Pressure And Kinematic In-Suit Sensors: Assessing Human-Suit Interaction For Injury Risk Mitigation

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Abstract— **With NASA's current trajectory under the Commercial Crew program, spacesuits will become a critical system for the successful implementation of commercial orbital transportation services (COTS). All the current flown spacesuits are gas pressurized and require astronauts to exert a substantial amount of energy in order to move the suit into a desired position. The pressurization of the suit therefore limits human mobility, causes discomfort, and leads to a variety of contact and strain injuries. While suit-related injuries have been observed for many years and some basic countermeasures have been implemented, there is still a lack of understanding of how humans move within the spacesuit. The objective of this research is to gain a greater understanding of this human-spacesuit interaction and potential for injury by analyzing the suit-induced pressures against the body along with joint kinematics of how astronauts move inside the space suit.**

The rise of wearable technologies is changing the paradigm of biomechanics and allowing a continuous monitoring of motion performance in fields like athletics or medical rehabilitation. Similarly, pressure sensors allow an in-suit sensing capability to better locate the areas of contact between the human and the suit and reduce the risk of injuries. Coupled together these sensors allow a better understanding of the complex interactions between the astronaut and his suit, enhance astronaut's performance through a real time monitoring and reducing the risk of injury. An experiment was conducted in conjunction with David Clark Incorporated Company on the Launch Entry Development spacesuit. The experiment analyzed the mobility and human-spacesuit system behavior for isolated and functional upper body movement tasks, with each motion repeated 15 times: elbow flexion/extension, shoulder flexion/extension, shoulder abduction/adduction and cross body reach, which is a complex succession of critical motions for astronaut and pilot task. The contact pressure between the person and the spacesuit was measured by a high-pressure sensor located on the shoulder (Novel). Joint angles were measured internally and externally to the suit with 6 inertial measurement units (Opal IMUs): three external and three internal. The spacesuit was tested in its natural recumbent position. The analysis of the mobility of the spacesuit, and the interactions between the suit and the person are analyzed and conclusion and recommendations are given.

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1. INTRODUCTION

Human spaceflight programs are facing new challenges rising from the evolution of the exploration agenda, the need for Commercial Crew and the new entry on the market of space tourism. These different paradigms bring new challenges: planetary exploration missions will require intensive extravehicular activities (EVA) [1], space tourism will require new, cheap and user friendly space systems [2]. Spacesuits need to adapt to this new era of space exploration and democratization of space. Spacesuits are technical marvels: their main functions are providing oxygen, pressure, food, water, waste removal, communication, thermal control, mobility, radiation protection, direct sunlight protection, and micrometeorite protection [3]. The human body cannot survive in the vacuum of space because all air would expand the lungs, blood vessels would rupture and the blood would eventually boil [3]. However, lower pressure than atmospheric pressure can keep the astronaut alive and be an adequate environment to work in. One of the most important functions of a spacesuit is to provide mobility: "the advantage of a human in space over a robot is the ability to see, touch, and adapt instantly to real-time conditions. This is an advantage only if the astronauts are able to effectively use their hands, arms, legs, eyes, and brains" [3]. Spacesuit joints are one of the most critical parts of the design of the spacesuit since it defines its mobility. A key challenge to spacesuit development is the dynamics of a pressured enclosure and its effects on joint mobility. A gas pressurized suit joint can be seen as a cylindrical balloon. When the balloon is bent, the internal volume is decreased, leading the inner pressure to increase and tending to move back the cylinder to its initial position. The common gas-pressurized spacesuit designs tend to keep a constant or near constant volume in the joints [3, 4]. Spacesuits have evolved since the initial designs but many issues remain. Over time, these gas-pressurized suits cause fatigue, increase metabolic expenditure, and eventually may lead to injuries in

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astronauts [5-14]. Gas-pressurized suits cause astronauts to experience discomfort, hot spots, skin irritation, abrasions, contusions, and over time injuries requiring medical attention. Injuries occur primarily where the person impacts and rubs against the suit to change its position. 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 [9, 10, 12]. While the most common injuries occur in the hands, feet, and shoulders, shoulder injuries are some of the most serious and debilitating injuries astronauts face as a result of working in the suit [10, 11, 13, 15-17]. Countermeasures have been developed to mitigate suit-related injuries, but still relatively little is known of how humans move within the spacesuit.

