/adduction) and 2 functional tasks (overhead hammering and multi-join cross body reach). We discuss the implementation of this experiment, our lessons learned, quality of the data, and follow-on work. Finally, we propose future improvements for the characterization of human biomechanics and injury mechanisms from a human-space suit perspective.

Nomenclature

ABF	= Anthropometry and Biomechanics Facility
DCCI	= David Clark Company Incorporated
EMU	= Extravehicular Mobility Unit
EVA	= Extravehicular Activity
HUT	= Hard Upper Torso
IMU	= Inertial Measurement Unit
ISS	= International Space Station
JSC	= Johnson Space Center
LCVG	= Liquid Cooling and Ventilation Garment
NASA	= National Aeronautics and Space Administration

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NBL = Neutral Buoyancy Lab
SSA = Space Suit Assembly

I. Introduction

EXTRAVEHICULAR activity (EVA) requires substantial preparation and the proper hardware to ensure the safety of the astronaut and the success of the mission. EVA has allowed us to perform the most important moments in human space flight. The space suit is a technical marvel, through design and iterative enhancements of the system assures each of the primary requirements to sustain life in the harsh vacuum of space is achieved. However, accumulated time in the suit causes fatigue, increases metabolic expenditure, and eventually may lead to injuries [2-11].

The space suit that U.S. astronauts currently fly and train in is the extravehicular mobility unit (EMU), which causes a variety of musculoskeletal injuries. This system includes the space suit assembly (SSA), protective and comfort pieces, and the life support system. A sketch of the EMU and comfort equipment is shown in Figure 1. A comprehensive description of these systems can be found in [12] and [13]. The EMU is gas-pressurized to 29.6 kPa (4.3 psi), making the soft goods somewhat stiff and rigid, requiring the wearer to work to deform the suit itself in addition to the work required for the task he or she is performing [5, 14-18]. As a result, astronauts experience discomfort, hot spots, skin irritation, abrasions, contusions, and over time injuries requiring medical attention. The most common types of reported suit incidences are to the hands, feet, and shoulders. The remaining reports occur primarily where the person impacts and rubs against the suit to articulate it. Although most injuries have been minor and did not affect mission success, injury incidence during EVA is much higher than injury that occurs elsewhere on-orbit [6, 7, 9]. EVA-associated injuries have been further exacerbated with the increased number of EVAs and training sessions for the construction of the International Space Station (ISS) in the Neutral Buoyancy Lab (NBL) training pool [18]. Astronauts and tools are made neutrally buoyant to simulate the weightlessness of microgravity, allowing for realistic mission preparation with mockups of the ISS, robotic arms, and other pieces of space hardware. Many hours of training are required for each EVA, and the injuries seen on-orbit are magnified as more time is spent inside the suit. During NBL training astronauts shift inside the suit due to gravity and hydrodynamic resistance which must be overcome, both factors likely cause new injuries not seen in flight. For example, some training positions when inverted cause the weight of the body to rest on the shoulders, causing discomfort and injury, and in some instances leading to surgical intervention. Shoulder injuries are some of the most serious and debilitating injuries astronauts face as a result of working in the suit [7, 8, 10, 19-21]

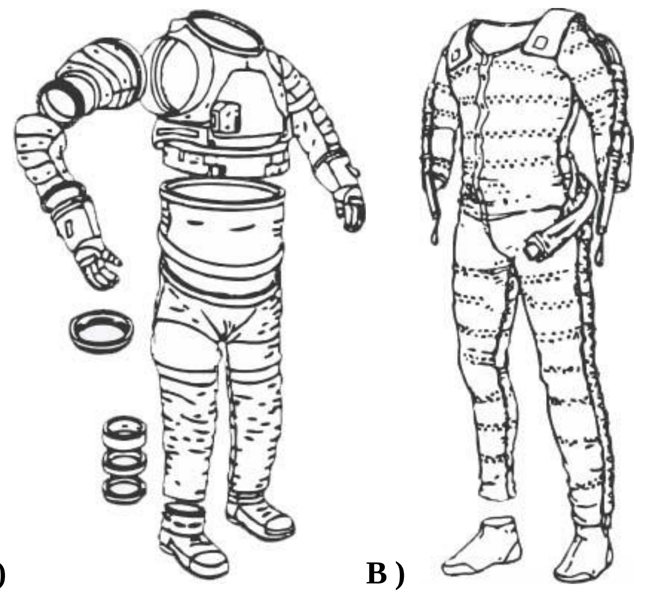

A) B)

Figure 1. EMU spacesuit pieces and comfort garments. *A) The EMU in an exploded view so the hard upper torso, soft pieces sizing rings, and boots may be seen. Courtesy of Hamilton Sunstrand. B) Each of the comfort pieces, including the LCVG with padding, ventilation tubes, and boot inserts. Courtesy of "Human Spaceflight".*

In addition to the EMU, there are several prototype suits geared toward improving capabilities for planetary and deep space exploration. The Mark III (Figure 2B), originally built in 1987 by NASA and ILC Dover, is the most well characterized prototype suit. It incorporates some hard components and rotating bearings (rather than soft fabric pieces) over the torso and hips to improve mobility and mitigate the effects of volume change. The concept was originally designed with planetary exploration in mind, hence the focus on mobility. The suit has seen several iterations and improvements since its original design. Although the bearings reduce the joint torques required to move the suit, their designs give the suit additional programming, making movements less natural. This effect was also seen in the AX-5, a full body hard suit designed at NASA Ames [22]. Soft suits, such as the Modified ACES, Demonstrator Suit, and the Mobility Mockup, are designed by the David Clark Company, Incorporated (DCCI). The Demonstrator Suit (Figure 2A) was designed to address launch and entry requirements and contingency EVA situations. Their Mobility Mockup allows these concepts to be implemented on a full pressure suit rapidly to determine relative success or failure of components design[1]. Additional prototype suits include the REI-Suit and the Z-1 suit designed by ILC Dover for NASA. Finally, there are a few space suit concepts being developed in academia, such as the University of Maryland's MX-2, the University of North Dakota's NDX-2, and MIT's mechanical counter-pressure BioSuit™, which are test-beds for advanced space suit design and operations research [25, 26].

