UNDERSTANDING HUMAN-SPACE SUIT INTERACTION TO PREVENT INJURY DURING EXTRAVEHICULAR ACTIVITY

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Extravehicular Activity

Extravehicular Activity (EVA) is a critical component of human spaceflight. Working in gas-pressurized space suits, however, results in numerous challenges, causing fatigue, unnecessary energy expenditure, and injury (Morgan, Wilmington et al. 1996; Williams and Johnson 2003; Strauss 2004; Scheuring, Mathers et al. 2009; Opperman 2010; Scheuring 2012). These problems are exacerbated with the additional hours astronauts spend training inside the suit, especially underwater in the Neutral Buoyancy Laboratory (NBL) (Williams and Johnson 2003; Strauss 2004). Although space suit performance and improved system designs have been investigated, relatively little is known about how the astronaut moves and interacts with the space suit, what factors lead to injury, and how to prevent injury.

Our focus

To understand human-space suit interaction and design hardware to assess and mitigate injury.

- Address upper torso, shoulder, and arm injuries as proof-of-concept for injury prevention.
- To quantitatively measure with a wearable pressure sensing garment where the suit impacts the body during normal EVA movement.
- Mitigate injury and discomfort with protective devices providing individualized solutions.

Pressure sensing

To quantitatively assess the effectiveness of the protective devices, a pressure sensing capability will be developed. This capability will be an important contribution of our work since it will be the first of its kind to assess human movement in the space suit.

Quantify where the person impacts the space suit
–Assess areas of discomfort
–Inform a human-suit interaction model
–Determine the effectiveness of prototype protective devices

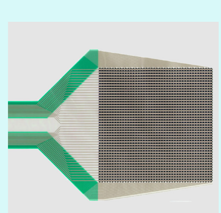
Additional utility:
Assess and compare suit designs; Optimize fit and comfort; Monitoring tool to prevent injury; Biomechanics research

Sensor selection

Depending on the type of impact, the body will experience different ranges of pressure. The pressure where the person impacts the soft goods over the arms, wrists, and elbows will be very different than the pressure on the shoulder and neck where the person's body weight rests on the HUT. Our design uses two different pressure sensors to accommodate the anticipated regimes. We will use both commercial and custom sensors to fit our needs.

High-Pressure Sensor Concept
For high-pressure sensing, we are evaluating commercial sensors.
Parameters: Targeting 750-1500kPa range
Pro: Low developmental overhead, well characterized, reliability increases with pressure
Con: Expensive, difficult to adapt for specific purposes, hardware encumbrance, reliability decreases with movement
We are pursuing two commercial sensors: Tekscan and Novel

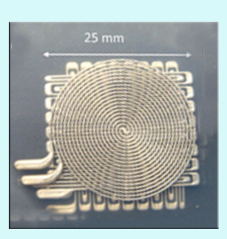
Novel: Segmented plastic grid with deformable spacer between plastic plates. Capacitance changes with plate separation as pressure is applied. (Novel, GmbH, 2012)



TekScan: Grid of small "sensels" with conductive dye. Resistance changes with deformation caused by pressure. (Brimacomb, D. Wilson et al. 2009)

Status:
- Both systems are being demoed to assess their applicability to our project
- Novel systems for borrow have been identified both in NASA's Anthropometry and Biomechanics Facility and the University of Washington
- Our group may upgrade our TekScan system if issues with data fluctuation and accuracy during movement can be resolved

Low-Pressure Sensor Concept
For low-pressure sensing against the soft goods, we are building custom sensors.
Parameters: Targeting 0-50kPa range, 2kPa resolution
Pro: Inexpensive, develop for desired range and resolution, conformal to the body, reliable readings with movement
Con: Development time, labor intensive process, creating robust data transmission



