

Feasibility Assessment of an EVA Glove Sensing Platform to Evaluate Potential Hand Injury Risk Factors

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Injuries to the hands are common among astronauts who train for extravehicular activity (EVA). When the gloves are pressurized, they restrict movement and create pressure points during tasks, sometimes resulting in pain, muscle fatigue, abrasions, and occasionally more severe injuries such as onycholysis. A brief review of the Lifetime Surveillance of Astronaut Health's injury database reveals that 58% of total astronaut hand and arm injuries from NBL training between 1993 and 2010 occurred either to the fingernail, MCP, or fingertip.

The purpose of this study was to assess the potential of using small sensors to measure force acting on the fingers and hand within pressurized gloves and other variables such as blood perfusion, skin temperature, humidity, fingernail strain, skin moisture, among others. Tasks were performed gloved and ungloved in a pressurizable glove box.

The test demonstrated that fingernails saw greater transverse strain levels for tension or compression than for longitudinal strain, even during axial fingertip loading. Blood perfusion peaked and dropped as the finger deformed during finger presses, indicating an initial dispersion and decrease of blood perfusion levels. Force sensitive resistors to force plate comparisons showed similar force curve patterns as fingers were depressed, indicating suitable functionality for future testing. Strategies for proper placement and protection of these sensors for ideal data collection and longevity through the test session were developed and will be implemented going forward for future testing.

Nomenclature

A	=	amplitude of oscillation
a	=	cylinder diameter
C_p	=	pressure coefficient
C_x	=	force coefficient in the x direction
C_y	=	force coefficient in the y direction
c	=	chord
dt	=	time step
F_x	=	X component of the resultant pressure force acting on the vehicle
F_y	=	Y component of the resultant pressure force acting on the vehicle
f, g	=	generic functions
h	=	height
i	=	time index during navigation
j	=	waypoint index
K	=	trailing-edge (TE) nondimensional angular deflection rate

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I. Introduction

THE purpose of this study was to perform feasibility testing for a method of measuring the environmental variables acting on the fingers and hand (forces, moisture, barometric pressure, and temperature) and the physiological subject based variables (blood perfusion, skin perspiration, and nail strain) being affected within a pressurized glove. In order to optimize the design for an EVA glove, these independent environmental variables acting on the hands and fingers must be examined. A series of sensors were placed on the fingers and hands of two male test subjects of similar hand anthropometry to gather data while they performed a battery of tasks to elicit physical stresses similar to what an astronaut may experience during training or an EVA. Tasks were performed in three conditions; ungloved, Series 4000, and Phase VI EVA gloves. The ungloved condition was performed in an unpressurized Glove Box, whereas the EVA glove conditions were in a pressurized environment in the Glove Box.

The High Performance EVA Glove (HPEG) investigation for EVA glove-hand injuries is an element of the Next Generation Life Support (NGLS) funded by the Space Technology Mission Directorate (STMD). During the HPEG Glove Injury Data Mining Effort investigation in FY13, investigators questioned whether potential risk variables could be quantified from the actual EVA glove environment through real-time and/or pre- and post-test data collection equipment. Previous Glove Box and Neutral Buoyancy Lab (NBL) studies performed in 2008 to 2009 had shown that placing sensor equipment in an EVA gloved environment was possible. Sensors that were tested in those studies assessed fingertip blood perfusion levels (Ansari et al., 2009) and hand moisture changes (Jones et al., 2008). Unlike the Ansari et al. (2009) study, the study by Jones et al. (2008) was a pre- and post-test sample study that did not introduce a real-time integrated feedback system. These examples incentivized investigators into proceeding into a new investigation that would look to quantify the EVA glove environment. Like the FY13 EVA Glove Sensor Feasibility study, a follow-up extensive search was conducted for FY14 for feasible, miniature, low profile COTS sensor equipment that could be placed on the hands and fingers of test. Results from this follow-up sensor feasibility study helps to better understand the following questions in regards to two male test subjects of similar hand dimensions being tested in a Glove Box setup.

The primary objectives for this study were:

- 1). Develop a feasible method for downselecting sensors and measuring tactile forces, moisture, and blood perfusion levels on the finger and hand while performing tasks in a pressurized glove
- 2). Obtain viable data that can be associated with Lifetime Surveillance of Astronaut Health (LSAH) injury data and literature
- 3). Depending on the outcomes, use results from this protocol to plan either A) additional low-level testing to validate methods for quantification, or B) a robust protocol using the tested methods to further investigate the variables contributing to hand injuries during EVAs

II. Methods

The test subjects chosen for the project were two males of right hand dominance. Both subjects were suit engineers with pressurized suited and Glove Box experience. Average age of the two subjects was 32 (± 4).

A. NASA-University Collaboration on Sensor Carrier Glove Prototyping

To improve on the wire related comfort and mobility issues found from testing conducted in 2013, custom Sensor Carrying Gloves (SCG) were designed and fabricated by the EC2 Soft Goods group. These gloves were used by all test subjects for all test conditions (ungloved and gloved). Prior to this development point, collaborative work between university students at Georgia Tech, Virginia Tech, and Rhode Island School of Design (RISD) and JSC were carried out to help create different conceptual prototypes which were then adapted into the EC2 Soft Goods design. Georgia Tech and Virginia Tech were given the objective of designing a glove using today's existing technology, whereas RISD was given the objective of using near future technology to emphasize design. All schools were given the design criteria of allowing sensor wire routing with limited mobility and tactility impedance, allowing access to the fingertips of the wearer without removing the gloves, and designing gloves that would not hinder or move sensors applied to the hand. More specifically, the primary criteria included:

1. Design a garment that can be worn on the hand as either a) a thin/low profile comfort glove or b) on sections of the hand such as the fingers, palm, back of hand, etc.
2. The garment can either be designed to exclusively integrate specific types/sizes of sensor such as force sensitive resistors (FSRs), or designed to encompass a variety of sensor types/sizes (force, humidity, temperature, etc.)
3. Design must be able to fit inside of an EVA glove

Due to project schedule limitations on the project, the final EC2 design only incorporated aspects of the Georgia Tech and Virginia Tech concepts; however, for follow-up development and testing currently ongoing, design aspects from all three universities are being leveraged.

Georgia Tech Concept

Students at Georgia Institute of Technology (Georgia Tech) modified a cotton glove to allow the integration of finger cots at the fingertip ends. Created from a cotton glove and multiple thread colors, their design implemented wire routing anchor points on the back of the hands and fingers to allow for wire guidance from where the sensors would be placed on the back of the MCP knuckles and the fingertips (Figure). The final design can be seen in Figure demonstrating how wires are routed to the fingertips from the wrist access area and how the finger cots can be removed. One drawback noted on this design by investigators was that by running the sensor wiring along the dorsal aspect of each finger, hand and finger joint flexion may likely lead to tension on the wiring and could result in severing the sensor lead connection with the wire or increase dexterity resistance. Investigators found that wire routing along the sides of the fingers would be preferable to help reduce these risks.

