Developing a Spacesuit Injury Countermeasure System for Extravehicular Activity: Modeling and Analysis

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Extravehicular activity (EVA) is one of the most critical enabling capabilities for human spaceflight. Performing EVA is both technically challenging and physically demanding, requiring many hours of training and detailed preparation. As a result of working and training in the extravehicular mobility unit (EMU) spacesuit, many astronauts sustain musculoskeletal and minor injuries. Although injuries are typically minor and self-limited, they have the potential to impact mission success. We outline our research methodology to investigate EVA injury ultimately providing solutions that can be implemented both in the EMU and in future spacesuit designs. We review the issues and mechanisms causing injury as documented in the literature. The result of this work will be an injury database with input from many NASA stakeholders. We also highlight our work to model the astronaut performing realistic EVA motions to study the interaction between the person and the suit. Spacesuit models of the EMU and Mark III spacesuits will be used in combination with a human body model driven by the biomechanics of EVA motions. We will investigate joint torque, muscle activation, and contact pressure between the body and suit. This modeling effort informs our spacesuit injury countermeasure designs and recommendations. We present our design process for protection devices that ameliorate current astronaut suit-induced injuries.

I. Introduction

EXTRAVEHICULAR activity (EVA) is critical for human spaceflight to achieve tasks such as habitat construction, hardware repair, and exploration. These activities are complex, requiring substantial preparation to be executed safely and successfully. Despite its many advantages, these activities are not without cost to those who perform the EVA. The U.S. spacesuit, the extravehicular mobility unit (EMU), is simultaneously an amazing engineering achievement as well as a challenging environment in which to work. The EMU is pressurized to 4.3 psi

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(29.6 kPa), forcing the astronaut to expend energy to bend and move the suit to perform tasks, which limits mobility(1-3). Despite attempts to improve its functionality and comfort, the EMU has associated with injury and irritation(4-9).

EVA in the immediate future will continue to be performed in microgravity. However, the next generation spacesuit will need to be optimized for both microgravity and planetary environments(2, 10, 11). Enhanced designs, modeling, and injury tracking tools are needed in order to predict and prevent astronaut injury beyond what can be tested on the Earth's surface.

II. EVA Related Injury

The EMU and currently used comfort/protection garments are seen in Figure 1A. Many of the components are available in multiple sizes to allow astronauts to mix pieces and provide a better fit. The hard upper torso (HUT) is a hard fiberglass shell forming the central structural component of the EMU on which other suit pieces are mounted. A planar HUT design is used on orbit and replaced the pivoted HUT design. The pivoted HUT allowed for greater shoulder mobility at the shoulder scye bearing, but is only used in no longer used on orbit(9). The arm pieces are made of fabric and are designed to maintain nearly constant volume during movement to improve mobility. Sizing inserts can change the length to accommodate astronauts of different sizes. The glove attaches to the soft arm pieces through the wrist bearing. There are many glove sizes, some of which are custom made for astronauts. The lower torso assembly covers the trunk from the waist, pants, and boots. It connects to the HUT at the waist bearing and to the leg pieces through another bearing. Mobility in the hips and knees is limited, but is usually not required for microgravity operations. The knee and elbow joints use a convolute pattern to improve mobility. The boots come in two sizes and do not have structure built in, other than the flat sole(12, 13).

The protective comfort pieces are worn to mitigate some of the negative effects of wearing the ~140 kg spacesuit, seen in Figure 1B. The primary component is the liquid cooling ventilation garment (LCVG). It regulates body temperature by circulating water through Tygon tubing so it flows over the body and absorbs heat from the skin. Additionally, the LCVG circulates air in the suit by moving air from the extremities returning it to the portable life support system (PLSS). The LCVG covers the body from the wrists to the ankles and neck(12-14). An optional suit element used to protect the hand is a comfort glove, which prevents rubbing and absorbs moisture, however, some astronauts choose not to wear it to improve their finger tactility(15). A wrist cuff (essentially the upper part of an athletic sock) is also an option. The boots are modified to accommodate multiple users with sizing inserts. These inserts partially fill the boot volume, but are not optimized for protection. An optional internal toe cover may be used to protect against impact(5). Current injury countermeasures accommodate thin strips of padding that can be sewn to the LCVG in areas where astronauts may feel hot spots of discomfort; however, they are not intended for long-term use(1, 5). The HUT has a built–in harness system with restraint straps to prevent shifting during training. This system has recently been brought back into use, but is optional(9, 13).