Relatively little is known about how the person moves inside the space suit to move the suit itself. We hypothesize that injuries occur due to improper suit fit, shifting, limited use of protective garments, and repetitive motions and contact working against the suit [8, 10, 27]. Suit fit is a critical element in preventing astronaut injury and achieving optimal comfort, but there is no universal solution for every person. Achieving the best fit is extremely individualized and discomfort "hot spots" may exist in an area for one crewmember but not for another. Even between training sessions minor adjustments are made to suit enhance fit [28]. Additionally, a person's body dimensions, especially height, change as they adjust to microgravity [29], which may necessitate further suit adjustment. No matter which environment the astronaut is working in, movement in the suit is unnatural due to each space suit's inherent programming [30] and stiffness. Astronauts learn to change their biomechanical movement strategies, rather than attempting to move as they do naturally when unsuited [28].

The difference between how a person moves as compared to the suit has not been previously quantified. The performance and movement of the space suit have been studied both experimentally and theoretically. However, evaluating how the person interacts within the space suit has not been rigorously measured. Performance is usually measured for the person and the space suit as a combined system. There have been many experiments to characterize range of motion, work envelope, reach envelope, and the strength required by a person to move the suit, especially for isolated joints. Previous studies use a variety of techniques, such as photogrammetry, motion capture, and ergomic strength measurement [5, 14, 22, 31-36]. Results from these three techniques, however, are highly variable in that their methodologies are inherently different. Only comparison within one technique is possible and is not generalizable across subjects. Experimental evaluation of the human-space suit system gives gross metrics of performance and the upper bound of human capabilities within the environment. Modeling EVA has been used to get a sense of human-suit system performance for each of these metrics over a broad range of conditions not possible to be evaluated experimentally, such as modeling astronaut reach and work envelope over a population or modeling metabolic costs [31] [11, 14, 16, 17, 37-39]. In addition, there is currently no way to evaluate human movement within, although some work has focused on determining body joint angles within the suit [40, 41]. Knowing joint angles or where the body impacts the suit would improve performance data collection techniques through precise torque measurements, human range of motion inside the suit, and greater insight into metabolic cost data. Building from these studies could provide direct insight into resolving issues associated with EVA injury, comfort, fit, and mobility of future suit designs.

Future gas-pressurized space suit designs are governed by mobility requirements as we shift focus to planetary exploration. Surface exploration will require greater range of motion and more frequent sorties, leading to more time spent in EVA. This could potentially lead to higher injury incidence if the system is not enhanced to find long-term, healthy solutions to prevent EVA injury [18, 42, 43].

Figure 2. Advanced concept space suits for technology demonstration. *A) The David Clark Demonstrator suit. Photo credit [1] B) The Mark III worn during the experiment presented here in.*

The objective of this research is to develop an understanding of how the person interacts with the space suit, and use that information to assess and mitigate injury. The approach was to quantify and evaluate human-space suit interaction with two pressure sensing tools, focusing on the arm and shoulders under different loading regimes. Additionally, inertial measurement units (IMUs) were placed both internal and external to the space suit arm to assess biomechanics. Both custom and commercially produced sensors were incorporated into a modified athletic garment to realize a wearable pressure sensing system inside the suit. This experiment establishes a precedent and proof of concept, opening the doorway for future technology development. The successes, failures, and lessons learned in performing EVA experiments are presented herein, while detailed discussion of the data and its consequences are presented elsewhere.

II. Methods

A. Sensor Systems

The human-suit interface is currently an unknown in space suit characterization. Subjectively, astronauts describe contact locations and areas of discomfort; however, there is no way to quantify the nature of that contact. Pressure measurements would allow greater insight into how these interactions occur and help characterize suit performance. Additionally, an understanding of the joint angle differences between the suit and the person would give us more information about the biomechanics of movement in the space suit. Sensors integrated into a wearable garment are shown in Figure 3. The two systems selected to measure pressure at different pressure sensing regimes and the inertial measurement units (IMUs) used to measure kinematics are shown in Figure 4.

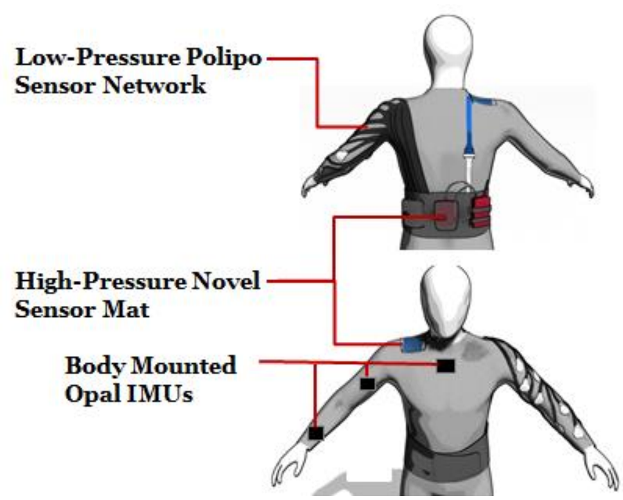


Figure 3. In-suit sensor systems. *Each of the three sensor systems are attached to the person's body before donning the space suit. The two pressure sensing systems, the Polipo and Novel, are integrated to a conformal garment, while the IMUs are placed directly on the subject's body.*

The Polipo is the system of 12 sensors developed as part of this research effort for the low-pressure regime expected to be measured on the body under the soft goods. Full characterization of sensor performance is presented elsewhere[44], but under dynamic loading conditions the sensors have a root mean square deviation from the applied pressure of 3 kPa, with a time constant of 0.1 seconds, and have been measured as highly repeatable. The sensors are 2.5 cm in diameter and cover the pressure range from about 0-100kPa with approximately 1kPa resolution. The sensors are molded using a hyperelastic polymer that is cured to have a microfluidic channel into which liquid conductive metal is deposited. The sensors measure normal pressure by a change in resistance of the conductive metal when the channels are deformed. These sensors are placed over the arm in a way that targets anticipated hot spots, and secondarily for uniform coverage. The Polipo is integrated into a conformal athletic garment with targets into which the sensors are mounted with Velcro. The system is detachable, allowing independent pressure sensing system to be used on many differently sized people, each donning the wearable pressure-sensing garment. The experimenter can move the sensors to desired anatomical locations and/or concentrate them over a certain region of the body. Due to limitations