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 [11, 13, 18]. Previous studies use photogrammetry, motion capture, and ergonomic strength measurement to measure performance by characterizing range of motion, work envelope, reach envelope, and the strength required by a person to move the suit [8, 19-26]. There is currently no way to evaluate human movement within the suit, although some work has focused on determining body joint angles within the suit [27, 28]. Data collection of joint angles and impact points would provide performance information via precise torque measurements, range of motion within the suit, and greater insight into metabolic cost data. Wearable inertial measurement units (IMU) using gyroscopes, magnetometers, and accelerometer data, combined using orientation algorithms such as Kalman Filters, have been recently used to better understand spacesuit kinematics [29-31]. Additionally, previous research started to look more closely at the human spacesuit interaction through a combination of data from different sensors: 1) wearable kinematic sensors located inside and outside the suit, and 2) soft and hard pressure sensors inside the suit that map the intensity and location of the point of contact between the human and the suit for the upper body region [29, 32]. The study focused on isolated joint motions, as well as functional tasks, and highlighted the interactions between the human and the suit and informed spacesuit designers on the criticality of some types of motions. However, the pressure and kinematics sensors could not be digitally synchronized to provide a more complete and comprehensive analysis. This paper presents a congruent human-spacesuit interaction study performed on the new David Clark Launch and Entry Development suit in a recumbent position with synchronization between sensor systems.

2. METHODS

Sensor Systems

The two pressure-sensing systems and the inertial measurement units (IMUs) used to measure kinematics are shown in Figure 1.

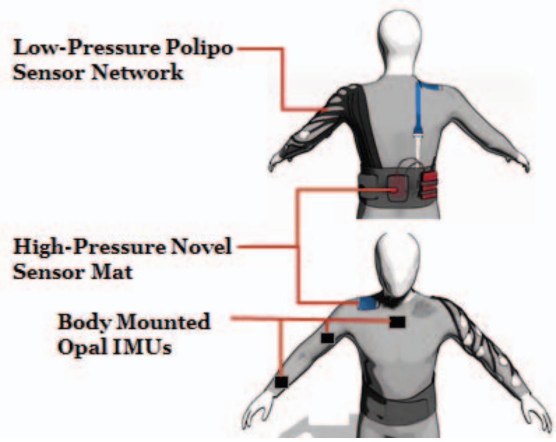

Figure 1. Pressure-Sensing Systems and IMU Kinematics System Placement

The garment used to attach the sensors incorporates a pocket interface over the shoulder to house the Novel (Munich, Germany) pressure-sensing mat, which is used for the high-pressure range between 20-600 kPa. The high-pressure regime is at the interface between the person's body and the hard upper torso of the suit. For this experiment a modified S2073 sensor mat with 128 1.4 x 1.4 cm sensor points was used. The Novel system uses ten 1.2V nickel metal hydride batteries with 2000 mAh and is run at 330mA. 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 second sensors system, the Polipo is a distributed network of small low-pressure sensors located at different critical locations around the left arm. This sensor has been previously developed as part of this research effort for the low-pressure regime (between 0.5 and 70 kPa) expected to be measured on the body under the soft goods [33]. The data from the Polipo, is not being analyzed in this paper. 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 Wearable Technologies. Each IMU consists of three accelerometers, three gyroscopes, and three magnetometers. A complementary filter combines all the sensor data from each IMU into an orientation quaternion, representing the orientation of each IMU. 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 motions, but their relative orientations allow the detection of off-axis rotations. 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. 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.

Experimental design

Two subjects were tested in David Clark Incorporated Company. They were asked to perform a series of upper body motions inside the spacesuit while lying in the recumbent position. The pressure profiles and angle histories were recorded for each subject. The test protocol consisted of 15 repetitions of 4 different motions inside the spacesuit. A representative schematic of the test protocol is shown in Figure 2. The selected motions engage the upper body, particularly where the sensors are placed. The four motions chosen were three isolated joint motions (elbow flexion/extension, shoulder flexion/extension, and shoulder abduction/adduction) and one multi-joint functional task (cross body reach). Figure 3 shows the cross body reach motion.

