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Key Personnel Changes/Previous PI:	(I) The PI and Co-I remain the same. (II) We are actively working with all of the NASA personnel listed below: Terry Hill, Crew Health & Safety Deputy Manager, NASA Johnson Space Center; Jason Norcross, EVA Discipline Co-Lead Scientist, Wyle Science, Technology and Engineering Group; Jessica Vos, Multisystem Portfolio Manager, NASA Johnson Space Center; Amy Ross, Technical Manager, Space Suit Technology Development Group, Johnson Space Center; Shane McFarland, Senior Engineer, Space Suit Technology Development Group, Johnson Space Center; Sudhakar Rajulu, Ph.D., Technical Manager, Anthropometry and Biomechanics Facility, Johnson Space Center.		
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Task Description:

The objective of this research is to understand human-space suit interaction and design hardware to assess and mitigate injury and discomfort inside the space suit. This will be achieved through the following specific aims.

1.1.1 Specific Aim 1: Analyze data for correlations between anthropometry, space suit components, and injury.

Shoulder injuries are some of the most serious and debilitating injuries associated with EVA (extravehicular activity) training. Using a database compiled by NASA personnel on subject anthropometry, training time in different space suit components, and reported shoulder incidents, the following hypotheses will be evaluated:

Hypothesis 1: Anthropometric dimensions will be a predictive factor in identifying astronauts with a reported shoulder incident.

Hypothesis 2: Suit training variables in the planar hard upper torso (HUT), rather than training in the pivoted HUT, will be a predictive factor in identifying astronauts with a reported shoulder incident. Suit training variables are defined by aggregating training information, such number of or percentage of training incidences in the planar or pivoted HUT.

Hypothesis 3: Operational training variables will be a predictive factor in identifying astronauts with a reported shoulder incident. Operational training variables are defined by aggregating training information, such as frequency of training, accumulation of days between training incidences, or career duration of active duty training.

Hypothesis 4: Record of previous injury will be a predictive factor in identifying astronauts with an additional shoulder incident.

Each of these hypotheses investigates a specific causal mechanism found in the literature associated with EVA shoulder injuries and relates it to a reported shoulder incident. Hypothesis 4 will only be evaluated for those subjects with injury incidents directly attributable to the space suit.

1.1.2 Specific Aim 2: Quantify and evaluate human-space suit interaction with a suite of sensors. There is currently no method by which to measure how the person moves inside the space suit. Focusing on the upper body, a pressure sensing tool will be created to quantify human-space suit interaction under different loading regimes. Additionally, a commercially purchased pressure sensing tool will be used over the shoulder under the space suit Hard Upper Torso (HUT). Finally, inertial measurement units (IMUs) will be used to measure and assess kinematics both of the suit and the person inside.

The following design requirements will be evaluated to determine the success or failure in designing a wearable pressure sensing garment for the space suit environment:

Design Requirement 1: A pressure sensing tool will achieve both high wearability and high utility in a space suit environment. Wearability is defined by mobility, comfort, and safety of the user. Utility is defined by range, accuracy, resolution, and coverage of the sensor system.

Design Requirement 2: Human and space suit interaction characterized by interface pressures will show trends consistent with expected loading regimes. Trends are defined by sensor pressure profiles over isolated or functional tasks. Expected loading regimes are defined by subjective feedback or inferred loading based on anticipated contact.

Design Requirement 1 evaluates the performance of the pressure sensing system to ensure it is properly scoped for its intended use. Design Requirement 2 investigates the system's ability to function properly in the environment of the space suit so its results may be interpreted with confidence.

The pressure sensing tool will be used to evaluate human-space suit interaction to assess consistency of movement. Consistency of movement is an important metric revealing fatigue or changes in biomechanical strategies, both of which could be precursors to EVA injury. The following hypothesis will be evaluated in a human subject experiment inside the space suit:

Hypothesis 5: Subjects with experience working in the space suit will perform motion tasks with consistent movement strategies. Movement strategies are defined by peak pressures averaged over trials or full time averaged pressure profiles.

The commercially purchased pressure sensing tool that is placed at the interface between the shoulder and the Hard Upper Torso will be used to quantify and analyze the pressure distributions and profiles that arise in this region, thus developing a biomechanical understanding of the potential for shoulder injury in pressurized suits. A human subject experiment was performed inside the space suit to evaluate motions and regions that are particularly prone to injury. We determine subject-specific anthropometric regions of concern by considering pressure distributions, frequency of loading, and regional pressure responses. Subject consistency is also evaluated through statistical analysis of the peak pressures.