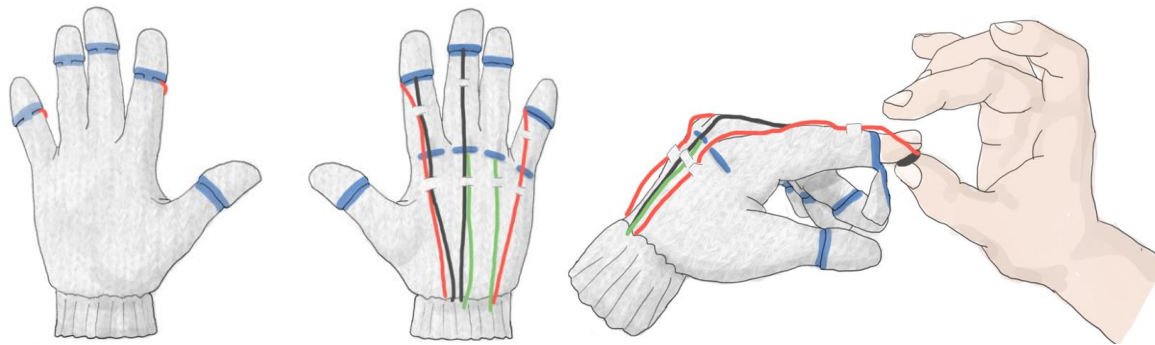


Figure 1: Georgia Tech conceptual design

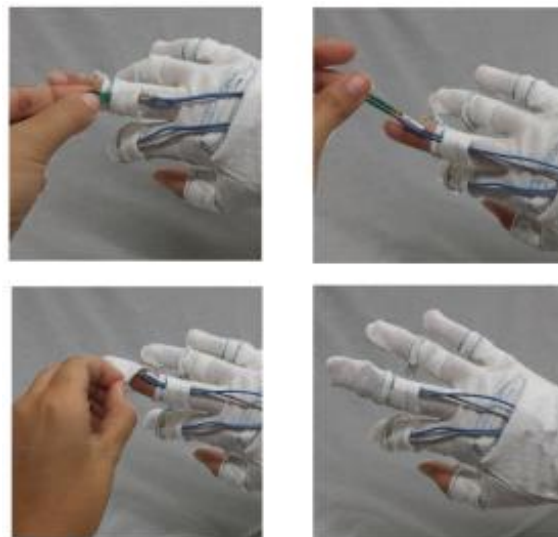


Figure 2: Georgia Tech final glove design

Virginia Tech Concept

Virginia Polytechnic Institute and State University (Virginia Tech) students were inspired by concepts from keyless piano gloves, Mi.Mu music gloves, and Elastic phone cases. Their glove design is composed of three layers, a base layer and two layers for wire routing. Fingertip cots were employed with an original foldup design (Figure 3) that was later transitioned to a removable cot in the final design (Figure 4). The glove was sewn using cotton thread on two types of spandex-polyester weaves. Wire routing housing material (the blue tubes on the glove) was made from elastic polyester. Some areas of the glove also utilized fabric glue. The final design utilized a small circuit board at the wrist which sensors would be routed to along with a continuous set of wire routing tube from the wrist to the fingertips.



Figure 3: Virginia Tech's conceptual design process

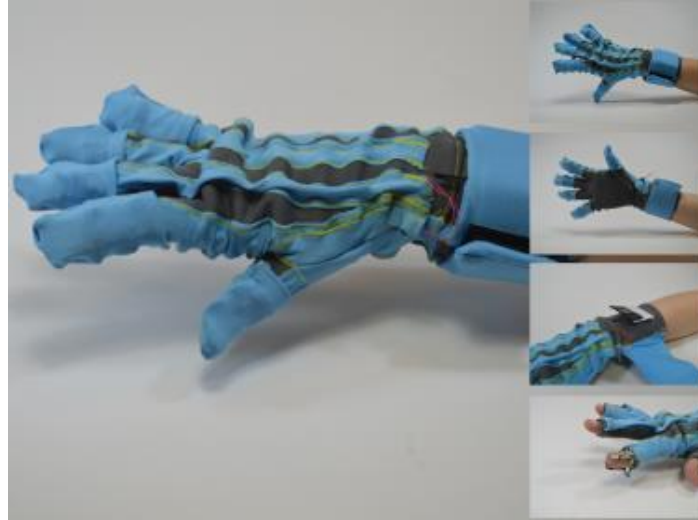


Figure 4: Virginia Tech final glove design

Rhode Island School of Design Concept

Students at the Rhode Island School of Design (RISD) were given the challenge of designing a SCG using concepts of near future technology. Pivoting off of technology that currently exists in other applications, near future aspirations were brought to the present through multiple prototype designs, each evolving on its predecessor. RISD students were given the same constraints as the Georgia Tech and Virginia Tech students. Similar to the other two universities, RISD students were inspired by COTS items as well as technology still being prototyped such as the Mi.Mu music glove, machine embroidered led matrixes, Pressure Profile system gloves, and other glove-sensor integration projects. Utilizing more than 12 concepts (Figure), the team created a design that primarily utilized serpentine (zigzag) wiring to allow wires to stretch with the hand without placing tension on the wire leads on the sensors.



Figure 5: RISD conceptual designs

Initially their designs used stitching and flexible fabric glue to hold their wire patterns to the gloves. Eventually though this would evolve into a flexible 3D printable framework that would house the wiring bundles along the back of the hands and fingers. Experiments were also done on creating a pattern between the MCP and finger junctions that allowed for decreased impedance on the hand and on the sensor lead was opening and closing. Their final design consisted of a single cotton glove layer with a 3D printed flexible filament housing integrated with an AWG30 wire bundle (Figure). The 3D printed housing was adhered to the cotton glove using fabric glue. Access port concepts utilized in their second to last prototype design used fabric tape to keep the fabric from delaminating. These ports were on the top and bottom of the fingertips and the backs of the MCP knuckles. While it wasn't utilized in this study's sensor feasibility tests, the concept is one that can be utilized for any future work that will need to implement an integrated sensor glove for subjects to wear.



Figure 6: RISD final design (without hand access ports)

B. Sensor Overview

The articles that were tested included various sensors for measuring tactile force, temperature, humidity, barometric pressure, skin and nail perspiration, and blood perfusion. The sensors were housed or covered by custom built SCGs on both hands (Figure 9). Figures 7 and 8 show that all sensors were inside the SCG which took the place of the standard cotton or spectra-knit comfort glove.