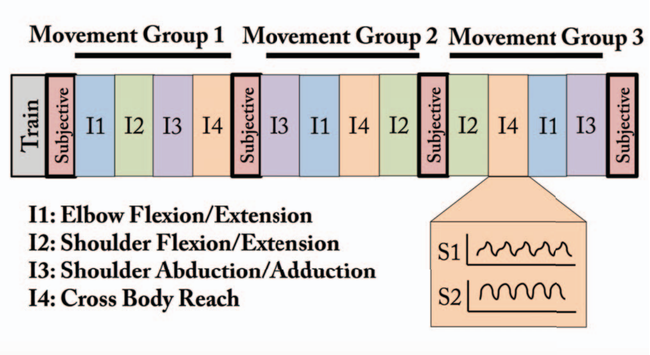

Figure 2. Experiment Design Protocol

Cross Body Reach

The subject begins in a relaxed position and reaches across their body to touch their hip on the opposite side. The subject moves their arm up to chest level and sweeps in front of their body. When the arm is extended in front of the shoulder, the subject touches the helmet on the same side. The movement is then repeated with the opposite arm.

Figure 3. Cross Body Reach Schematic

Prior to the test, subjects were trained on each motion and allowed to repeat it as many times as they desired before the experiment commenced to minimize the effects of learning and maximize motion consistency. For each motion, the 15 repetitions were further subdivided into 3 movement groups of 5 repetitions each. This was done to evaluate subject fatigue or potential change of biomechanical strategies over the course of the test period. After each movement group, 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 motion. This information was also collected prior to the pressurization portion of the experiment to determine initial contact with the suit. Three different pressures were tested: venting pressure at 0.25 psi, intermediate pressure at 2.5 psi, and full pressure at 3.5 psi. Unsuited data was also collected. Outside of the experimental protocol, additional data was recorded in static positions at anthropometric landmarks and certain dynamic motions for the purposes of calibrating the IMUs and determining baseline loading from the suit before the suit was donned. Finally, measurements were performed after the experiment to determine changes from the pre-experiment data.

Spacesuit

The spacesuit tested for this experiment was the David Clark Launch and Entry Development Suit, shown suited with IMUs in Figure 4.

Figure 4. David Clark Launch and Entry Development Suit

The suit is still being developed, so no information can be revealed at this time.

Data analysis

The data for the different systems was first analyzed separately. The IMU data was extracted from each sensor and the quaternion representing the orientation of each IMU were combined to provide information on the elbow and shoulder joint angle. More details of the different operations performed can be found in a previous study [29]. The amplitude of the joint angle was extracted for the isolated tasks and a statistical analysis using a non-parametric test (Kruskal Wallis test) followed by multi-comparison test was performed on the range of motion of each condition, because the data was not normally distributed according to the Shapiro-Wilk test. The Novel data was extracted from the mat and processed for total force on the mat, average pressure (in kPa), and maximum pressure (in kPa). The maximum pressure point represents the maximum pressure felt at any sensor at the mat for that particular time stamp. Then, all 128 sensors were evaluated as a matrix of 8 x 12 sensors (the mat configuration) to view the pressure profiles of the mat over time. Finally, the synchronized data from the two systems were combined in a single analysis. Preliminary results are presented for the shoulder flexion/extension.

3. RESULTS

Kinematics analysis

The maximum amplitude of each motion was analyzed through the different repetitions of the isolated motions (elbow flexion/extension, shoulder flexion/extension, shoulder abduction/adduction) for each of the two subjects. For the shoulder abduction/adduction motions, one of the subject performed off-axis and highly non-planar motions that biased the results and thus was not included in the analysis. Figure 5 presents the mean average of the maximum amplitude of the different motions through the different conditions of pressurization: unsuited, venting pressure (0.25 psi), intermediate pressure (2.5 psi) and full pressure (3.5 psi).