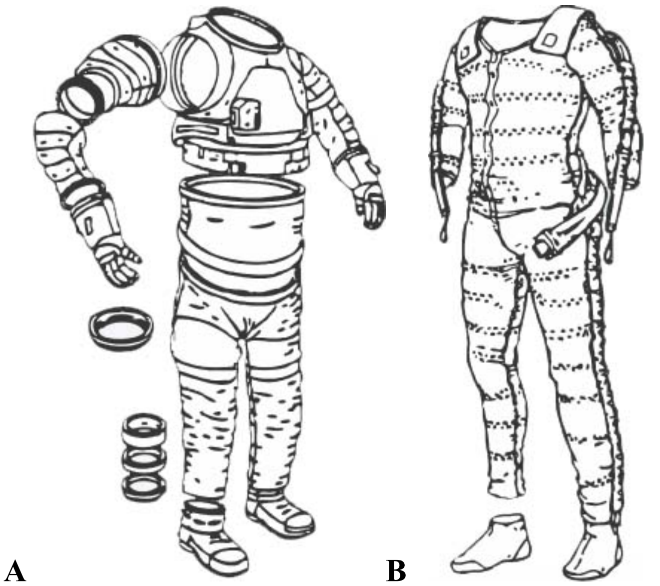

Figure 1. EMU spacesuit pieces and comfort garments. *A)The EMU in an exploded view so the hard upper torso, soft pieces sizing rings, and boots may be seen. Courtesy of Hamilton Sunstrand. B) Each of the comfort pieces, including the LCVG with padding, ventilation tubes, and boot inserts. Courtesy of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

Although no EVA-related injury has prevented successful completion of a mission objective, there are several cases of near mission impact. Scheuring et al. reported 0.26 injuries per EVA, a dramatic increase over injuries in other phases of flight(8). The importance of EVA-associated injuries has been highlighted with the increased number of EVAs and training sessions in the Neutral Buoyancy Lab (NBL)(9). Although astronauts and some tools are made neutrally buoyant to simulate the weightlessness of microgravity, NBL training is very fatiguing and leads to many types of injuries. Time constraints may also prevent astronauts from fully recovering before performing another session in the NBL(5, 6, 16). The effects of gravity (1G) cause additional injuries not seen on–orbit as the person changes orientation and shifts inside the suit. Figure 2 shows representative regions on the body where astronauts incur injury inside the EMU.

Hand and finger injuries are the most common injuries both during training and in–flight. They are also some of the most serious. Injuries include onycholysis, or fingernail delamination, blisters, contusions, and abrasions(5, 6, 8, 15, 17, 18). Astronauts size their suits based on personal preference, optimizing whether they prefer working either near or far from suit contact (i.e., tighter or looser fitting suit)(15). Resolving hand injury is one of the most difficult challenges spacesuit designers face and is not addressed in this research effort, nor reported on herein.

Shoulder injuries typically occur during training and are some of the most severe injuries astronauts face. These injuries are extensively covered by Williams and Johnson(9). In a study by Strauss, thirteen of the study's twenty-two participants were followed for shoulder-related injuries, and two required surgical interventions(6). There are two primary causes for EVA-related shoulder injury: restriction of normal shoulder movement by the HUT and supporting body weight against the HUT. Depending on the lateral position of the scye bearings, scapulothoracic motion can be restricted, preventing normal shoulder abduction and adduction. To compensate, astronauts rely more heavily on the rotator cuff muscles, which normally stabilize the joint, causing overuse of the rotator cuff, leading to injury(9). Additionally, as astronauts shift within the suit during training, their bodies press up against the HUT, resting their weight on their shoulders. This is particularly true when the astronaut is in an inverted position, either fully head down, face forward, or face upward. Resting weight on the shoulder impinges on the rotator cuff muscles, causing tears and pinched nerves, in addition to causing uncomfortable pressure contacts(5, 9). Inverted NBL training is still performed, but in limited duration.