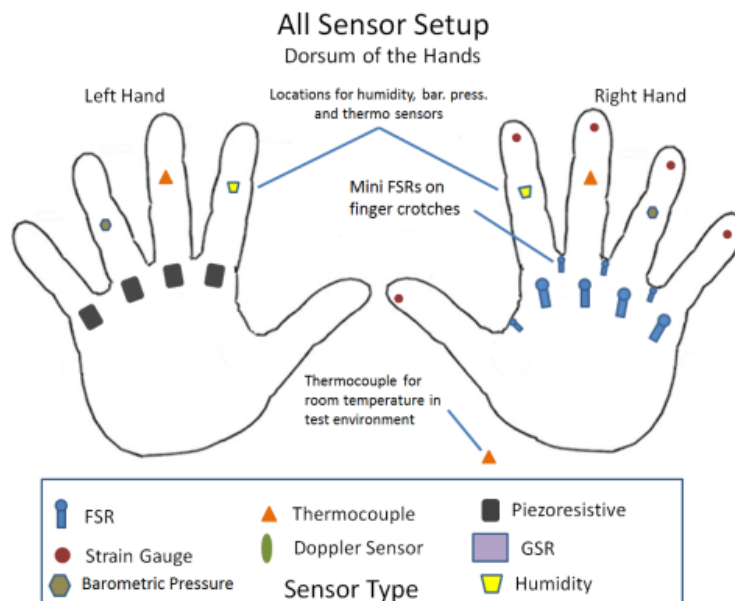


Figure 7: Sensor layout on the dorsum side of the hand

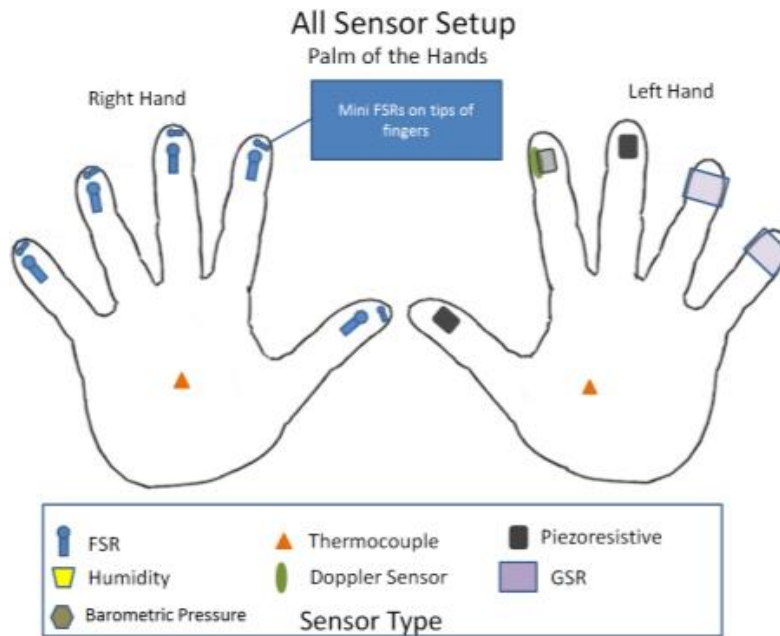


Figure 8: Sensor layout on the palm side of the hand

C. FY14 Sensor Carrier Glove

The final EC2 Soft Goods Lab design (Figure 9) was a dual layer integrated design that allowed for sensors to be placed between the skin and base layer of the glove or between the base layer and the cover layer of the glove. Hand molds and plaster casts were taken for both hands of the individual subjects that the Soft Goods lab could use them for their prototype gloves during the fabrication process (Figure). Additionally, anthropometric measurements of the two subjects' hands (left and right) were also given to appropriately match the glove sizing. These anthropometry measures were taken using the ABF laser scanning protocols.



Figure 9: Final EC2 Soft Goods Lab sensor carrier glove



Figure 10: Test subject hand casts with sensor marking locations

Two prototype versions of the glove were developed with the final being an evolution on the first. The initial prototype (Figure II) consisted of a dual layer glove system (base layer and cover layer) as was utilized in the Georgia Tech and Virginia Tech student designs. The cover layer was a closable jacket designed around the dorsum of the hand. Wire guides on the fingers utilized a tri-fold concept to allow investigators to be able to access the wiring along the fingers.



Figure III: EC2 Soft Goods Initial Prototype Concept

Like its predecessor concept, the final Soft Goods Lab glove design consists of a base layer and a cover layer. It was decided to remove the jacket and tri-fold access areas along the dorsum of the hand and fingers by replacing them with pull-away covers similar to that of the Georgia Tech student design. These covers when released would quickly return to their covered rest state over the sensors and wiring. The cover layer and wire guide design in combination with the low friction glove material allowed for the wiring to slide back and forth in place as the fingers and hand articulated during movement (Figure). All layering of the gloves consisted of an elastic Lycra fabric sewn with Nomex thread size B. The combination of 3M 950 transfer tape and small cutouts of the Lycra fabric were used to create a reusable stretchable “fabric tape” that was implemented as both an anchor and cover system for the different sensors on the hand. Patterning of the glove was done by measuring the hand molds and laying out flat patterns to trace and cut the material. Sewing was performed using a lightweight Bernina sewing machine that was able to produce a stretch stitch operation. Through multiple fit checks and evaluations with investigators and test subjects, this patterning was refined to meet with the requirements of the project.



Figure 12: Glove wire guides and covers on fingers (left) and back of hand (right)

A primary criterion for the design was to allow investigators to be able to access different areas of the hand without having to remove the SCG itself. This criterion created the need to pattern access ports at the fingertips (Figure 13), middle finger intermediate phalanges, palm, and dorsum of the hands (Figure). These access ports and their accessibility methods are similar in design to that seen from the Georgia Tech and Virginia Tech student concepts. Certain sensors such as the strain gauges on the fingernails, thermocouples, GSRs, LDPM sensor, and FSRs on the finger crotches (Figure) needed access to skin and fingernail regions beneath the glove's base layer. These were attached using either glue, double sided, or the fabric tape.



Figure 13: Glove fingertip base layer cover on (left) and off (right)



Figure 14: Small FSR finger crotch sensors beneath the base layer of the sensor glove

Other sensors were attached to the base layer of the glove using double sided tape or fabric tape. These sensors were then covered with the final cover layer of the glove to prevent them from interacting with the bladder of the EVA glove as seen in Figure 15.

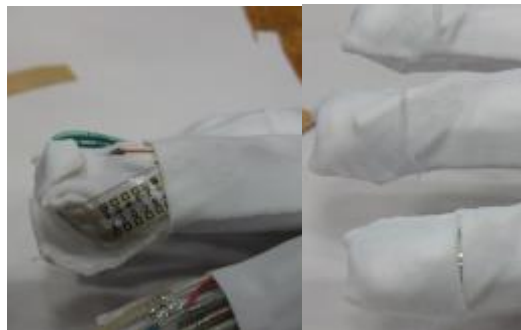


Figure 15: Attachment of small and large FSRs on fingertip and fingerpad of glove base layer (left) and view of the sensors with their fingertip cover layer in place (right)

Additional criteria included keeping all of the sensors covered by the glove fabric and providing wire routing guides in the design of the glove for investigators to route wiring through. These criteria led to a reduced sensor loading time for investigators (when the glove was pre-wired), added sensor protection, reduced sensor and wiring discomfort (due to reduced wire crowding), and reduced wire tension impedance on sensor leads and subjects fingers during articulation.