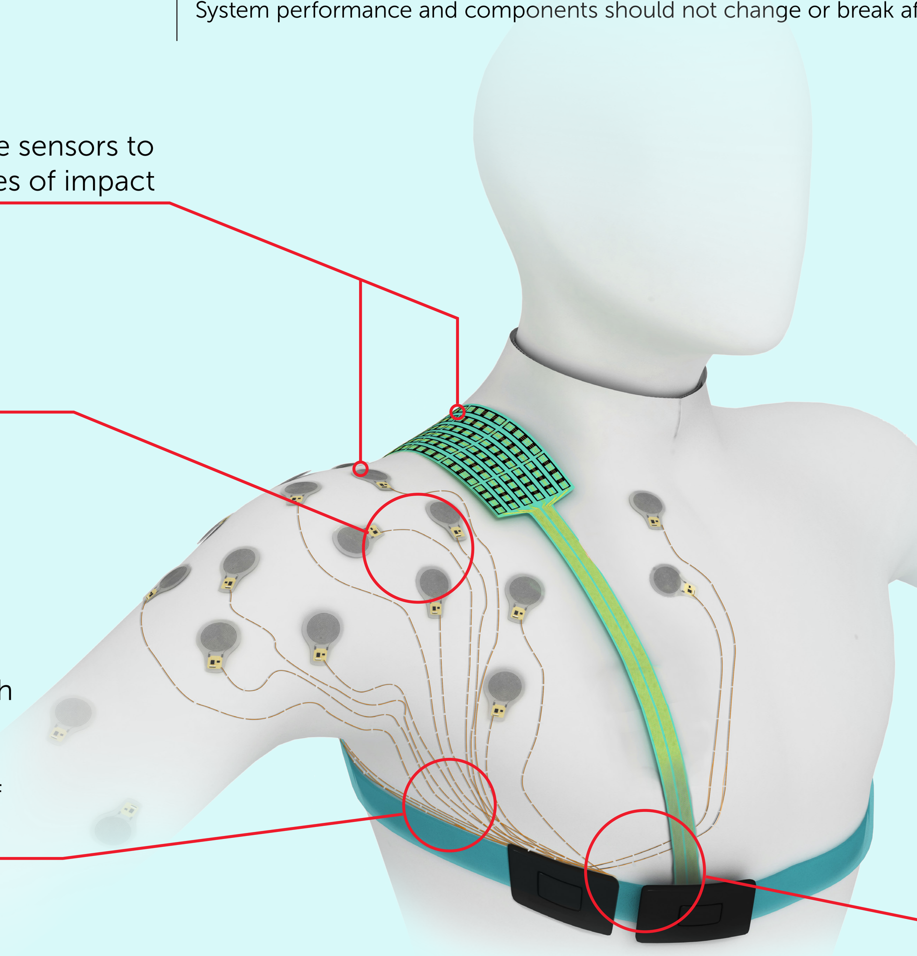
Wyss Institute: Hyperelastic soft sensor with microfluidic channels filled with conductive metal. Deformation of the channels with pressure causes change in resistance. (Park, 2010, 2012)

Status:
- Initial design has been created and built
- Sensor will be characterized using a force transducer and mechanical loading profile over both hard and deformable surfaces
- Vacuum chamber testing to baseline loading regime

Requirements

The following are preliminary requirements for the pressure-sensing garment.
Additional requirements for both the high- and low-pressure sensors have also been established.

Category	Trait	Requirement
1. Resolution	1.1 Spatial	Placed over anticipated "hot spots". In no case should there be more than a 10cm longitudinal and 6 cm circumferential gap.
2. Mobility	2.1 Flexibility	Sensors will flex to follow body radii of curvature.
	2.2 Stretchability	Sensors and wiring should accommodate human skin strains of 45%, either by sensor properties or placement design (Wessendorf and Newman, 2012).
	2.3 Integration	Sensors and wiring will be integrated to body garment.
	2.4 Anatomical mapping	Sensor center point will shift no more than 1cm in any direction.
3. Environment	3.1 Temperature	Sensor readings will change no more than 5% with EVA expected variations in temperature
	3.2 Humidity	Sensor electronics will be resistant to expected EVA variations in humidity.
	3.3 Electromagnetic interference	Sensor electronics should be resilient against interference by space suit metal components.
	3.4 Durability	System performance and components should not change or break after 100 uses.

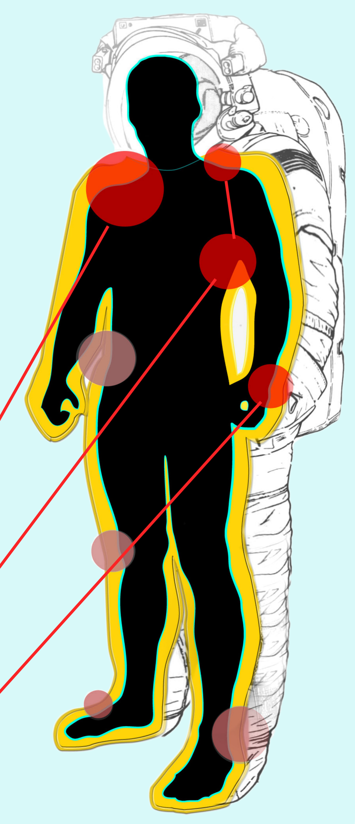


Mechanisms of injury

Relatively little is known about how the person moves inside the space suit to move the suit itself. The hypothesized causes of these injuries are suit fit, shifting, improper use of protective garments, and repetitive motion working against the suit (Williams and Johnson 2003; Strauss 2004; Benson and Rajulu 2009). Achieving the best fit is extremely individualized and discomfort "hot spots" may exist in an area for one crewmember but not for another. Additionally, movement in the suit is unnatural due to each space suit's inherent programming (Cowley, Margerum et al. 2012). Astronauts learn to change their biomechanical movement strategies, rather than attempting to move as they do unsuited (Carr and Newman, 2007 A&B, Gast and Moore 2010).