The primary injuries that occur at the limb joints (wrist, arms, knees, and ankles) are abrasions and contusions as a result of rubbing and impact against the soft suit components to move the garment. When the convolute suit joint is not aligned well with the body joint, the propensity for injury is increased(5, 19).

Hip and trunk injuries on orbit are fairly limited. They are primarily caused by impact and rubbing with the HUT, waist bearings, and soft elements resulting in abrasions and contusions. In training, additional injuries are seen in both the face-up and face-down supine position, since the weight of the astronaut is supported by the HUT and the ventilation tubes of the LCVG. This pressure can lead to skin indentation and reddening(6, 8).

Many EVA tasks are performed in footholds as the primary restraint. Although the EMU is designed with limited lower body mobility, astronauts must produce a counter torque by flexing leg and ankle muscles to maintain proper orientation while they work. Poor fitting boots and boot inserts allow the astronaut to rotate backward, causing the foot and toes to impact and rub against the boot(5). Additional discomfort is caused by bootie and pressure layer wrinkles, which cause blisters, contusions, abrasions and loss of feeling. In one instance, this almost led to early termination of the EVA(8). In training and during experiments to evaluate planetary locomotion and exploration procedures, the shifting body also causes the tops of the foot and distal toes to impact the boot(5, 20).

Figure 2. EMU injury hotspots. *Conceptual representation of the areas where injuries and pressure contact points most often occur from the EMU.*

III. Spacesuit Ergonomics

The biomechanics of movement in the spacesuit have been studied both experimentally and theoretically. Typically, however, many efforts have not been specifically directed at resolving issues associated with EVA injury.

There have been many experiments to characterize range of motion, work envelope, reach envelope, and the suited strength required to move the suit. Example data from work envelope and reach tests is seen Figure 3. Although none of these types of test are specific to EVA injury, their analyses have implications for the problem and lead to a greater understanding of human-suit interaction. One of the most commonly studied metrics is joint torque required to move the suit. There are three testing methodologies: unsuited externally applied torque(21, 22), robotically applied internal torque(21, 23), and suited internally applied torque(24). Unsuited, externally applied torques are perhaps the easiest to measure, but do not account for the additional

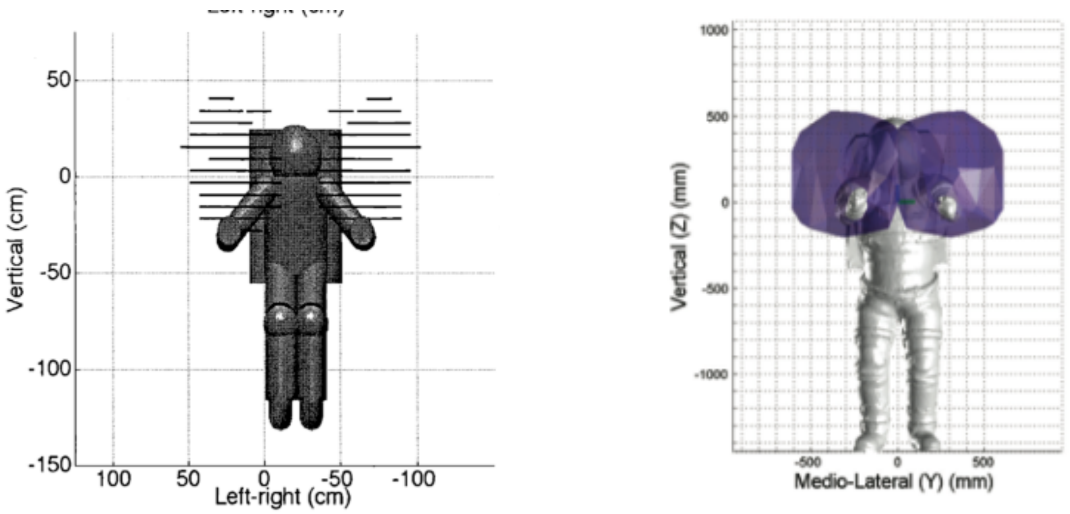

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Figure 3. Example work envelope modeling and experimental suit testing. *A) Modeled data shown for female of size 50th percentile with 95% strength. Image taken from Schmidt 2001 B) Experimental data shown for male crew member with arm length between 57 and 60cm. Image used with permission from Jaramillo and Rajulu, 2008.*