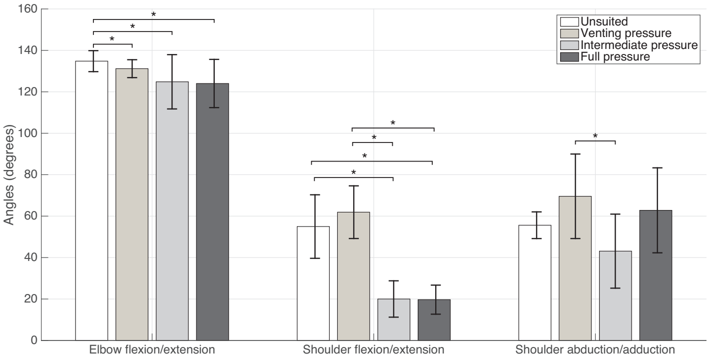

Figure 5. Average Angle Amplitude of Different Motions and Conditions

Overall, the elbow amplitude is very similar to elbow flexion/extension amplitude of human body when standing up unsuited and suited with a range of different suits (MK III, EM-ACES, I-Suit) as seen in England [34]. It is not the case for the shoulder motions due to the recumbent position: the subject performed the motions while seated in a horizontal seat that affected his shoulder mobility. The baseline static position consisted of having the arms bended in front of the body, ready for accessing commands of a spacecraft, with the elbows slightly bent initially, and corresponds to the static position that the suit was designed for. The elbow joint is the joint that has the highest mobility. Overall, there was a significant effect of pressurization on mobility ($X^2(3) = 11.4$, $p= 0.010$). The unsuited mobility was higher than the three different levels of pressurization: venting pressure ($p= 0.009$), intermediate pressure ($p=0.009$) and full pressure ($p=0.031$). There was no significant difference between the levels of pressurization. The shoulder flexion/extension shows a very different profile. There is a significant effect of pressurization on mobility ($X^2(3) = 78.3$, $p<0.001$), but the maximum amplitude does not decrease with the level of pressure. There is no significant difference between the unsuited amplitude or the venting pressure mobility, and no difference between the intermediate pressure and full pressure. However, we see that the shoulder joint is losing its mobility during the flexion/extension between the venting pressure and the intermediate pressure: the unsuited mobility is significantly different than the intermediate pressure ($p<0.001$) and full pressure ($p<0.001$), and the venting pressure mobility is significantly higher than the mobility with intermediate pressure ($p<0.001$) and full pressure ($p<0.001$). It is surprising that the subject mobility seems higher between unsuited and the venting pressure, but this difference is not significant, and is due mostly to the large variability of motions unsuited and suited with venting pressure within and between subjects. There is a significant effect of pressurization on the shoulder abduction/adduction mobility ($X^2(3) = 10.9$, $p= 0.012$), but only the venting and intermediate conditions are significantly different ($p=0.009$). The shoulder abduction/adduction was a highly variable motion due to the non-planar aspect of this motion when the subject was seated and suited.

Table 1. IMU Statistics of Different Motions and Conditions

Condition	Elbow Flex/Ext	Shoulder Flex/Ext	Shoulder Abd/Add
Unsuited	134.8 (5.1)	55.0 (15.3)	55.6 (6.4)
Venting pr.	131.2 (4.3)	61.9 (12.7)	69.6 (20.4)
Intermediate pr.	124.8 (13.1)	20.0 (8.8)	43.1 (17.9)
Full pr.	124.0 (11.6)	19.7 (7.0)	62.8 (20.5)