Hypothesis 6: Subjects perform motion tasks in a consistent manner as measured by pressure values over the shoulder. The kinematic sensors (IMUs) will be used to evaluate human-space suit interaction between body motions and suit motions. Externally measureable suit kinematics may not reflect the human body's motions inside the suit due to complex design involving non planar bearing or convolutes and pressurization. The following hypothesis will be evaluated in a human subject experiment inside the space suit:

Hypothesis 7: Body and suit joint angle amplitude differ significantly in amplitude for upper body motions.

Hypothesis 8: Body and suit joint angle differ significantly in axis of rotation for upper body motions. The purpose of Hypotheses 6 and 7 are to evaluate differences in suited motion between the person and the space suit. Additionally, we seek to evaluate the impairment of mobility for upper body joints in different suits, using IMUs, as compared to baseline range of motion. The following hypothesis will be evaluated in a human subject experiment inside the space suit:

Hypothesis 9: Space suit pressurization significantly impairs the joint angle amplitude of upper body motions.

1.1.3 Specific Aim 3: Model human-space suit interaction. The purpose of SA3 is to gain a better understanding of the EVA injury mechanisms, particularly strain injuries caused by the Extravehicular Mobility Unit (EMU). The objective is to determine the extent to which muscle activity is affected by the presence of the highly-pressurized space suit. A musculoskeletal human-space suit interaction model is developed in order to quantify musculoskeletal performance of astronauts during Extravehicular Activity, and to assess their injury susceptibility.

1.1.4 Specific Aim 4: Design and Develop modular protective devices. Our work develops conceptual solutions to

mitigate injury. As part of this effort, we identify promising materials and build prototype protective devices. We aim to alleviate injury prone areas and improve the person's comfort within the suit. Protective devices will be integrated to the protective garments and can be personalized for each crewmember.

Rationale for HRP Directed Research:

The need to mitigate injury and discomfort is not exclusive to the harsh environment of space. The contributions from this work have the potential to be used in other extreme working environments, such as dry-suit scuba diving and high altitude pilots. In both cases, gas-pressurized suits are worn and have similar rigidity. The envisioned countermeasure and protection system capability may also be used in biomedical and rehabilitation applications. The elderly population often encounter minor trauma, but with much more severe consequences than their younger counterparts. Falls resulting in hip fractures place a disproportionate burden on healthcare costs, recovery, and death (Hayes, Myers et al. 1996). Hip injury is highly variable with position, muscle tension, and individual factors, making predicting and preventing injuries both important and challenging (Hayes, Myers et al. 1996). Injury prevention both in extreme work environments and against fall impacts for the elderly are promising crossover applications. The transferability to each of these environments warrants further study.

Research Impact/Earth Benefits:

Our team is very active in bringing our work and passion for human spaceflight to the general public through outreach. Our education and outreach efforts increase the visibility of human spaceflight and astronaut injury. We have participated in informal education through talks at museums, such as at the ExplorationWorks museum in Helena, MT where human spaceflight exhibits were developed by our team and bring space education to a chronically underserved area. We have also provided extensive outreach through many talks to the public, media, and general audiences, such as Think2012 (Goa, India), Suited for Space (American Textile History Museum; Lowell, MA), Business Innovation Forum 9 (Providence, RI). We have also given numerous tours of our lab and facilities to elementary, middle, and high school students, as well as international visitors and students from other universities. Finally, our team members have volunteered to participate in classroom teaching programs for middle and high school students. One such example is the SEED Academy developed at MIT where high school students come for 10 Saturdays and take a course in Aeronautics and Astronautics, learning about human spaceflight. Our efforts are always geared toward improving STEM (science, technology, engineering and math) education, whether in a formal classroom setting or through interactions with the general public.

We have completed our grant reporting period. The major contributions of our research effort are outlined below: Specific Aim 1: Statistical Shoulder Injury Analysis. The first specific aim is to analyze data for correlations between anthropometry, space suit components, and shoulder injury. Four hypotheses were proposed to relate injury to 1) body morphologies, 2) space suit HUT components, 3) training variables, and 4) previous injury. Each hypothesis was confirmed, since for both models variables for each of the first three hypotheses were identified and record of previous injury was associated with the Neutral Buoyancy Laboratory (NBL) model.