volume taken by the human. It is not possible to achieve accurate torque data from human suited testing, but is the most desirable information. Robotic testing has the advantage of being repeatable while still accounting for the way the spacesuit geometry changes when articulated internally, but only partially represents the volume of a person. Data among these three testing methodologies is highly variable. Additionally, there has been a recent increase in spacesuit testing on newer spacesuits, such as the Mark III and I-Suit, including metabolic measurements, operational feasibility,(11, 20) and range of motion data(25, 26). Additional testing on newer suit configurations is ongoing.

Although there are many studies, the fundamental limitation is generalizability between suits, people, and diversity in test conditions. EVA modeling helps bridge the knowledge gap between experimental data and future spacesuit design recommendations and concepts. Work envelope has been the primary human-spacesuit interaction modeled, which is then compared to experimental subject testing(21, 25). Schmidt and Newman also derived theoretical models for spacesuit joint torques and the metabolic costs of EVA(21, 27). Additionally, scenario-based EVA modeling helps give a greater understanding of how the astronaut interacts with the environment(28, 29). These efforts, however, have not focused on how the suit impacts and constrains the wearer and where contact between the person and the suit occurs, which is critical information to reduce EVA injury.

The causes of these injuries may include improper suit fit, shifting or improper use of protective garments, and repetitive motion working against the suit(5, 9, 19). Current injury prevention is achieved by workaround modifications to the suit environment and individual physical training, rather than by implementing substantive design changes. Although this may be acceptable for short-term prevention, the system must be modified to find long-term solutions. A greater understanding of human-suit interaction would help achieve future suit designs to minimize injury caused by the next generation of spacesuits.

IV. Current Research

This research effort strives to improve future spacesuit design by contributing to injury analysis in three different areas. The first aspect of the project develops a comprehensive astronaut injury database specific to EVA. The second objective is to build a human-spacesuit interaction model to reproduce the motion of the human inside the spacesuit to simulate the mechanisms of spacesuit injuries. Finally, the third objective is to design new prototype protection devices that will address the underlying causes of astronaut injuries elucidated by the database and modeling work.

A. Database

The primary objective of the astronaut spacesuit injury database is to gain insight into the mechanisms of spacesuit injuries. This information will help us identify focus areas for our human-suit interaction model and prototype design. It will leverage current efforts to consolidate all types of injury and health information ongoing at NASA JSC. The database will be useful in tracking countermeasures and assessing their effectiveness.

In the first phase of research we have identified existing sources of information for the EVA injury database, a summary of which is seen in Table 1. The Injury Tracking System (ITS) is an astronaut injury database that contains pre-, in-, and post-flight information. It is one of the most complete existing sources of injury data today(30). However, it also includes injury data not related to the spacesuit. The Lifetime Study of Astronaut Health (LSAH), formerly the Longitudinal Study of Astronaut Health, program was created to assess long-term health issues of the astronauts during spaceflight and training. The program keeps track of astronaut medical records. The former LSAH used JSC employees as control group(31), but is now used only to track astronauts. However, injuries related to spacesuit are in general short-term injuries, whereas the LSAH is more focused on long-term concerns. Finally, the Astronaut Strength and Conditioning and Rehabilitation Program (ASCR) program was designed for astronauts to meet the physical demands of spaceflight and their return to Earth's gravity. Personal records, rehabilitation programs, as well as the personnel involved in the program constitute useful sources of injury information. Each of these resources contains different types of information, potentially spanning the entire career of the astronaut.