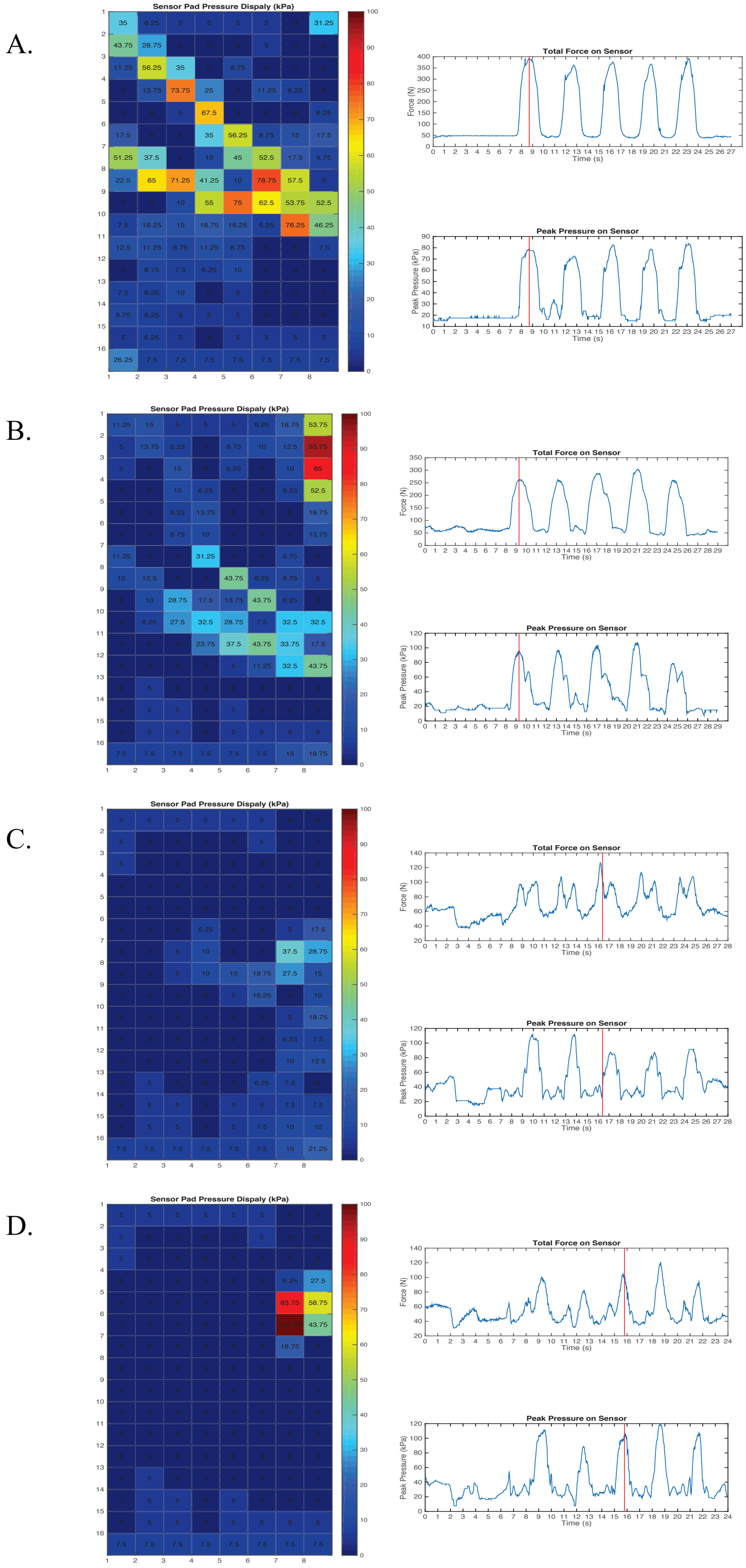

Figure 6. Pressure mat profiles of shoulder flexion-extension at different conditions (*top to bottom: unsuited, 0.25 psi vent pressure, 2.5 psi intermediate pressure, 3.5 psi full pressure*)