The major contributions of this work are to: 1) Add quantitative statistical analysis to the causal mechanisms of injury found in the literature. 2) Provide a framework for identifying relevant predictor variables related to injury given the small number of data points, large number of predictor variables, and the differences in their distributions. 3) Identify variables related to injury which can be addressed and resolved through operational changes to training, suit design and accommodation, and identification of higher risk subjects given previous medical history. 4) Propose future areas of study for which additional data may continue to be collected and analyzed, such as HUT sizing information as related to clearance anthropometry.

These contributions address the current gap in our understanding of the causal mechanisms of injury. Although HUT style has been reported as a major cause based on anecdotal evidence (Williams and Johnson 2003, Strauss 2004), it has not been until recently that this causal mechanism has been quantitatively evaluated (Scheuring, McCullouch et al., 2012). This research corroborates these findings, but expands upon them to include additional relevant factors not previously explored. It also includes other shoulder incidents, which, although not defined as medical injuries, have had negative impact on crew comfort and health, as well as impacting an astronaut's operational availability. This work also supports the conclusions reached by Williams and Johnson (2003) regarding the import of the training environment as a contributory factor, but this is the first quantitative assessment of the impacts of training frequency and recovery. Finally, it supports that suit fit is essential to achieve the optimal working environment (Benson and Rajulu 2009, Gast and Moore 2010) and allows future designs to pinpoint the most relevant anthropometric dimensions for suit fit accommodation. This work provides a quantitative analysis through data mining grounded in our historical understanding of the use of the EMU and NBL training environment. The remainder of this research allows a look forward into how additional data collection on human-space suit interaction can help prevent the occurrence of future injury and discomfort.

Specific Aim 2: Experimental Evaluation of Human-space Suit Interaction. Development of a wearable pressure sensing garment. The novel Polipo low-pressure sensing system for extreme environments achieved here has many advantages. With the Polipo human-suit interaction can be measured for the first time through dynamic movement. It can accurately measure low-pressures against the body over underneath the soft-goods. The system of 12 sensors is transferable between many different people, creating an independent stand-alone pressure-sensing system. Sensors can easily be changed to allow for improved designs or to accommodate different target pressures. The wiring was intentionally designed to achieve the best trade-off between flexibility, resistance, and stretch ability. The system achieves near shirt-sleeve mobility as sensors are moved to accommodate users. It can also be used in conjunction with a high-pressure sensing mat placed over the shoulder to measure loading between the person and HUT. The electronics architecture allows for low power onboard or real-time data collection. The entire system has been designed with extreme environments in mind, where considerations of shock, battery hazards, and material properties in mixed gas environments were minimized to ensure user safety. Finally, it has a cover shirt to slide easily over the system and prevent catching and ensure proper placement. Nearly all requirements were met and those that were not were evaluated for extent of their impact on the system performance. Therefore, this work confirms Design Requirement 1 "A pressure sensing tool will achieve both high wearability and high utility in a space suit environment." This system could easily be extrapolated to other environments where biomechanics and comfort under load needs to be evaluated, for example, soldier pack accommodation or wearable protective devices for the elderly where discomfort substantially decreases compliance.

The Polipo system in its described configuration was used in a human subject experiment inside the space suit. These experiments validated the system's performance in the space suit environment and confirmed the conclusions reached after the assessment of the requirements presented here.

The primary contributions of this work are to: 1) Establish baseline requirements for in-suit sensing and wearable electronics. 2) Develop pressure sensors and evaluate their performance for human movement applications. 3) Develop a wearable, stand-alone pressure-sensing system to be used for a large group of subjects in harsh working environments. 4) Create a system that is specifically targeted to provide quantitative information about human-space suit interaction not previously possible.