In our next phase of research, we will work in collaboration with the NASA JSC team lead by Dr. Scheuring, consisting of experts in the field of astronaut and EVA injury. Dr. Scheuring's team is combining information from the previously described sources into a comprehensive injury database. Data such as form, severity, location, and pre-disposing factors leading to the injury will be recorded and consolidated in a searchable format. Our work will use this resource to inform our modeling and design work. We will contribute to the database by collecting additional information through astronaut and suit expert interviews, oral histories, and astronaut debriefs. We hope to not only include clinically documented injuries, but also some of the more subtle aspects of physical discomfort felt during EVA. We also intend to include public engagement by soliciting input from the public for novel ideas for prevention and protection from injuries. Our work will allow future researchers, spacesuit designers and engineers, medical personnel, and other stakeholders to gain new insight into the problems associated with EVA injury and discomfort, and to contribute with new ideas and solutions to the EVA injury problem.

B. Modeling

Another major aspect of our research effort is to model human-suit interaction. Although there has been a great deal of data taken on the effects of the suit on the astronaut's strength, mobility, and work envelope, relatively little is known about how the human interacts within the suit in order to use it. Understanding where impact and contact pressure occurs will allow us to understand how injuries occur and how to prevent them. It will also move beyond documented injuries from the EMU and consider next-generation spacesuit designs, such as the Mark III, and inform future suit designs as a method by which to predict spacesuit injury potential.

Table 1. Existing sources of astronaut injury information.

Sources	Description	Data Source	Additional Information
Injury Tracking System	Comprehensive (pre-, in- and post-flight).	NBL records; Electronic medical records	Allows remote access with authorization; Not all injuries spacesuit related
Longitudinal Study of Astronaut Health	Long-term health issues	Astronaut medical records over career; JSC employees as control	Spacesuit injuries are short-term, minimal published data for EVA
Astronaut Strength, Conditioning, and Rehabilitation	Preparation and recovery from physical demands of spaceflight	Training and rehabilitation personal records	Personnel as additional source of information

The first step entails developing the human and suit models, as represented in Figure 4. The spacesuit models, including EMU, Mark III, or other advanced concept spacesuits, will be derived from existing 3D CAD models used by spacesuit designers at NASA JSC. The models will be geometrically accurate and represent the pressurized suit. Current models are static and will be sectioned to mimic movement and predict shifting over the body. This allows for additional modification to account for sizing differences among astronauts. Protective garments, such as the LCVG, are modeled based on information in the EMU handbook(13) and NASA Standard 3001, Volume 2(32).

Figure 4. Astronaut and Mark III suit model. *Figure represents the human and spacesuit models to be used for injury analysis. Representative, not based on data.*

The astronaut models are created utilizing the Santos human-body modeling program to predict posture and motion using user-selected optimization cost functions. Cost functions include minimizing joint torque, potential energy, or joint displacement(33).. Both male and female models will be built from individual anthropometric measurements taken in the NASA JSC Anthropometry and Biomechanics Facility. These models are combined to predict motion within the suit given the joint torques and work envelop calculated in the studies discussed previously. We will impose these constraints on the model, then predict motions and postures, comparing against existing motion capture data of people performing realistic EVA motions in a pressurized suit. This will validate our optimization cost function criteria to validate that our model may be used to predict motion in a more generalized case. To validate the model's prediction of contact pressure and location, additional testing will need to be performed. Once we have a model which represents known cases of human suit interaction, our methods can be further extrapolate to general cases, modeling multiple differently sized people performing additional EVA tasks. A table of our desired outcomes and the description/utility of the analysis is seen in Table 2.

In parallel, the team will design concept protection devices to mitigate injury. In order to assess their effectiveness, the prototypes are modeled in the 3D CAD program CATIA and incorporated into the human-suit interaction model. The motion and posture analysis will be reevaluated to assess changes from baseline.

Table 2. Desired human-suit interaction modeling analyses.

Desired Outcome	Description
Body shifting	Movement within the suit in different orientations
Posture Prediction	From neutral posture in Earth and micro-gravity. Calculate difference between body and suit position. To be used for suit sizing
Range of Motion	Movement modified by physical encumbrance of suit bulk. Location of suit interference shown as output to aid design
Contact pressure	Motion is discretized and finite element solution is run to calculate impact area and contact force between suit and human. Detected by collision between surface geometry of avatar and mesh of suit
Joint torque	Both static posture and dynamic profile over full range of task. Related to discomfort, fatigue, and population capable of posture
Muscle activation and Strength requirements	Joint torque and angle related to muscle activation needed to maintain posture. Will include both normal and deteriorated muscle
Vision analysis	Model perspective option available. Visual targets added as optimization constraint

C. Design

The design process proposed here is directed toward an in-suit protection system worn by the astronaut to alter the way he or she interacts with the spacesuit. It may include an enhanced–LCVG, padding, comfort inserts, or restraint harness upgrades. The design process is adapted from industrial design methods presented by Best(*34*).