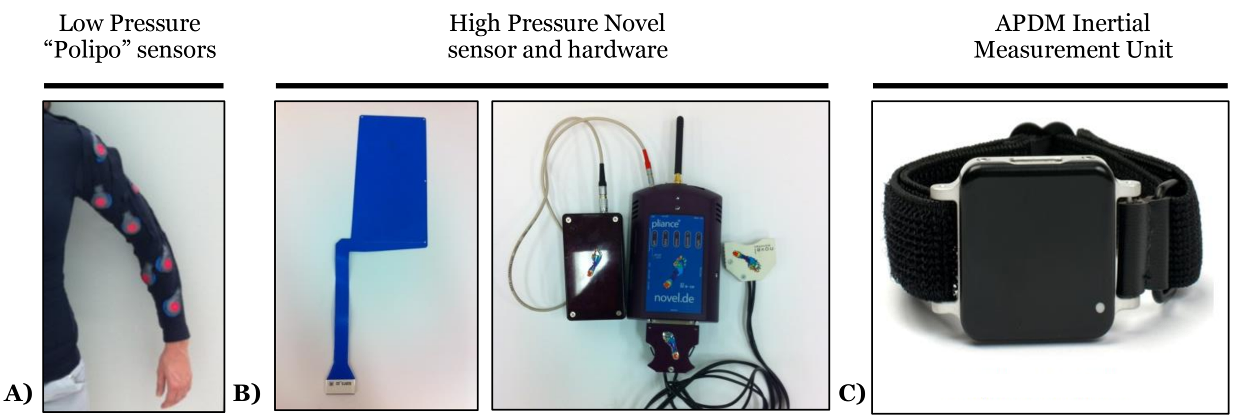


Figure 4. In-suit sensor systems. *A)Polipo low-pressure sensors to measure the pressure between the arm and soft goods. B) Novel high-pressure sensor and associated hardware to measure pressure on shoulder under the HUT. C) APDM Opal inertial measurement unit with three place internally and three placed externally to the suit to measure joint angle differences.*

of power and inability to transfer data wirelessly with multiple systems, the Polipo is wearable and run with on-board data collection with electronics attached at the base of the back. An Arduino Microprocessor is used for data collection. Each sensor is powered with constant current of 0.5mA. The entire board in nominal operation with 12 sensors runs ~100mA. The system uses a commercial off-the-shelf 9V battery encased and mounted next to the electronics board, giving a 4 hour test duration limit.

The garment used to attach the Polipo sensors incorporates a pocket interface over the shoulder to house the Novel (Munich, Germany) pressure-sensing mat, which is used for the high-pressure sensing regime. The high-pressure regime is at the interface between the person's body and the hard upper torso of the suit. A Novel pressure sensing mat has been used previously in a study by the Anthropometry and Biomechanics Facility (ABF) on an Extravehicular Mobility Unit hard upper torso in unpublished work. For this experiment a modified S2073 sensor mat with 128 sensor points is used. Each sensor is 1.4cm in each dimension and has a pressure range between 20-600kPa. The Novel system uses ten 1.2V nickel metal hydride batteries with 2000 mAh. The sensor is run at 330mA. Like the Polipo, data collection hardware is mounted at the base of the back and data was stored onboard. Finally, a cover shirt slides easily over the entire sensor suite to prevent catching and to ensure proper sensor placement.

The inertial measurement units (IMUs) chosen for this experiment are the APDM Opal IMU Sensing System (Portland, OR), which are commercially available and are the highest quality sensor system offered by APDM. The IMUs can be seen in Figure 4. Each IMU consists of three accelerometers, three gyroscopes and three magnetometers. An algorithm combines the measurements of the accelerometers and the magnetometers to update the gyroscopes readings that are subject to drift. When the magnetometers measurements are perturbed by external ferro-magnetic field fluctuations, the algorithm preferentially updates the gyroscope with the accelerometers. The algorithm is described in greater details in Yun[45], but the algorithm as implemented by APDM is proprietary. Three sensors were mounted internally on the upper arm, lower arm, and chest. The IMUs were placed in-plane with one another to optimize the output for isolated joint movements, but their relative orientations allow the detection of off-axis rotations. Three externally mounted IMU sensors on the upper and lower spacesuit arm and suit torso were attached to the suit such that they corresponded to the internal sensors. The internal sensors were attached to the body with a harness or straps and were secured with athletic tape to prevent them from moving during the experiment. The external IMUs were fixed by straps and athletic tape, or Velcro©. Each sensor is 4.8x3.6x1.3 cm and weighs less than 22g. The gyroscopes and magnetometers were recalibrated before each subject and each experiment to take into account the magnetic environment and minimize the gyroscope drift over time. They are powered by a lithium ion battery at 3.7V nominal. The maximum current through the sensor is approximately 56 mA, and battery failure is highly unlikely. The data from the IMU sensors was collected wirelessly and continuously synchronized in real time. In addition, the unsynchronized data was saved on board the sensor in the event of a wireless signal failure. The sensors had 8GB of onboard storage and a battery life of 8 hours. The data was synchronized in real time through the IMU with a resolution of 10 μs.

Three high-resolution cameras were used to record the motions of the subjects from both the head on and profile views during the experiment. This data was helpful to review the details of the experiment and to visually track the kinematics to compare to IMU results.

B. Subject Selection

This experiment was performed on a total of four subjects. The first experiment was performed in conjunction with the DCCI where one subject was tested in their Mobility Mock-Up, which is an internal test article that was used in the development of the "Demonstrator Suit"[1]. The same experimental protocol was performed at NASA's Johnson Space Center in the Advanced Space Suit Lab. The test was performed in the Mark III space suit. For all tests, the criteria for suited subject was: 1. Current fit-check in relevant suit, 2. Current test subject medical approval, 3. Extensive experience working in the pressurized suit to aid in comfort and consistency while performing movements. In each instance, the subjects gained their high level of experience through being a suit design engineer, and therefore had performed many testing runs inside their respective suits. Their fit inside the suit had been iterated upon multiple times before the experiments, to achieve the optimal sizing. It should be noted, however, that for the DCCI experiment, the subject's fit was noted as abnormal because the suit was not in its normal configuration. The experiment proceeded due to time constrains, and the fit improved once the suit was pressurized. Due to individual variability in the way subjects move and how the suit fits them, the data collected from the experiment cannot be directly compared across subjects. However, descriptively, it is instructive to look at each subject's data side by side to get a sense of the variability we might see in future studies beyond this baseline analysis.

Each subject was briefed on the experiment and potential hazards associated with participating prior to signing an informed consent. This protocol was reviewed and approved by both the MIT Committee on the use of Humans as Experimental Subjects and NASA Johnson Space Center's Institutional Review Board. Additionally, each sensor system was reviewed for electrical, encumbrance, and material hazards. The experiment could be terminated by the subject at any time for any reason, or by the test conductor, suit technicians or suit engineer due to any safety or hardware concerns or concern for the suited subject.