This final SCG version was utilized throughout all test conditions and in the case of the ungloved condition, was used as a baseline for EVA gloved condition comparisons.

D. Sensors

Force Sensitive Resistor (FSR) - Large Sensor and Small Sensor

FSRs are polymer thick film devices that experience a decrease in resistance with applied normal force. Large sensors were placed on all five of the fingerpads and last four of the MCPs (index through little finger) of subject's right hand using double sided tape and or fabric tape to adhere them to the base layer of the SCG. Small sensors (Figure 16) were placed on all of the fingertips and the finger crotches of the right hand. Double sided tape was used to adhere the finger crotch sensors to the skin and was also used along with fabric tape to adhere the fingertip sensors to the base layer of the SCG. Output voltages were converted into pounds of force values.



Figure 16: Interlink 400 Series FSR

Strain Gauge Sensor

Strain gauge sensors produce a change in resistance when subjected to physical deformation. Strain gauge measurement dimensions were 1.5 mm x 1.5 mm (Figure). Strain gauges were placed on the approximate center of each of the five fingernails of the right hand of the test subjects. The sensors were temporarily bonded to the subject's fingernails using Precision Nail Glue (cyanoacrylate) between the bottom of the sensor and the top of the fingernail. An additional coating of Hard-as-Nails fingernail hardener was added to surface of the strain gauge to further adhere it to the fingernail as well as add an increased level of durability to the sensor for the testing. The nail glues were removed after the testing using acetone nail polish remover and emory boards. Output voltages were converted into unitless μ -Strain values.

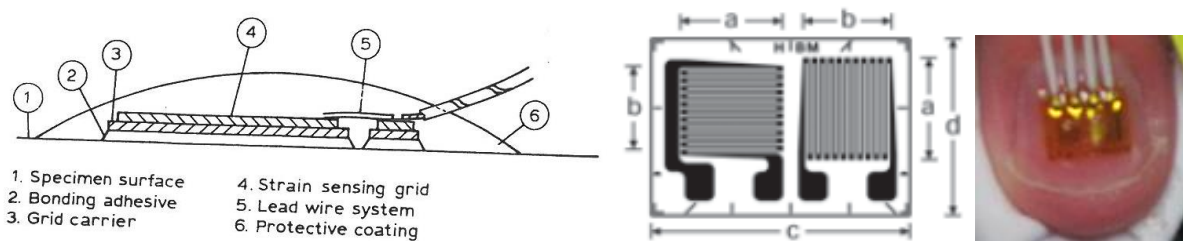


Figure 17: HBM strain gauges

Piezoresistive Pressure Sensor

Piezoresistive pressure sensors produce a change in resistance with applied with normal force (Figure). These sensors were made in-house and were used as a possible alternative to using FSR sensors to measure normal force. These sensors were made by isolating a film of anti-static material (e.g. Velostat) between two conductive materials. For this study, conductive fabric was be used to build the sensors. These sensors were attached to the all of the fingerpads of the fingerpads of the left hand except for the ring and little finger whose pads were covered with the GSR sensors. Additional piezoresistive sensors were attached to the MCP knuckles 2-5 (index to little finger). The adhesion method included double sided tape and fabric tape for adhesion to the base layer of the SCG at the appropriate hand locations. Output voltages were converted into pounds of force values.

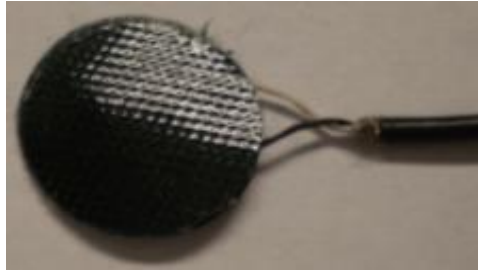


Figure 18: Piezoresistive sensors fabricated in-house

Thermocouple Sensor

Thermocouples are circuit elements that produce voltage when heated (Figure 19). Omega Engineering Type K thermocouples (0.254 mm diameter) were used to capture skin surface temperatures of the test subjects and the room temperature of the test environment. The size of the voltage is dependent on the difference in temperature. Thermocouple sensors were adhered to the skin using double sided tape. Body locations included the dorsum aspect of the intermediate phalanx of the middle finger on both hands, the palm of both hands, and the room temperature of the test location. Output voltages were converted to temperature units in degrees Fahrenheit.



Figure 19: Omega Engineering Type K thermocouple sensor

Laser Doppler Perfusion Monitor (LDPM)

LDPMs measure microcirculatory blood flow. Laser light is applied to the skin and illuminates blood cells, causing the light to scatter and change frequency due to Doppler Shift. A photodetector receives the scattered light, electronically processes the signal, and converts it to a perfusion value. Perfusion values were captured by the system in perfusion units (PU) which are based on a volume of blood per minute per 100 grams of tissue (PeriFlux System 5000 Extended User Manual, 2009).



Figure 20: PeriFlux LDPM probe 404-1

Galvanic Skin Response (GSR) Sensor

GSRs measure the conductance across the skin on two fingers using surface electrodes (Figure 21). Skin conductance is measured in micro Siemens (μS). The Skin Conductance Flex/Pro sensor along with the Stress Control Suite from Thought Technology Ltd. measured both the skin conductance level (point-by-point variation in

μ S) and skin conductance response (stress/arousal reaction to stimulus). The voltages picked up by the electrodes were fed to a preamplifier that was powered by a battery operated controller unit (ProComp 2 encoder). The electrode's housing was modified by the investigators to reduce their thickness profile. These sensors were only used on the ring and little finger of the left hands of the test subjects and were attached to the skin of the fingerpads using double sided tape and fabric tape.



Figure 21: Thought Technology Ltd. GSR sensor

Barometric Pressure Sensor

Barometric pressure sensors measure barometric pressure levels in the environment (Figure). This study utilized a miniature PS-2KC by Kyowa Electronic Instruments. The pressure sensor was adhered to the base layer of the SCG on the dorsum side of the intermediate phalanx on the ring finger of both hands. Voltages captured were converted to absolute barometric pressure values (psia).