The first stage of the design process is to define and fully understand the problem. Our effort is informed by information from the database, literature, and hands-on experience with the suit components. From the first phase of data collection, preliminary design requirements were created, seen in Table 3. These requirements are based on EVA spacesuit design requirements, and therefore form a high-level baseline from which to begin generating potential solutions. Additional research further investigates the design space, including consideration for working environment (microgravity or planetary bodies). To further understanding of the problem of EVA injury, NASA operations in the NBL and on orbit are investigated. Additional comparative studies on similar injuries in other fields, such as athletics, medicine, and other harsh work environments, help elucidate how these problems have been resolved in other areas.

Table 3. Preliminary design requirements for protection devices. *Further in the design phase, detailed design requirements will be created, using these as a baseline.*

Desired Trait	Requirement
1. Comfort	1.1 Decreases friction between suit and skin 1.2 Minimizes hard impacts between suit and body 1.3 Controls body moisture 1.4 Less prone to wrinkling
2. Suit fit	2.1 Body restricted from shifting inside suit 2.2 Suit moves more naturally with the body
3. Customization	3.1 Size of protection system is adjustable or personalized 3.2 Shape of protection system is adjustable or personalized 3.3 Protection system in adjustable or personalized location
4. Maintain functionality	4.1 Maximum range of motion is maintained 4.2 Joint torques not increased 4.3 Finger tactility is maintained
5. Easy to don	5.1 Simple integration to the spacesuit or other protective devices 5.2 Does not significantly increase EVA preparation time 5.3 Does not require additional equipment 5.4 Able to be self-donned
6. Safe	6.1 Not made from flammable materials 6.2 High reliability 6.3 High technology readiness level
7. Operations	7.1 Minimal stowage space, mass, and power usage 7.2 Minimal training requirements 7.3 Minimal maintenance requirements

Next, the team will begin the Conceptual Design phase. Research on materials (such as foams and gels) and structure (such as meshes and inflatables) will identify promising combinations for protection concepts, as seen in Figure 5. Creative problems solving methods, such as brainstorming or mind mapping, will be used. The objective is to create many concepts, potentially going beyond what is most intuitive, to seek creative, unique solutions. These initial concepts should include the understanding of whole mission process – using scenario methods to illustrate, for example, the process of donning, doffing, or daily operations. These concepts will be generated using rapid physical prototyping to better understand their limitations and narrow the field of concepts.

Figure 5. Representative prototype solutions. Initial design *concepts in our injury prevention and comfort protection design process. These examples are for illustration only.*

With the remaining solutions, the most promising concepts will be iterated upon and detailed designs will be created. This includes selecting the appropriate technology, materials, and interface to the LCVG. These detailed concepts will be modeled using a 3D CAD program allowing the concept to be virtually tested using the modeling methodology described previously. The acquired data will be used to improve concepts, and verify the conformity with the requirements.

Finally, the down selected concepts will be produced into full physical prototypes. In this phase, the team will develop the construction process and realize production limitations. The prototypes will be tested to determine their effectiveness for preventing injury. Initially, this will include testing load-induced compression, durability, and failure conditions. From these results, the design and production methods will be refined, ultimately with the goal of achieving a usable prototype for human subject testing. Ultimately, this process will lead to an enhanced LCVG prototype and protection devices.

V. Conclusion

This research effort outlines the methodology to assess astronaut injury that occurs inside the spacesuit during EVA training and on-orbit. With our three–pronged approach: database development; modeling, and design we hope to develop a better understanding of how the human and spacesuit interact and how injuries occur. We will develop novel solutions to address these problems and provide future spacesuit designers tools by which to track the problem of EVA injury and prevent it for future missions.

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