C. Experimental Design

Subjects were asked to perform a series of upper body motions inside the space suit. Experienced subjects were selected so they would not develop new, potentially confounding movement strategies to learn the way they move best in the space suits. The pressure profiles and angle histories were recorded for each subject. The test protocol consisted of 12 repetitions of 5 motions inside the space suit. A representative schematic of the test protocol is shown in Figure 5. The selected movements engage the upper body, particularly where the sensors are placed. The 5 motions are 3 isolated joint movements (elbow flexion/extension, shoulder flexion/extension, and shoulder abduction/adduction) and 2 multi-joint functional tasks (overhead hammering, cross body reach). These tasks are described in detail in Figure 6. Prior to the test, subjects were trained on each movement and allowed to repeat it as many times as they desired before the experiment commenced to minimize the effects of learning. For each movement, the 12 repetitions were further subdivided into 3 groups of 4 repetitions each. This was done to evaluate subject fatigue or potential change of biomechanical strategies over the course of the test period. After each group of movements, the subject rested for a minimum of 5 minutes and qualitative information was gathered on subject comfort, subject fatigue, perceived contact with the suit, and perceived consistency of movement. This information was also collected prior to the experiment to determine initial contact with the suit. The experimental design was counterbalanced and each test condition randomized for each subject. Unsuited data was collected after the suited test to form the baseline pressure profile used to mitigate the effects of erroneous readings caused by movement without contact with the suit. For the unsuited condition, subjects were asked to perform the task matching the pace and range of motion while suited.

Outside of the experimental protocol, additional data was recorded in static positions and for additional dynamic motions for the purposes of calibrating the IMUs and determining baseline loading from the suit. This was done before the subject donned the suit, while pressurized inside the suit, and in some instances while the subject was suited, but unpressurized. Finally, measurements were performed after the experiment to determine changes from the pre-experiment data. The calibration consists of 1) a static calibration where the subject was asked to maintain two different postures for 20 seconds each, and 2) a dynamic calibration where the subject moved through 4 specific isolated joint movements. The dynamic motions included: wrist pronation/supination, elbow flexion/extension, shoulder flexion/extension and shoulder abduction/adduction. The dynamic calibration was used to check the

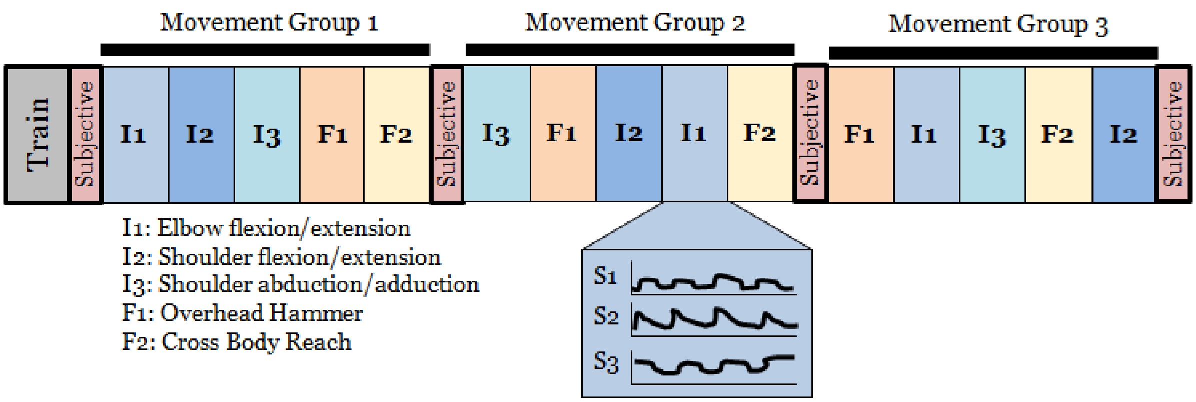


Figure 5. Experimental test protocol for a single subject. *Subjects are given time to train each of the 5 movements inside the space suit. Subjective information is taken on comfort and pressure hot spots. The 5 movements are performed in 3 groups with subjective information taken after each group. The order is counterbalanced within the group and randomized between subjects and space suits. Each of the movements is repeated 4 times each. Sensor pressure profiles over time are recorded for analysis.*