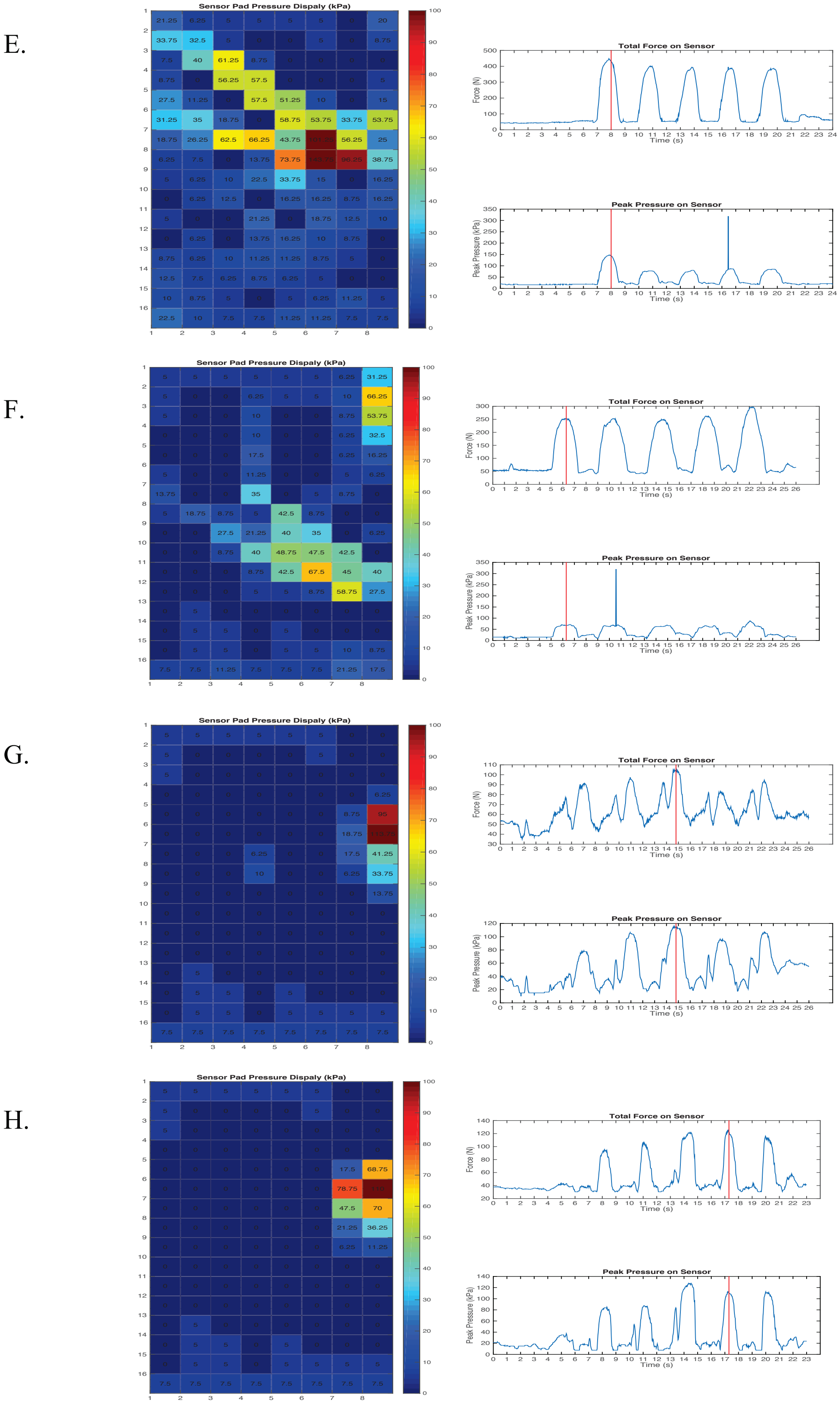

Figure 7. Pressure mat profiles of and shoulder abduction-adduction at different conditions (*top to bottom: unsuited, 0.25 psi vent pressure, 2.5 psi intermediate pressure, 3.5 psi full pressure*)