The Polipo system as designed overcomes the issues associated with wearable electronics in that it allows for high mobility at low-pressure with less encumbrance from hardware and wired data transfer (Cork 2007; Witt and Jones 2007; Brimacombe, D. Wilson et al., 2009). It builds upon previous sensor designs (Park, Majidi et al., 2010; Park, Chen et al., 2012) to measure normal pressures targeted to the 5-60 kPa range through dynamic motion. In-suit sensing concepts have focused on traditional physiologic measures (Carr 2000, Dismukes 2002, Catrysse 2004, Tang 2007) or display and control information (Rochlis 2000, Graziosi 2005, van Erp 2005, Graziosi 2006). The Polipo builds from previous in-suit wearable electronics, but expands upon it to establish design requirements and a precedent for implementation. Future iterations of the pressure sensing system could utilize work done on distributed computing and data collection in a space suit environment to allow for sensor coverage over the entire body (Carr 2002, Simon 2013, Taj-Eldin 2013). The results presented demonstrate the Polipo's success in meeting its targeted design. The following demonstrates its performance in the pressurized suit environment and its utility to elucidate human-space suit interaction.

Experimental Analysis. 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 and is our first glimpse "inside the space suit" and will be the baseline for future studies.

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, which 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 successful in opening the door for this type of space suit testing. The data provide valuable insight into how motions occur, how consistent subjects are, and how discomfort and fatigue may build up over time while working in the suit. It demonstrates the value in using pressure sensing to characterize human-suit interaction in a way not previously possible. The implications of the test are valuable in finding an initial baseline of human-suit interaction and will guide future tests to optimize sensor design, influence space suit design, and ultimately prevent injuries that occur inside the space suit.

The primary contributions of this work are to: 1) Establish a precedent for pressurized human subject testing in the space suit and a baseline for pressure interface interaction. 2) Validate the use of the Polipo in the space suit environment and suggest future pressurized suit testing work. 3) Add quantitative information to subjective feedback on human suit interaction. 4) Assess human movement inside the suit through the temporal activation of sensor located over the arm. 5) Use peak pressures to assess the consistency of subjects' movement as a means to evaluate discomfort, fatigue, or change in movement with an eye toward injury prevention.

This is the first work to use untethered pressure sensing systems to measure the contact interface between the person and space suit. Space suit evaluation is traditionally measured treating the human and space suit as a system, evaluating gross metrics of performance (Morgan, Wilmington et al., 1996; Jaramillo, Angermiller et al., 2008; Matty and Aitchison 2009; Norcross, Lee et al., 2009; Norcross 2010; Aitchison 2012; Valish and Eversley 2012). Previously, no technology has allowed their separation. This system is the first to specifically target the interface between the person and space suit at the body's surface to overcome this limitation, allowing us to move beyond external visual measures, such as motion capture and photogrammetry. Recent work on joint angle kinematics of the person and space suit as measured independently have allowed us to look at these differences (Di Capua and Akin 2012; Kobrick, C. Carr et al., 2012; Bertrand, Anderson et al., 2014), but they provide limited information regarding the injury mechanisms of space suited motion. This new capability allows us to index a person inside the suit and quantify contact pressures to assess propensity for injury and discomfort.

This experiment has proven that in-suit sensing with pressure and inertial sensors can provide new and interesting results aimed at enhanced space suit design and improved astronaut performance for space exploration. Future experiments should improve the integration of the three data collection systems. 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. Detailed conclusions are presented for each system below.

The results and discussion of the Novel sensor presented above provide us with an "inside look" of how the Mark III space suit affects the pressure distributions and pressure profiles experienced at the shoulder. From the pressure distribution analysis, we came to a few general observations: 1) the least experienced subject generated the highest pressures, 2) the region just above the clavicle over the soft musculature at the top of the shoulder is of particular concern, as pressure was concentrated in this location for the majority of movements for all subjects, and it is also one of the regions in which maximum pressure is located most frequently, and 3) the top of the shoulder blade is a secondary region of concern for some subjects, as it experiences maximum pressure with mid-to-high frequency. We also made a number of detailed observations on each of the four movements for each subject and how these individual distributions are affected by the suit. From the pressure profile analysis, we determined that 1) for most subjects,

general profile trends vary in shape across movement groups, 2) repetitions within each movement group are consistent in shape, and for most subjects also in magnitude, 3) the highest pressures are typically found near the top of the shoulder, and 4) the shoulder blade area is of concern for at least one subject. Again we also made a number of detailed observations on the profiles of individual motions. A brief statistical study for consistency of peak pressures reached in each of the motions suggests that subjects were not necessarily performing motions consistently despite their subjective feedback responses that stated otherwise. Further studies should integrate pressure data with joint angle information, so that we can determine at exactly what point in the motion these peak pressures are arising, how different movement strategies affect the pressure profiles and distributions of pressure, and how suited motions compare to unsuited ones. All of this information would allow us to more accurately determine when injury is most probable, and therefore aid in preventing such issues.