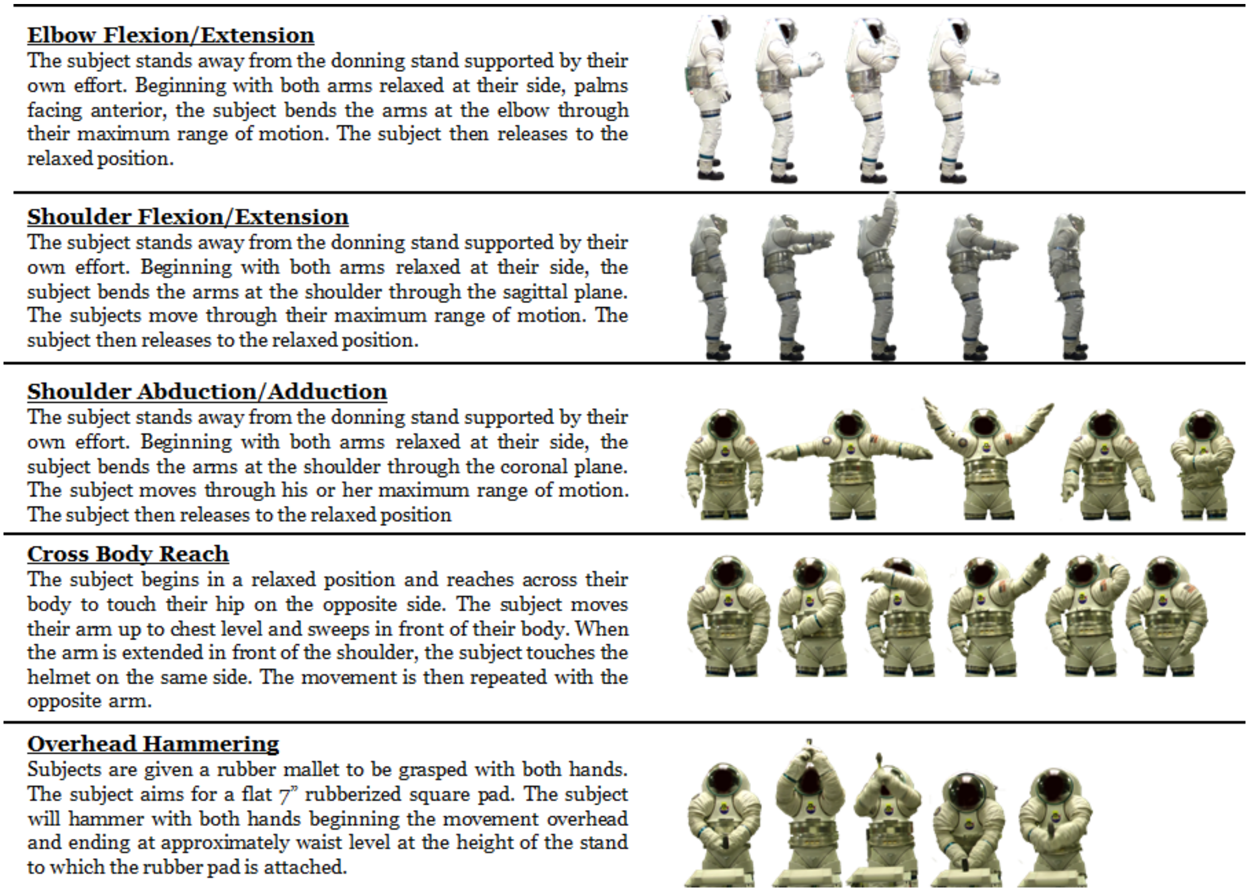


Figure 6. Space suit movement tasks performed by each subject. *Three isolated joint tasks are performed: Elbow Flexion/Extension, Shoulder Flexion/Extension, and Shoulder Abduction/Adduction. Two functional tasks were performed: Cross Body Reach and Overhead Hammering. Subjects were given very specific instructions on how to perform the isolated joint tasks, while subjects were given way-point markers to meet and allowed to develop their own biomechanical strategies for the functional tasks. Subject in Mark III suit is shown.*

amplitude of the motions as recorded by the sensors. A steel square with level bubbles was used to ensure that subjects reached the requested 90° movement amplitude.

III. Results

A. David Clark Company Experiment

The first experiment was performed on one subject at the DCCI inside their Mobility Mockup space suit, following a pilot study in the MIT arm vacuum chamber. The DCCI Mobility Mockup suit was pressurized to 3.5 psi and used an air cooling system. The subject wore comfort garments and padding as desired for comfort and suit fit. The suit is used to evaluate new suit concepts, and therefore the upper body configuration was different for each arm/shoulder. In addition to the test protocol outlined previously, the subject also performed the experiment suited while un-pressurized.

The testing at DCCI proved extremely useful to finalize the experimental protocol for the NASA Mark III testing. Subjects were given very specific instructions as to arm orientation during the motion, when to focus on which isolated joint movements, and ensuring the subject returned to a neutral position before beginning the next repetition. This evolved over the course of the pilot and DCCI experiments based on the subject feedback and observation. We adjusted the ordering of tasks based on subject feedback, such as changing cross body reach to 4 repetitions with the right arm followed by 4 with the left. It also became clear that taking subjective feedback after each motion instead of after each movement group would improve our results. Finally, it allowed us to improve our data collection timing-tool so we could sync the data after the experiment, without which analyzing across sensor systems would not be possible.

The Polipo system did not produce rigorous data results for the DCCI experiment. Due to technical issues, the data logged once every 7 seconds, rather than the intended 0.3 seconds. Therefore detailed results corresponding to specific movement pressures were elusive. However, DCCI test was successful in allowing us to finalize the procedural aspects for the Mark III space suit experiment. The subject was asked to evaluate the garment fit and evaluate the degree to which the system inhibited motion. Adjustments were made in real time, a practice that was used in the follow-up experiment at NASA. Additionally, it was determined that turning on and beginning data collection prior to initializing the Novel data collection system was necessary. All hardware issues were resolved prior to any additional testing.

The DCCI experiment was extremely important for evaluating the performance of the Novel pressure mat. Our ability to mimic the testing environment was limited in our laboratory pilot experiments, giving us very limited information of how the system would function in a full body pressurized suited environment. The experiment gave us a general idea of the durability of the system, as well as the range of pressure data, including localized pressure magnitudes, noise levels, and ease of identifying pressure profiles of various movements. One important aspect of the data was the occasional erroneous pressure readings that spiked to the maximum possible pressure value of the sensor. It was determined that this was likely caused by bending or folding of the sensor due to the motion of the arm with respect to the placement of the sensor on the subject's body. Also of note was that nearly every sensor in the sensor mat was loaded during each movement, indicating that the subject is broadly loaded over the entire shoulder in the DCCI suit.

The IMU sensors recorded accurate and reliable data for the DCCI experiment. The experiment demonstrated the reliability of the wireless signal through the suit. The root mean square error (RMS) was calculated for the yaw and pitch angles over 20 seconds for all IMUs under each static calibration. The average drift was 5.8° (7.1° standard deviation) for the elbow joint angle and 4.9° (standard deviation 5.5°) for the shoulder joint angle. However, prior to the final two motions of the experiment, the IMU laptop recording the data crashed, which reemphasized the need to take both wireless transmission of data and onboard data storage, allowing this portion of the experiment to be recovered in post processing. The most effective way to mount the sensors to minimize shifting was to use elastic straps (APDM, Portland, OR) with athletic tape on the back of the sensor attached directly to the subject's skin. Using the DCCI IMU data, the methodology for analyzing kinematics through quaternions was developed. However, at the time of the experiment, only five IMUs were available. The IMU located on the suit torso was not used, making it impossible to quantify the suit shoulder joint angle. For this reason, a comparison of the shoulder suit joint angle between the Mark III and the David Clark Mobility Mockup is not possible. In addition to establishing the final protocol, the analysis of the IMU data also showed statistically significant decrements in motion while suited compared to the unsuited case. A full review of the IMU data analysis can be found in "Feasibility of Spacesuit Kinematics and Human-Suit Interaction" (Bertrand et al., ICES, 2014).

B. NASA Johnson Space Center Experiment

The second experiment was performed at NASA Johnson Space Center with three subjects inside the Mark III space suit. The suit was pressurized at 4.3 psi for these experiments, but is capable of being pressurized to 8.3 psi. As per normal operation, the subjects also wore a liquid cooling garment, thermal comfort undergarment, wristlets, comfort gloves, and socks to aid in comfort and thermal control. Padding was used based on the subject's normal suit requirements, however any shoulder padding was removed to prevent interference with the Novel system located over the shoulder.