In-suit pressure analysis

The pressurized mat configuration is shown in Figure 6 and 7, with the top of the mat towards the front of the shoulder, and the bottom of the mat placed to the back of the shoulder. As you move from left to right, the mat is oriented from the inside of the shoulder to the acromion. The graphs to the right of the mat configuration show total force (top graph) and peak pressure (bottom graph) across the five repetitions for each motion's movement group. The most consistent movement group was displayed for the figures. The unsuited pressure profiles for all motions appear to be higher than any suited configuration. Figure 6(a) shows a diagonal pressure band during the unsuited shoulder flexion extension. The wide range of motion caused a crease in the mat at the top of the shoulder, which led to such large pressure and force readings. Figure 6(b) and 6(c) show the pressure profiles at venting and intermediate pressures. Figure 6(d) shows the pressure distribution for shoulder flexion-extension in the fully pressurized configuration at 3.5 psi. As seen in Figure 5, shoulder flexion-extension mobility is significantly impaired. The limited range of motion caused by the fully pressurized suit prevented the subject from reaching the point at which the pressurized mat creased. Figure 6(d) shows he peak pressures during the fully suited configuration reach between 100-120 kPa at an isolated pressure point at the acromion. However, the Novel sensor could have shifted during testing and further geographical validation must be done. Shoulder flexion-extension and shoulder abduction-adduction show similar pressure profiles across the motions. The pressure profiles for shoulder abduction adduction for the unsuited, vent pressure, intermediate pressure, and full pressure configuration are shown in Figure 7. Statistical analyses between motions needs to be done in order to confirm that there is no significant difference across motions for this spacesuit.

Synchronization of the systems

Preliminary results have been processed through the synchronization of the kinematic and the pressure sensor systems. Due to the large variability of the shoulder abduction/adduction motion and the bias reading during the unsuited trial in the pressure sensor, the analysis focused on the shoulder flexion/extension across the different levels of pressurization. Figure 8 shows the in-suit pressure across the mat felt on the shoulder during five different repetitions of the shoulder flexion/extension, across different levels of pressurization. The thick line is the mean and the transparent in represents the combined standard deviation (on kinematic data and pressure data) around the mean.

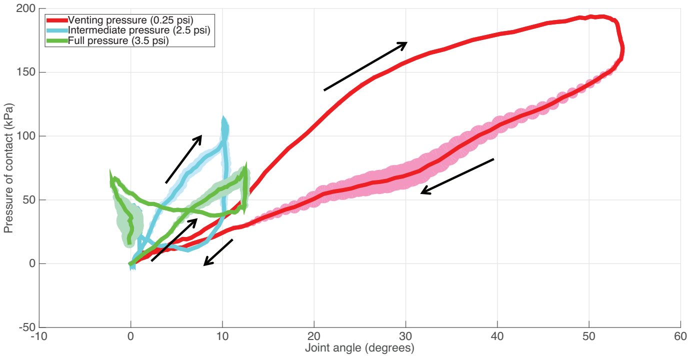

Figure 8. Synchronized Kinematics and Pressure Data for Shoulder Flexion-Extension

The venting pressure motions have the highest mobility and the highest pressure of contact inside the suit. It is due to the fact that, in recumbent position, during the venting pressure, the subject fits very tightly in the suit while during more pressurized condition, the air inside the suit "detached" the suit from the body, actually providing less pressure on the body during motions. The venting pressure profile has a slowly increasing and decreasing pressure profile with mobility, with high hysteresis effect: the pressure felt during the flexion is very different than the pressure felt during the extension. The intermediate pressure shows a more abrupt profile, especially for the transition between flexion and extension, where the pressure of contact substantially drops, due to the suit acting like a spring. The full pressure profile shows a similar profile than the intermediate pressure in terms of range of mobility and pressure and in terms of abrupt drop during the flexion to extension transition. However, we also observe another peak of pressure during the transition between extension and flexion that can barely be seen for the intermediate pressure.

4. DISCUSSION

Kinematics analysis

The suit kinematic analysis gives us different interesting results. First, we do observe an effect of pressurization on mobility as expected and highlighted in the literature. While we see that the recumbent position does not affect elbow mobility, the shoulder mobility for flexion/extension and abduction/adduction motion is smaller than the usual shoulder mobility when the subject stands-up. The different joints lose their mobility at different level of pressurization: while the elbow loses its mobility due to the presence of the suit (the venting pressure being almost a suited unpressurized condition), the shoulder motions lose their amplitude from the venting pressure to higher level of pressurization. The loss of mobility for the shoulder is thus essentially due to the internal pressure (loss of approximately 60% of the mobility), while the elbow maintains a good mobility even with the pressure. There is a much larger variability in the data for the shoulder motions due to the possibility of performing off-axis motions with the shoulder. These first results did not use a dynamic calibration that can be found in previous study [35], and thus fail to recombine the off-axis motions into planar motions. It does explain some non significant but surprising effects showing an unsuited mobility smaller than a suited unpressurized mobility for the shoulder motions. These results are also due to the fact that the subject unsuited tried to mimic the spacesuit motions in terms of direction shape but could not perfectly do so.