The difference between how a person moves relative to the suit has not been quantified.

Anatomical Location	Description
Shoulder	Nerve impingement, rotator cuff pinching and tearing from impeded motion
Neck	Impact with the HUT, specifically while inverted in training with body shifting and pressure on HUT
Arm and Wrist	Contusions and abrasions from rubbing at joint. Discomfort from impact with the soft goods, bearings, and sizing rings to produce movement



Protection devices

Liquid cooling ventilation garment (LCVG) - Regulates body temperature by circulating water over the body to absorb heat. Also ventilates by removing air from the extremities

Padding - Thin teflon strips sewn to the LCVG at desired location. Not designed for long-term injury prevention.

Hard upper torso (HUT) harness Built–in harness system with backpack-style restraint straps to prevent shifting. Its use is optional.

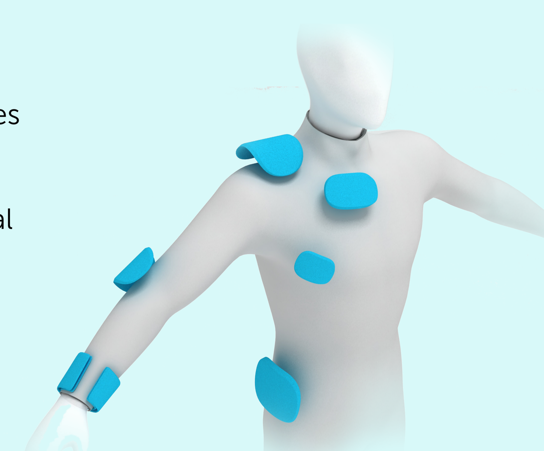
Wrist cuff - Essentially the upper portion of an athletic sock to bridge the gap between the comfort glove and LCVG

Limitations

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 maybe acceptable for short-term prevention, the system must be modified to find long-term solutions (Opperman et al., 2008; Newman, 2008; Newman et al., 2009; Holschuh et al., 2009; Anderson et al., 2011; Diaz et al., 2012). A greater understanding of human-suit interaction would help achieve future suit designs to minimize injury caused by the next generation of space suits.

Design

The design methodology to create the protective devices will draw upon several disciplines, including industrial design, ergonomic design, and engineering design. Desired characteristics of the prototypes and conceptual design has begun. Solutions will be modular and personalized so as to be usable by the entire astronaut population in multiple suits. Some of the solutions will be geared toward preventing shifting to ensure proper placement within the suit, while others will be geared toward improving comfort by preventing hotspots, abrasions, and contusions.

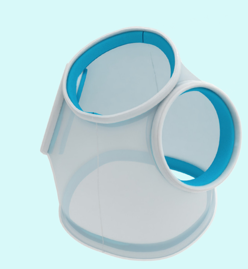


simple approach

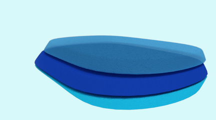
Mitigation strategy - simple

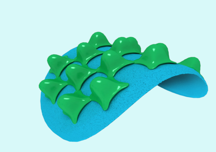
Foam: advanced multi-layer with variable softness uses current attachement method or other simple technique (pockets, grip layer, adhesive)

HUT liner: multi-layer foam directly integrated to HUT interior



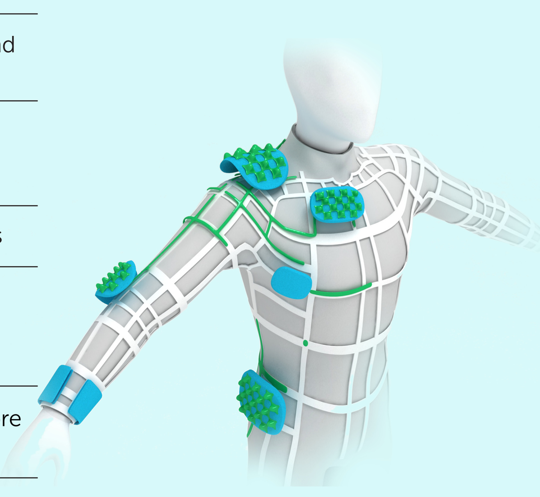
Inflatables: variable thickness for individual comfort