Static data taken prior to donning the suit was used to establish the zero-pressure value while on the subject's body. Once the suit was donned and pressurized, static data collected during IMU calibration was used to determine the suit loading on the person's body. After the pressurized portion of the experiment, static data collected during unsuited IMU calibration was used to determine any shifts from the baseline readings and to identify sensors that broke over the course of the experiment.

All Polipo sensors were calibrated prior to the experiment. However, any sensors replaced over the course of the experiment were calibrated upon returning to MIT. Some sensors were known to give erroneous results. Sensor 8 is excluded from the experiment because it had a wire break inside the Polipo cover. Sensors 7 and 12 were known to give jumpy responses prior to the beginning of the experiment due to internal fraying of the copper wiring inside the Polipo's fabric cover. With pressure on the wires, however, the connection could be reestablished. Therefore, these sensors were able to give responses, but their recorded profiles were treated with particular caution.

The 3 subjects performed 5 movement tasks spread over 3 movement groups. Data was collected by 11 sensors, for a total of 495 response profiles to evaluate. Each profile was examined to determine if the output was useful. Table 1 summarizes the survivability of the Polipo sensors inside the space suit environment for all subjects across all movement tasks. Figure 7 shows the location of the sensors on the arm. Of the 165 possible sensor loading regimes (3 subjects, 5 motions, 11 sensors), 44% of the profiles were useful. The integrity of the data deteriorated as the experiment progressed. Subject 1 registered a sensor response for 58% of his loading scenarios, while Subjects 2 and 3 had 44% and 29% respectively. The continual decrease in data integrity reflects deterioration of the sensor system with use, due primarily to breakage of the copper strands in the wiring.

There is a distinction to be made between sensors that broke and sensors that didn't register a response because the motion did not load it. Sensors broke for a variety of reasons. The first reason was due to losing the connection at the solder joint between the wiring and the sensor itself. This typically resulted in a total loss of signal. However, for some sensors, the movement itself would reestablish the circuit's connection, allowing some intermittent data to be used. The most common form of failure was in the slow deterioration of the wiring. Internal breakage of the copper strands in the wires caused the data to be jumpy, either increasing or decreasing the resistance as the subject moved and copper strands came in and out of contact with one another. This progressively became more problematic with each subject as wear on the system increased. Table 1 shows the breakdown of which sensors gave useful results not only because the sensor was not broken, but also because it was loaded during the movement group. Profiles are divided by subject and movement task for each sensor. The table indicates under which movement group the sensor was loaded and the profile was readable. Sensors which also gave a reading during the unsuited movement are designated with a "U".

In general, Sensor 1 did not provide useful information due to internal breakage of the wires. The response profiles were very jumpy, although occasionally a consistent response could be detected below the noise. Sensor 2 was extremely useful for Subject 1, but broke early during the experiment for Subject 2. The wiring was repaired and performed well for Subject 3, although it was only loaded during elbow flexion/extension (and therefore also cross body reach). Although Sensor 3 survived the entire experiment, it was also nearly never loaded. The sensor was located on the back side of the forearm, and seemingly rarely made contact with the suit. Sensor 4 broke early in the experiment for Subject 1 at the solder joint. It was repaired and provided useful data for Subject 2. However, over the course of the experiment the wires began to break internally, making it unusable for Subject 3. Sensor 5 was very useful for Subject 1, but broke at the solder joint late in the experiment. It broke again at the solder joint early in the experiment for Subject 2, but was repaired for Subject 3 and remained intact, providing useful profiles for the duration of the experiment. Sensor 6 remained intact for all subjects, but broke midway through the experiment for Subject 3. It provided some of the clearest profiles, but also exhibited an unsuited response due to its placement on the elbow. This artifact should be removed from the data before considering pressure magnitudes. Sensor 7 was known prior to the experiment to give erratic responses due to wire breakage, and almost no usable profiles were detected. Sensor 8 was not included in the experiment. Sensor 9 remained intact for Subject 1,

Table 1. Useful movement profiles. *Summary of sensors detecting pressure over each subject, movement task, and movement group. Movement tasks are E – Elbow flexion/extension, S – Shoulder flexion/extension, A – Shoulder abduction/adduction, C – Cross body reach, and O – Overhead hammering. The movement groups are numbered 1, 2, and 3, while an unsuited profile is listed as "U".*

	Subject 1					Subject 2					Subject 3				
	E	S	A	C	O	E	S	A	C	O	E	S	A	C	O
Sensor 1				1 2 3 U						1 2 3 U					
Sensor 2	1 2 3	1 2 3	1 2 3 U	1 2 3	1 2 3	1	1	1	1	1	1 2 3			1 2 3	
Sensor 3	1 2 3														
Sensor 4	1 2	1	1	2		1 2 3	1 2	1 2 3		1 2					
Sensor 5	1 2	1 2 3	1 2	1 2 3		1			1 2		1 2 3	1 2 3	1 2 3	1 2 3	1 2 3
Sensor 6	1 2 3 U	1	1 2 3	1 2 3 U		1 2 3 U	1 2 3	1 2 3	1 2 3 U	1 2 3	1 2	1 2	1	1	1 2
Sensor 7	3														
Sensor 8															
Sensor 9	3		1 2 3						1				1 2 3		
Sensor 10	2	1		1		1 2	1	1 2	1 2	1 2		1			
Sensor 11	1 2 3	1 2 3	1 2 3 U	1 2 3 U	1 2 3						1 2 3				1 2 3
Sensor 12	1 2 3				1 2		1								