IMUs are low-powered, light, small, mobile, and represent an efficient technology to better understand these interactions hidden by the suit. The study has confirmed and specified the impairment of mobility in the elbow and the shoulder joints across different pressurized suits. Further work will focus on developing a 3 dimensional (3D) visualizer of IMUs that uses quaternion data directly in order to avoid the Euler angle singularity, and a better understanding multiple axis motions. Additional joints could be studied using new motions. Future work includes analyzing this information with the 3D visualizer. The IMUs could also be used to assess kinematics during a field experiment or during underwater training, while the motion capture video system is limited to laboratory settings. Studying in-suit kinematics could be particularly relevant for quantifying the difference between dry and wet space suit immersion during underwater training.

Specific Aim 3: Human-Space Suit Interaction Modeling. A new framework has been developed to analyze human-space suit interaction during EVA. The musculoskeletal analysis being developed will provide new insights into the human musculoskeletal performance inside the space suit, and will contribute to the assessment of astronaut health and safety during EVA. Ongoing research includes analysis of data in the MarkIII-suited conditions, together with knee flexion/extension motion capture data from subjects wearing the EMU and MKIII collected at Johnson Space Center. Future work includes refining the space suit model by incorporating EMU torques in other joints, and using a more accurate human musculoskeletal model that contains musculotendon actuators in the upper torso and arms.

The primary advantage to this approach is that it allows to us model the biomechanics of an astronaut inside the space suit, without needing to model the space suit itself. This would be both time intensive and limited in accuracy, given the current state of space suit models and dimensions.

The modeling research effort will address the EVA 11 gap by providing a biomechanical understanding of how the human interacts with the space suit. The biomechanical and musculoskeletal analysis will provide information about kinematics and muscle activation to accomplish specific tasks, either single joint movements or more complex movements representative of EVA activity. As the simulations improve, a more accurate muscle activity analysis will give an understanding of how muscle injuries occur during EVA, both in training and in-flight.

Specific Aim 4: Prototype Design. The present injury of astronauts during training and space operations are significant. Some injuries are mild, such as skin being chafed or irritated; others are more severe, such as sprains, torn muscles or ligaments. The preventive protecting system being used today provides the astronaut with foam pads sometimes layered with a rigid Teflon sheet. These vary in thickness depending on the size of the astronauts, and their physical relationship to the space suit. Although this system has proved to be effective, astronauts still report pain, and are getting injured.

Injuries happen when donning, training operations in the NBL, and during EVAs in space. We focus our work on the injuries incurred during training operations.

Our findings show that:

1) The simplest and most economic solutions are passive, such as foam pads. 2) The materials and combinations thereof to be used are extensive, and permanently being introduced to the market. There is an explosion on materials used in commercial protective garments for sports. 3) Foams and plates design in an articulated grid, such as hexagons, allow for much better contouring and conforming with the body than solid, monolithic foams and other materials. 4) Proper covering, contouring, and shaping of the pads to follow the shape and curves of the body dramatically reduces the possibility of injuries and increases comfort. 5) The thickness of the protection system varies significantly with different astronauts. Therefore increasing the selection of materials to the existing ones is a major step to improving the system, and reducing injuries. 6) The attachment method of the protecting system to the Liquid Cooling and Ventilation Garment (LCVG) could be improved to enhance efficiency and speed of installation. It is not a major contributor to injuries. However, the better the attachment and the more integrated the protection system is to the LCVG the better it will perform. 7) From the limited amount of designs and fabricated systems we tested, we can project that the active Airbag Protecting Systems (APS), although more expensive and more time consuming to fabricate can provide better protection during operations, and facilitate the donning procedures. 8) With a small investment on tooling the fabrication of the APS can be done on site at the NBL. 9) Further investigation of the APS inflating mechanism and pressure control at different atmospheric pressures are required. 10) In addition to protective systems, a rigorous and individualized training program needs to be developed for every astronaut on the donning, doffing, and operation of the space suit.

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Task Progress:

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