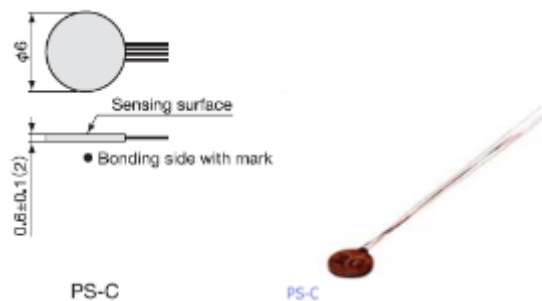


Figure 22: Kyowa barometric pressure sensor

Humidity Sensor

Humidity sensors measure the relative humidity in the air (%) and output the data in analog voltage (Figure). These sensors were adhered using double sided tape and fabric tape to the base layer of the SCG on the dorsum side of the index finger at the intermediate phalanx on both hands. Sensors were slightly modified by investigators to decrease their width and length dimensions.



Figure 23. Honeywell humidity sensor

MoistSense Meter

The MoistSense Meter measures skin moisture content quickly (Figure). Moisture is indicated in arbitrary numbers using a 100 point scale. There are multiple areas of the right and left hand where the meter was used to gather the moisture levels both before all testing and after each of the three gloved conditions (Figure). Only one measurement was gathered from each of these locations due to skin moisture levels returning to a normal state after the hand was removed from the Glove Box. Locations included four fingernails (thumb, index, middle, and ring), three fingerpads (index, middle, and ring), the palm, and the dorsum side of the hand. These measurement locations on the hand were the same ones used in the Jones et al. (2008) study.



Figure 24: MoistSense Meter moisture measurement device

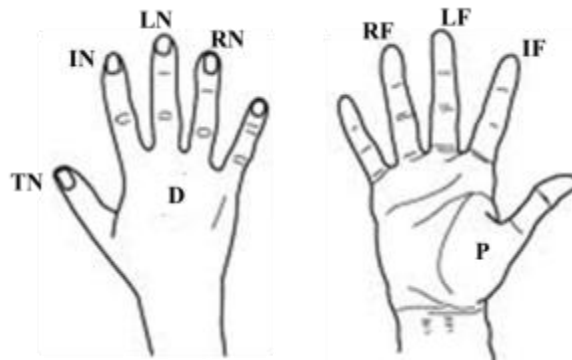


Figure 25: Hand moisture measurement locations shown from Jones et al. (2008)

Vapometer

The Vapometer was a second COTS product that measured skin moisture. It measures skin surface evaporation rate ($\text{g/m}^2\text{h}$), ambient relative humidity (%) and the ambient temperature ($^{\circ}\text{C}$). The device works using an enclosed humidity sensor whose results calculate the evaporation rate value of hydration using the capacitive structure of the epidermis' stratum corneum layer (outermost layer of the epidermis). Like the MoistSense meter, the Vapometer took single measurements for each hand location on both hands prior to all testing and after each condition's tests (Figure 26). The meter was powered by two AA batteries.



Figure 26: Vapometer moisture measurement device

Additional Sensor Instrumentation and Electronics

A Dewetron data acquisition system was used to synchronize and collect all of the sensor data. The exception to this was the GSR system whose timing ran independently from the other systems. This system was synchronized to the others by an auditory countdown (3, 2, 1, Go). Due to this, the synchronizing the GSR data results to the others by time may not be exact.

Also included in the setup was a display monitor and metronome for visual and auditory feedback for test subjects and investigators of relevant real-time sensor data.

All sensors were calibrated from the manufacturer to their unique specifications. The exceptions to this were for the two types of FSR sensors (large and small) and the piezoresistance sensor. These types of sensors were calibrated using a materials test machine that allowed for investigators to iteratively define the force-voltage curve for each type of sensor.

Minimum perceivable sensor values were calculated for each sensor type so that investigators would know what minimum levels in the results should be interpreted (0.1 lbs for large FSRs, 1 lb for small FSRs, and 5 lbs for piezoresistance). Additionally, through the calibration effort, sensor maximums were also accounted for (20 lbs for large FSRs, 21 lbs for small FSRs, and 25 lbs for piezoresistance).

Testing equipment included those necessary instruments used during testing that were not specific to being a sensor (Figure 27).

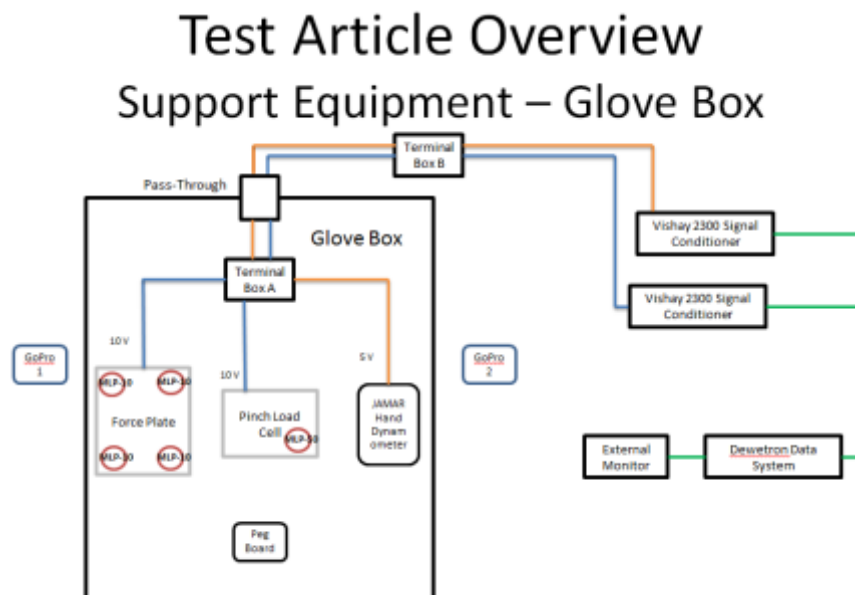


Figure 27: Test equipment diagram

A force plate, consisting of four analog Transducer Techniques MLP-10 force transducers in between two parallel steel plates, quantified the difference in force values between pressurized and unpressurized test conditions (**Error! Reference source not found.**). The force plate was used Fingertip and Fingerpad Button Press tasks.



Figure 28: Force plate used for finger button presses

A hand dynamometer quantified hand grip force for pressurized and unpressurized test conditions (Figure). The hand dynamometer was rated for 200 lbs. The dynamometer was used during maximum and repeated hand grip tasks.



Figure 29: JAMAR hand dynamometer used for grip tasks

A pinch load cell quantified pinch grip force for pressurized and unpressurized test conditions. The Transducer Techniques MLP-50 force transducer was rated up to 50lbs. The load cell was used during maximum and repeated pinch grip tasks.



Figure 30: Transducer Techniques pinch load cell

E. Test Procedures

The subjects completed the Glove Fit Questionnaire while attached to the Glove Box after each test condition. The questionnaire asked about finger length fit, finger circumference fit, and overall glove fit. Glove Fit Questionnaires were captured with the sensor glove and sensors in place on the hands.