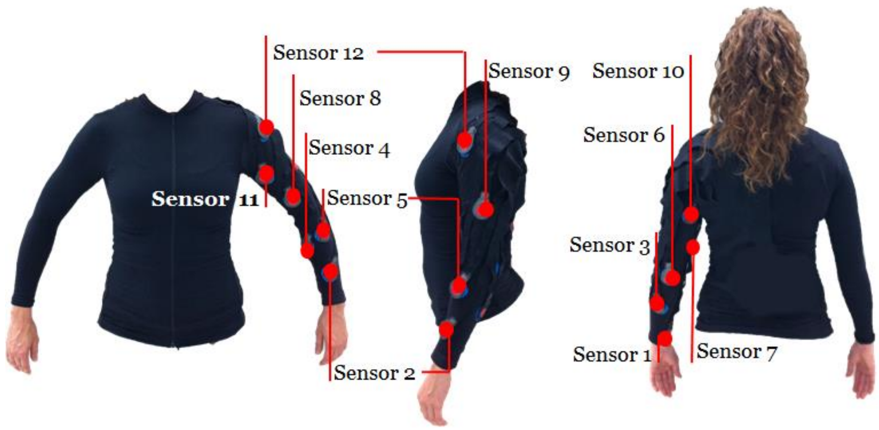


Figure 7. Polipo sensor locations. *The Polipo low-pressure sensing system is placed on the subject's left arm and is designed for anticipated pressure hot spots and for even distribution over the sleeve. Sensors 1 and 2 are located on the wrist; Sensors 3 and 4 on the forearm; Sensors 5 and 6 on the elbow; Sensors 7-9 on the upper arm, and Sensors 10-12 near the shoulder.*

however was rarely loaded against the suit. Short spikes in pressure were detected on occasion, likely due to impact with the upper arm bearing. This was confirmed with Subject 2, whose impact with the bearing caused the sensor to rupture. The sensor was replaced and Subject 3 showed similar response profiles to Subject 1. Sensor 10 was constantly loaded for all subjects in the neutral posture, due to its placement on the back of the upper arm. Therefore, the response profiles detected by this sensor are in offloading, rather than in loading. For all subjects, the sensor broke during the course of the experiment. Sensor 11 produced very useful results for Subject 1, but over the course of the experiment its responses deteriorated due to internal breakage of the wires. Finally, Sensor 12 was nearly unusable due to internal breakage, however occasionally response profiles were able to be detected through the noise.

In general, the Novel pressure sensing system proved to be very reliable in terms of quality of gathered data. While a few erroneous readings such as those that arose in the testing at DCCI also occurred for Subject 1, these were easily removed during data processing, and none occurred for Subjects 2 or 3. With regards to durability, the Novel system performed well, but by the end of all three days of testing there was noticeable damage to the sensor. Any future in-suit testing would necessitate reconditioning of the sensor. Another notable change over the course of the experiment was shifting of the Mark III shoulder straps inside the suit's HUT. As the right shoulder pad was located directly on top of the Novel sensor, any shifting would affect the measured distribution of pressure. This occurred noticeably for Subject 3, although this was likely a result of performing additional tasks involving extensive bending and reaching that were not performed with Subjects 1 or 2. Nevertheless, slight shifting could also have occurred for Subjects 1 and 2. This shifting of shoulder pads does not pose a problem for our data, as it still represents how pressures change when humans move within the suit; however, it is an observation to consider when comparing pressure distributions across subjects.

As sensor placement varied between subjects, we made a procedural adjustment during the experiment that involved locating and briefly applying localized pressure to pre-identified bony landmarks—the acromion, mid-shoulder, crux of the clavicle, and corner of shoulder blade. During data analysis, we could then determine how the sensor was oriented on each of the subjects based on where these pressure points were detected on the sensor grid. Table 2 shows representative loading maps of the Novel sensor for each subject during each movement. The percentage of sensors loaded is also given. The orientation of the sensor anatomically is shown in Figure 8. In general, Subject 1 was more broadly loaded than each of the other subjects. All subjects were loaded more broadly on the proximal end of the shoulder near the neck, which is consistent with shoulder pad placement. The results of this analysis show the sensor was well positioned for measuring load, but it is not clear how additional sensors or changes in placement would affect the results. Considering the interface between the Novel system and the internal suit architecture, the internal harness with shoulder padding prevented us from measuring the pressures that would be directly applied to the shoulder due to contact with the hard upper torso. We anticipate more concentrated and potentially higher pressure readings in the absence of such padding. However, this padding is part of the Mark III suit design, so our measurements accurately reflect the pressures an astronaut would experience while working in the suit. It would nevertheless have contributed to the interpretation of our results if we had known the exact placement of the shoulder pad on the sensor.

The IMU system functioned well during the experiment and gave useful data for the subjects. No sample drop occurred and there was no crash from the wireless signal or the computer recording the data. The root mean square error (RMS) was calculated for the yaw and pitch angles over 20 seconds for all IMUs for all static calibrations. Subject 1 had an average drift of 1.2° (1.1°) for the elbow joint angle and 3.3° (4.8°) for the shoulder joint angle, while subject 2 had 1.2° (1.0°) for the elbow joint angle and 1.5° (1.6°) for the shoulder joint angle. Two IMUs from the first subject had a constant gyroscope offset to the raw signal due to miscalibration, causing erroneous readings. The data was recovered by removing the constant offset and reprocessing the signals through the algorithm used by APDM to calculate the orientation quaternions, but the data has yet to be analyzed. The IMUs were recalibrated and performed as reported for the other two subjects. The placement of the sensors on the subject was the same as for the DCCI experiment, with the same attachment technique. On the suit, the torso IMU was attached on the hard upper torso of the Mark III with Velcro®, and stayed fixed during all the experiment for the three subjects. The IMU located on the suit lower arm, was attached with straps, and was secured with athletic tape just above the glove bearing. It did not move significantly during the all experiments. However, this placement disturbed the measurement of the elbow flexion/extension for Subject 2. Although the subjects were asked to perform the elbow flexion/extension without wrist bending, Subject 2 bent his wrist at the top of the elbow flexion. The IMU located internally on the lower arm could not bend because it was fixed on the forearm, while the corresponding suit IMU moved with wrist flexion, giving some biased results. The IMU located on the upper arm of the suit was attached with straps and athletic tape for Subject 1. The strap and IMU slid on the bearing over the course of the experiment. For the remaining subjects, the IMU was attached with Velcro®, which resolved the problem. The data analyzed from these experiments include measuring differences between the person and the space suit, the lag between the angles the subject's move through, and the constant offset of joint angles during maxima and minima of movement. Results showed suit multi-axis rotations for the shoulder bearing, as