The design requirements for the protective devices

Category	Requirement
Comfort	Reduce pressure impacts between suit and body from the baseline by at least 20 %
Suit fit	Must be integrated/ placed with in-suit items/ skin
Customization	Must accomodate full range of crew sizes
Functionality	Does not restrict work envelope Torque penalty no more than 5 %
Usability	EVA preparation time increased by no more than 5 %
Safety	Compatibile with 100% oxygen environment



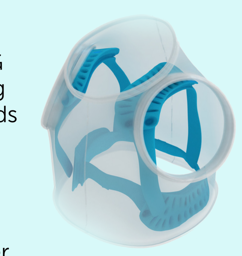
moderate approach

Mitigation strategy - moderate

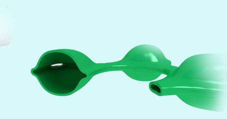
Body liner: worn under LCVG, advance materials for thermal and friction control

Mounting vest: worn over LCVG allows for easy to adjust padding placement to the individual needs

Alternative ways of mounting foam/ inflatables to LCVG



Redesign HUT harness for better pressure distribution



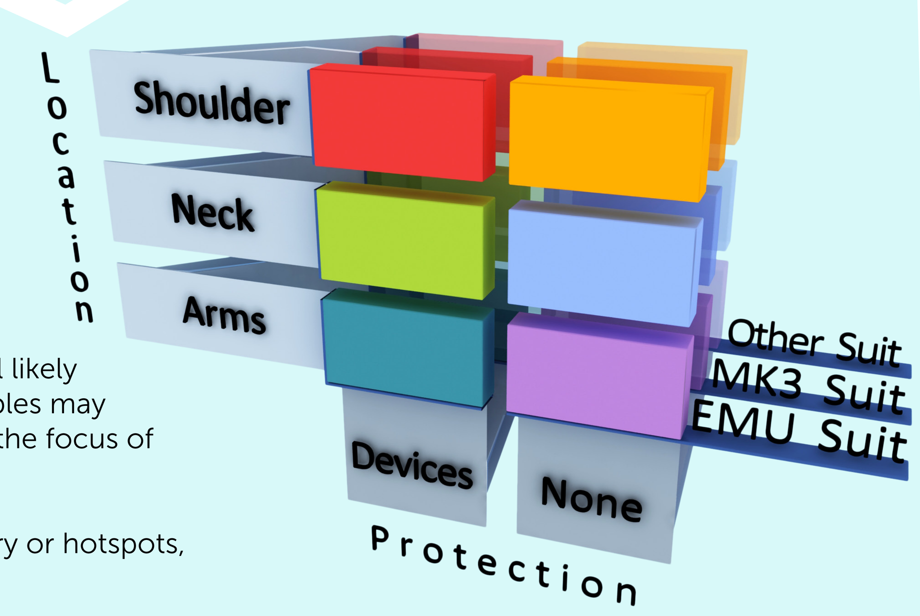
Experiment

An experimental study will be done to evaluate the prototype protection devices and determine if the protective devices/padding can qualitatively enhance comfort during realistic EVA motions and quantitatively alleviate pressure on the body.

Dependent variables
1. Subjective comfort of the subjects
2. Pressure profiles for each sensor over several EVA motions

Subjects must have experience moving inside the space suit. This will likely reduce the number of available subjects. Additional independent variables may include gender, age, and prior injuries. However, these factors are not the focus of our research.

This experiment assesses comfort. It does not attempt to evaluate injury or hotspots, since these often occur after several hours in the suit.



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Discussion

Our work will help researchers and designers gain a better understanding of human-space suit interaction and aid space suit sizing personnel and flight doctors improve the health and comfort of astronauts. We address the current limitation of knowing what occurs inside the suit to articulate it, which has implications for metabolic expenditure, fatigue, comfort, and injury. We also address the critical need for improved comfort and injury prevention during EVA.

The following is a list of expected contributions:
- Pressure sensing garment to provide quantitative feedback where the person impacts the suit over the upper torso, shoulder, and arm.
- Protective devices for the upper body, shoulder, and arm to aid comfort and alleviate injury.
- Methodology for assessing and evaluating comfort and injury that may be extended to the whole body for similar analysis and design.
- Protective garment concepts and pressure-sensing technique which can be used for other applications, such as minor trauma impact protection in the aging population and evaluating loads on soldiers.