Once the sensors were threaded through the SCGs in the correct configuration, the subject put on the gloves while a test investigator positioned the sensors in the correct corresponding locations. The sensors were attached to the hand using Precision Nail glue, Hard-as-Nails, Soft Goods Lab made fabric tape, or Double-sided tape. The B. Sensor Overview section of the document gives more detail to the specific sensor placement locations and adhesion methods by sensor type.

Subjects performed each of the following tasks in all three conditions: ungloved, Phase VI glove, and Series 4000 glove. The ungloved condition took place in the Glove Box under ambient air pressure. The Phase VI and Series 4000 conditions took place in the Glove Box at 4.3 psid.

Isolated Hand Postures

Subjects were shown five hand postures (Figure) and three wrist orientations (Figure). The five hand postures included relaxed, Open Palm, MCP Flexion, Tiger Palm, and Closed Fist. The three wrist orientations included neutral, max flexion, and max extension. The subject held each hand posture at each wrist orientation for five seconds, followed by a ten second break before the next position.



Figure 31: Static isolated hand postures



Figure 32: Static isolated wrist postures

Dynamic Test Matrix

Table 1 below shows the test analysis details for the dynamic tasks that were performed. Each of the tasks were performed with the right and left hand separately, with the exception of the Peg Board test in which case only one test was done in which the subject could use either or both of his/her hands. Button presses for the fingertips and fingerpads were done for three 5-second trials. For the Grip Strength and the Pinch Strength tasks, the subject exerted their maximum strength onto the data capture tool for either three 5-second trials or in a repetitive manner for two minutes of 2-second maximum exertions followed by 2-second relaxes.

The Fingertip and Fingerpad Button Presses allowed investigators to assess sensors using an ideal set of test circumstances; a controlled force stimulus with a controlled hand posture. Tasks then became more complex in hand dynamics and postures as well as frequencies and magnitudes of required force exertions from the subjects. Pinch strength added an additional finger into the assessment so that investigators would essentially assess a fingerpad

press from both the index and thumb. Grip strength tasks looked at multiple fingerpad presses from all of the fingers of the hand. The last incremental step of complexity added high frequency exertions of maximum strength effort to both the Fingerpad Pinch and Grip Strength tasks. This last piece was applied as the last set of tasks at the end of each condition so that investigators could assess strength performance, sensor performance, and physiological change such as perspiration, all within the same tasks. A final Peg Board task was added as a dexterity assessment and timed effort task between the test conditions.

Table 1: Dynamic based tasks performed by subjects

Analysis Type	Data Capture Method	Test Condition	Performance Measure	Time
Dynamic Based Task	Hand dynamometer	Ungloved, Phase VI, Series 4000; ambient/4.3 psid	Grip Strength	Grip 5 seconds, release 5 second, repeat 3 times
Dynamic Based Task	Load cell	Ungloved, Phase VI, Series 4000; ambient/4.3 psid	Fingerpad Pinch Strength	Grip 5 seconds, release 5 second, repeat 3 times
Button Press	Force plate	Ungloved, Phase VI, Series 4000; ambient/4.3 psid; index fingerpad, index fingertip	Maintaining 10 lbs of force	Grip 5 seconds, release 5 second, repeat 3 times
Peg Board Task	NA	Ungloved, Phase VI, Series 4000; ambient/4.3 psid	Quickness	As fast as possible
Dynamic Based Task	Hand dynamometer	Ungloved, Phase VI, Series 4000; ambient/4.3 psid	Repetitive Grip Strength	Grip 2 seconds, release 2 seconds, repeat for 2 minutes
Dynamic Based Task	Load cell	Ungloved, Phase VI, Series 4000; ambient/4.3 psid	Repetitive Fingerpad Pinch Strength	Pinch 2 seconds, release 2 seconds, repeat for 2 minutes

III. Results

Both static hand postures and dynamic hand tasks were evaluated during this study, some of which proved useful for investigators during the sensor evaluations and contributed towards the task objectives. It should be noted that a significant amount of data was analyzed for this study; with 40 sensors, 14 tasks, 2 subjects and 3 test conditions, as well as subjective glove fit/comfort questionnaire data, one will not be surprised to know that in excess of 100 graphs and corresponding analysis was generated. However, the intent of this paper is to provide an overview of the feasibility of the sensors themselves, not to compare gloves directly or provide full detail at the individual sensor location or task level.

Isolated Hand Postures Discussion

When comparing between the different static hand postures, the Relaxed Hand posture had the lowest levels of physiological and force related reaction as compared to the exact opposite, the Closed Fist. Overall, the only two static hand postures to really show difference between ungloved and gloved states were for the Tiger Palm and Closed Fist postures where clear influences of the subjects' hand position can be seen.

If use of a relaxed palm state is used as a low load part of a normalized static task assessment for sensors, then the Closed Fist hand posture can be seen as the high load opposite portion. As an example, MCP FSR sensor readings were fairly low (2 lbs or less) for the glove states with Closed Fist being the highest contributing state. The large FSRs located on the MCP locations were able to accurately measure down to 0.1 lbs so these readings can be considered reliable. One thing to note is that regardless of task, the FSR sensors are normal force sensors and cannot define the full vector of shear forces happening on the hands. Future work should look at finding and integrating these types of sensors to better define the forces acting on the back of the hands.

Again using the Closed Fist posture as a high load inducing static posture, most of the forces seen by the small FSR sensors on the crotches were lower in magnitude than the sensor was reliably calibrated to. Additionally, the low forces seen by the sensors may not necessarily be totally due to the hand postures used, but also may be due to the glove fit around the hand crotches as hand crotch fit data between the two glove conditions were rated as nominal (3) and too large (4) at times.

Although only two subjects were tested, there was a noted trend of increasing fingertip (FSR), fingerpad (FSR), fingernail (strain gauge), and fingertip perfusion (LDPM) when the hand transitions from a relaxed posture to a Tiger Palm posture to a fully Closed Fist posture. This positive relationship between force and perfusion was also noted to be seen in the fingertip perfusion study by Ansari et al. (2009). This combination of force, strain, and perfusion during the static tasks gave investigators a clear idea of how hand posture and glove condition relates to what the hand and fingers feel through the transmittance of forces.

A sample graph is provided in Figure 33 showing Subject 1's FSR data while in a relaxed pose (neutral, max flexion, and max extension) while wearing the 4000 Series gloves. This graph demonstrates the feasibility of these sensors to differentiate different loading cases even on the order of a small fraction of a pound of force.