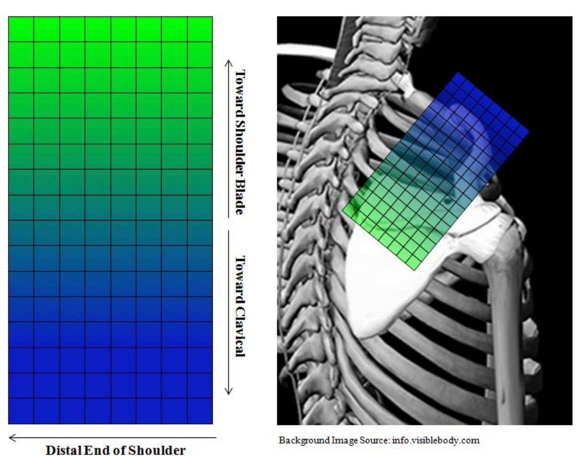
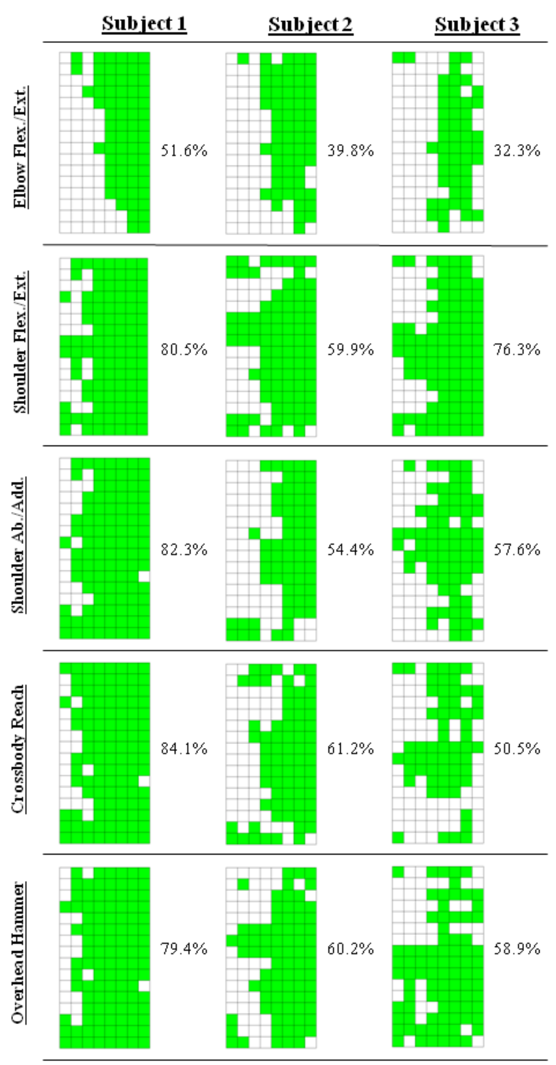


Figure 8. Orientation of the Novel sensor relative to each subject's body. *This orientation corresponds to the information in Table 2.*

Table 2. Sensor mat loading for all subjects over each movement task. *Sensor mat orientation corresponds to that shown in Figure 8. Individual variability may be due to fit and shoulder pad placement, but sensor coverage appears to be adequate.*



expected. A full review of the data analysis can be found in "Feasibility of Spacesuit Kinematics and Human-Suit Interaction" by the authors here-in.

IV. Conclusions

This research is, to our knowledge, the first experiment to characterize human-space suit interaction with pressure sensors placed inside the pressurized suit environment. Unpublished work from the NASA Anthropometry and Biomechanics Facility performed a similar study and future work includes comparing results and procedures. This research builds from previous work on measuring joint angles both internal and external to the suit. It is our first glimpse "inside the space suit" and will be the baseline for future studies.

Some of the most important lessons learned from this study were regarding identifying and evaluating potential hazards to the test subjects, as evaluated in the Hazard Analysis performed prior to the JSC experiment. Materials, electrical, battery, and hardware encumbrance were each analyzed and deemed to be an acceptable level of risk with controls. These considerations should be incorporated in future iterations of suited experiments with wearable electronics. Each sensor system was designed/selected to be stand-alone and wearable in the suit environment. This allowed us to move beyond traditional barriers of creating a suit pass-through or potential movement inhibition. Demonstrating a safe, well executed experiment will allow future iterations of this work to be completed more rapidly and with a track record for implementation, reducing uncertainty.

These experiments also allowed us to evaluate the sensor systems in the suit environment. As a result of these tests, limitations of durability were identified for both pressure-sensing systems. Improvements to the Polipo for future work include developing a wiring system where friction and repeated bending will not cause internal breakage of the wire. Additionally, the solder joint between the sensors and the wires should be improved to improve system resilience. Improvements may also be made for the Novel sensor. The sensor was bent and the cover began peeling near the edges with use. Although this did not negatively impact the results, future tests should not be performed until the sensor can be reconditioned. The sensor could be housed differently to prevent the cover peel, but the bending cannot be fixed given the sensor's size. Potentially in the future a smaller sensor or some of their newly developed stretchable sensors may be better suited for these tests. To improve the IMU results, further study beyond our cursory analysis could be performed to quantify the magnetometer perturbations and its effects on the estimation of the orientation of the IMUs. A 3D visualization tool of suit joint angles is being developed to better understand the multi-axis rotation of joints through the bearings, and will aid in comparing the human and space suit motions.

Future iterations of this experiment should improve the integration of the three data collection systems together. Due to potential concerns of interference with the communications system, not all the data was collected wirelessly. Currently, this problem is resolved by keeping individual timelines for each system, and the data is synced post-test, increasing the potential for error. Coupling the data from the kinematics sensors with the pressure sensors is ideal to determine the contact between the human and the suit. Either a new data initialization process should be developed, or the data should be collected by one central processor. Additionally, future areas of study should evaluate shifting the placement of the Polipo sensors to areas of the body we would like to target for further study. This may also include other areas of the body. Decreasing sensor size would also allow an increased density of sensor placement to collect additional pressure values against the body.

There were many successes in implementing this experiment that should be carried further into future experiments. The Polipo sensor system was built from scratch for this application. It was designed to be wearable through the full range of motion, stand alone for power and data collection, be transferrable between subjects, and was targeted at detecting pressure at the low-pressure range and resolution expected under the soft goods. Each of these design objectives was achieved. As a result, its applicability to the space suit environment was validated with this experiment. The Novel pressure sensing system also proved to be extremely useful even in the loading regime that was less than it was originally designed for. The experiment also proved that kinematics could be efficiently tracked inside the suit, wirelessly, and compared to the suit motions, with the use of inertial measurement units.

These experiments were very successful in opening the door for this type of space suit testing. Although the data is presented elsewhere, the results from the experiment provide valuable insight into how motions occur, how consistent subjects are, and how discomfort and fatigue can build up over time while working in the suit. Future planned experiments include continued collaboration with our colleagues at DCCI and the ASL to characterize new suited motions, new suit configurations, and other areas of the body. The implications of the test are valuable in finding an initial baseline of human-suit interaction and will guide future tests to optimize placement of sensors.

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