In-suit pressure analysis

This suit pressurization analysis shows that pressure profiles appear the same across the isolated joint motions, for the shoulder flexion and shoulder abduction. The elbow flexion-extension data was not analyzed since the pressure mat was located on the shoulder and only minimal data was collected for the elbow flexion extension. The following still needs to be performed: an analysis of the cross body reach, a statistical analysis, a peak-pressure analysis, as well as a frequency of pressure analysis to understand where loading is occurring for an extended period of time as done in [34]. Data must also be normalized for baseline pressure measurements in order to isolate peak pressures during intermediate and full pressure conditions.

Synchronization of the systems

The synchronized results represent a valuable piece of information for spacesuit designer. It is an unique way to link kinematics and intensity of pressure inside the suit and in that sense better understand the cause of injuries and discomfort. While unpressurized (or venting pressure) condition shows a more continuous and gradually increasing and decreasing pressure with the amplitude of the motion, the pressure rises and drops more abruptly when the suit is pressurized. A peak of pressure during at the end of the shoulder extension can be seen for a pressure of 3.5 psi, but not lower pressure. This effect suggests that even though the shoulder mobility is lost at early stages of pressurization, the risk of injuries keeps increasing with increasing levels of pressure.

5. CONCLUSION

Understanding how upper body motions are performed inside the spacesuit is particularly crucial for the current EVA where upper body mobility is critical. This paper showed the impairment of mobility for different joints across different isolated motions and how pressurization impacts both mobility and intensity of contact between the human and the suit. Overall, this research brings a new paradigm to understand human suit interaction through different motions and during different levels of pressurization. It thus allows diagnosing the loss of mobility and the risk of injuries inside the suit separately and in a combined fashion. It replaces the dependence of the kinematics community on expensive, lab-restricted, and heavy visual motion capture systems. This research is also a unique way to open the door to sensing systems inside spacesuit and bring a better understanding and real time monitoring of the astronaut's performance during EVA. This research is also currently extending to other areas: understanding Navy deep dive suits, designing optimal army protection gear.

ACKNOWLEDGEMENTS

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BIOGRAPHY

Pierre Bertrand *is a dual degree graduate student at MIT: master's in Aerospace Engineering and master's in Technology and Policy. He worked as a research assistant with Professor Dava Newman on spacesuit mobility using wearable sensors and stochastic estimation algorithms as a novel method to track biomechanics. Through the Technology and Policy Program, he performed research in public engagement and international cooperation for space agencies. He received a Bachelor in Engineering from Ecole Centrale Paris, in 2012.*

Sabrina Reyes *is a dual degree graduate student at MIT pursuing a master's in Aerospace Engineering and a master's in Technology and Policy. She worked with Professor Dava Newman on characterizing spacesuit injury using wearable pressure sensing systems. She earned her Bachelors of Science in Aerospace Engineering from the United States Naval Academy in 2014.*

Dr. Dava Newman is currently on leave from MIT serving as the NASA Deputy Administrator. Dr. Newman was the Apollo Program Professor of Astronautics at the Massachusetts Institute of Technology (MIT) and affiliate faculty in the Harvard-MIT Health Sciences and Technology Program. Her expertise is in multidisciplinary research that encompasses aerospace biomedical engineering.

Dr. Newman's research studies were carried out through space flight experiments, ground-based simulations, and mathematical modeling. Her past research efforts included: advanced space suit design, dynamics and control of astronaut motion, mission analysis, and engineering systems design and policy analysis. She also had ongoing efforts in assistive technologies to augment human locomotion here on Earth. Dr. Newman is the author of Interactive Aerospace Engineering and Design, an introductory engineering textbook published by McGraw-Hill, Inc. in 2002. She has published more than 250 papers in journals and refereed conferences.