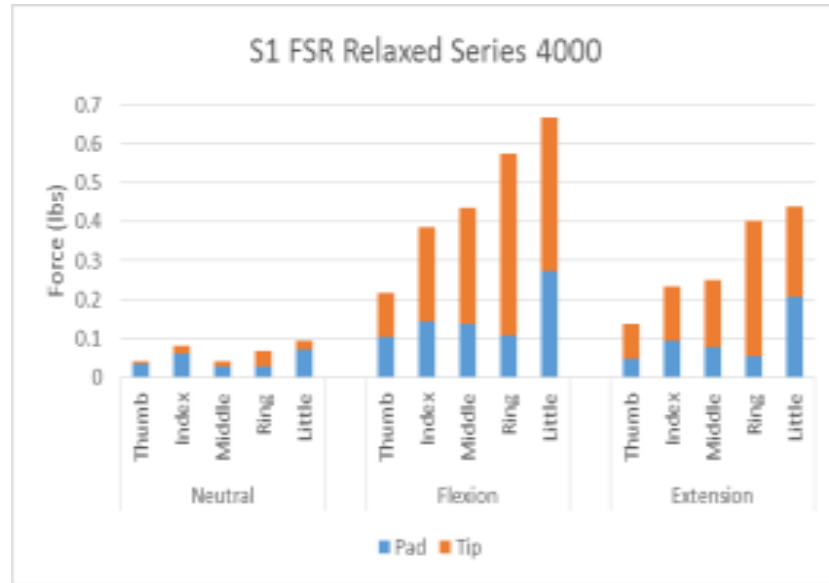


Figure 33: Sample data from Static Postures Tasks

A sample graph of the LPDM sensor in Figure 34 shows the change in perfusion across ungloved and gloved conditions during a tiger palm pose.

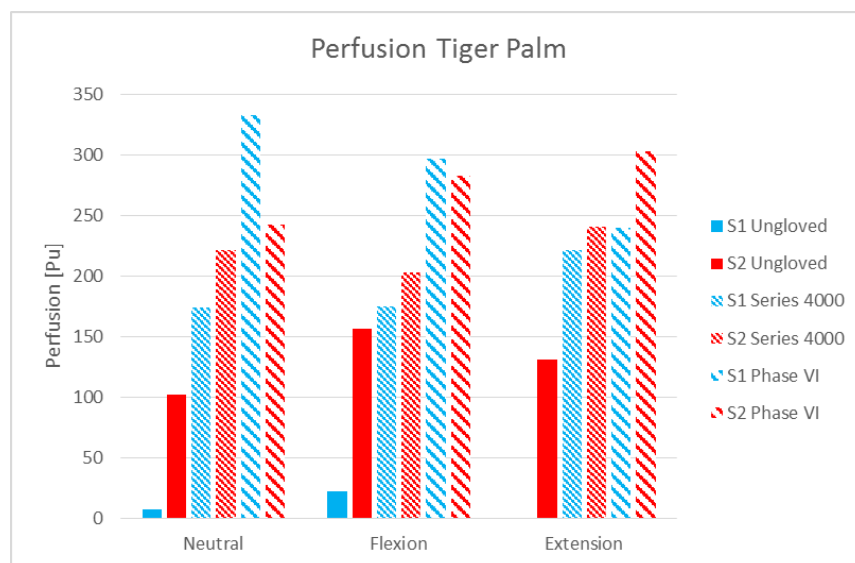


Figure 34: Blood perfusion during a tiger palm position

Dynamic Task Discussion

Similar to the static hand postures, the dynamic tasks were useful in assessing how the forces of the glove and task combined led to higher magnitude levels from the sensors compared to just being in the static isolated hand postures. As subjects would exert their maximum efforts, capture of these high magnitude sensor readings allowed investigators the opportunity to assess how high effort human hand performance translates to environmental and physiological change within the glove on the hand. If use of the offset hand grip is utilized in future work, investigators should make sure to double check that the sensors are aligned with the bar of the grip so that capture of the forces would be perpendicular to the sensors such as the FSR. Subject 1 and Subject 2 contrasting examples of being ideally aligned and mis-aligned for FSR sensor data capture during hand grip or pad pressing activities. Investigators found that by using a normalized task assessment such as the Fingertip or Fingerpad Button Press at 10 lbs, where the stimuli of force was controlled, the response of the sensors could be tried as working correctly and then compared objectively across sensor type. An additional add on to the current Fingertip and Fingerpad Button Press method would be to standardize the hand positioning for future work which will lead to more repeatable and predictable results within and between subjects.

Subject 35 below is a sample of the analyzed data from this portion of the study. In this case, the subjects are performing a fingerpad press to a certain target force threshold. The graph shows the levels of blood perfusion when normalized to the actual force applied to the sensor. Again, it demonstrates the feasibility for this sensor to differentiate reliably between two different glove models when performing the same tasks.



Figure 35: Normalized Perfusion for two subjects during fingerpad button press task

Figures 36 and 37 provide a sample of the thermocouple and humidity sensor data as the subjects go through the battery of tasks. The thermocouple in question is measuring the subject's right palm.

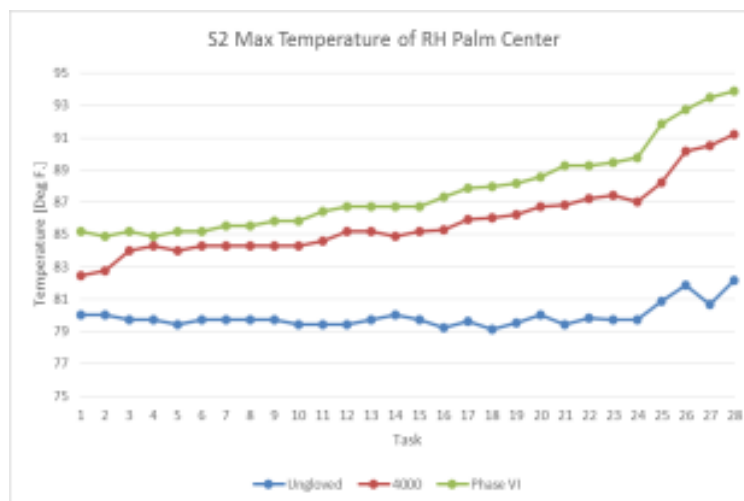


Figure 36: Thermocouple data sample for Subject 2

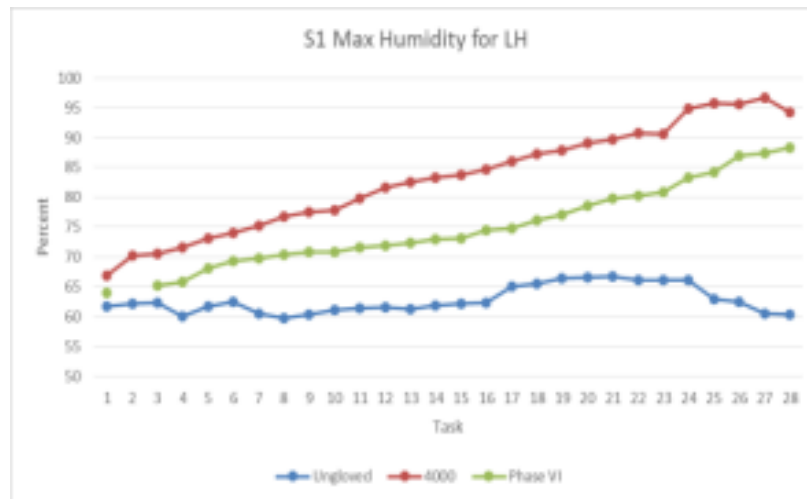


Figure 37: Humidity Sensor Data for Subject 1

A. Study Sensor Takeaways

Force Sensitive Resistor (FSR)

The FSR was the most distributed sensor among the sensor types tested in this study. Within the FSR category, two different sizes of the FSR were investigated with large FSRs covering the fingerpads and MCP knuckles and small FSRs the fingertips and finger crotches. FSR readings recorded decreasing force levels along with prolonged hand grip and pinch grip usage over time during the repeated trials. This was a positive relationship which confirmed that the sensors were working appropriately. Results of the study also found that in general, across both subjects and all dynamic tasks, the force readings in the gloved conditions were lower than the ungloved condition. Using the 10 lb Fingertip and Fingerpad Button Press as a normalized task assessment between gloves, the Series 4000 showed lower fingertip and fingerpad press FSR response forces than the Phase VI, even though all presses were a constant 10 lbs. The results of these two subjects show that it may be possible that the Series 4000 has a protective factor at reducing or dispersing fingertip and fingerpad pressure, but further study would need to be done to confirm this. When relating fingertip and fingerpad pressing activities to injury under normal non-EVA conditions, literature has shown that high levels of prolonged exposure may lead to onycholysis (Olszeska et al., 2009; Mosannen-Mozafari et al., 2011).

Ungloved conditions for Subject 1 had the best return on investment results with the FSRs due to ideal alignment circumstances showing objective force levels on the sensors for the stimulus applied to them. Subject 2's minimal force level results depict what happens when alignment is not ideal. This was most noted for the fingertip sensors, where mis-alignment could lead to forces being dissipated and or showing up on the fingerpad FSRs. Visa-versa Fingerpad Pinch tasks sometimes showed fingertip sensor activation for Subject 2, indicating mis-alignment of the pad sensors due to finger postures. As long as the FSRs are aligned correctly, the repeatability of the sensors was high and the data was shown to be fairly accurate. Durability was also high for the FSRs as they did not get damaged during any of the tests that were conducted. Future calibration should look to allow more refined calibration between 0 and 1 pound and extend up to 20 lbs. Additional improvements on the methodology may include making sure hand and finger positions are appropriately aligned for the sensor or finding FSR sensors that cover larger surface areas of the fingers or hand without imposing greater mobility and or tactility deficits. Lastly, an additional condition of testing the FSRs on a bare skin condition can allow investigators to rule out alignment based or glove multi-layer material distribution based concerns.

Strain Gauge

From the static hand posture trials more strain was prominent in gloved conditions than ungloved, even if the magnitude of the change was small. There were no major differences noted by the strain gauge between wrist positions of neutral, maximum flexion, or maximum extension.

Many of the dynamic tasks involved a modification of what is essentially a fingerpad press by one or more of the fingers, such as a pinch grip or hand grip. When a majority of the forces are applied to the pads of the fingers such as during a fingerpad press, the strain gauges show that fingernail underneath it is generally compressed in both the axial and transverse direction as the tissue surrounding the nail presses against it and the nail essentially flattens out from its neutrally curved shape. As the angle of the finger to the surface where force is applied increases, the force applied on the fingertip increases. This change in position angle may lead to more compression in the axial direction than in the transverse direction or a combination of tension and compression between the two directions. In the fingerpad press position where the fingerpad is perpendicular to the direction of force, the magnitude of strain in the lateral direction is either the same as or greater than the strain in the longitudinal direction, as seen during Fingerpad Button Press tasks, pinch tasks, and grip tasks. A compression of the fingernail from both directions means that the fingernail is being pushed towards its proximal center away from the surrounding skin. Repeated and prolonged exposure to this type of strain whether through direct fingernail contact trauma (Baran et al., 2012; Batan and Badillet, 1982) or through fingertip/fingerpad pressing (Olszeska et al., 2009; Mosannen-Mozafari et al., 2011) could lead to fingernail related injuries, such as onycholysis.

The strain gauges performed well by showing variations in strain as the forces on the hand change for both ungloved and gloved condition. Generally, the sensors showed that the strain on the fingernails was greater in the gloved conditions than in the ungloved conditions. The sensors stayed attached to the fingernails throughout the duration of testing for the most part, and the position of the wiring did not seem to affect the sensor readings. There was one case of sensor failure, which was on the middle finger of Subject 1 in the Series 4000 gloves. The way the sensor was attached did not provide adequate stress relief at the wire and strain gauge junction, and the wire broke during the MCP Flexion hand posture. It had only failed in one direction though, the axial axis, and the data shows that no data was recorded for the axial direction on the middle finger for the remaining tasks in that test condition. The other strain gauges attached to the fingernails for each testing day stayed intact for the duration of the test condition and performed well.

One unique takeaway for investigators with the strain gauges was understanding the level of displacement that actually took place due to strain. The worst case scenario that was noticed to have high levels of μ -Strain was during a maximum fingerpad pinch scenario where the index finger was noted to have a maximum of 3900 μ -Strain in the compression direction for the longitudinal axis at a 10 lb force output on the load cell for Subject 2. This magnitude of strain is equivalent to a 0.006 mm displacement which is a 0.4% change under the surface of the strain gauge (1.5 mm gauge length). The placement of the strain gauge on the fingernails was located just superior and distal to the lunula which is the crescent-shaped white part of the nail at the most proximal-central aspect of it. This portion of the nail known as being the densest location of the nail unlike the distal edges that flex more easily under stress. To give some context to this, Subject 2's fingernail length is approximately 20 mm in length so the strain gauge is only accounting for 0.8% of the attributable length.

Since the fingernail is also more anchored in its center and towards the proximal end where the lunula is, it may not deform as much in those places. Placement of the strain gauges in a different nail location away from the proximal center such as closer to the distal tip or side of the fingernail may give higher strain gauge values and corresponding displacement due to the nail undergoing higher deformation under stress in those areas. The movement of the skin around the nail causes strain on the sides and distal end of the fingernail. Injuries are more likely to begin where the nail is more deformable. A similar study by Sakai and Shimawaki (2007) looked at strain along the longitudinal and transverse axes at three sensor interfaces on the index fingernail. A difference in transverse strain was found between the 3 sensor positions, with the greatest strain seen on the radial-proximal side, then distal-central, and the least strain on the ulnar-proximal side. There was no difference in the longitudinal strain noted between the sensor locations however.

Barometric Pressure

The barometric pressure sensors were only used for a part of the testing and only for Subject 1. The sensors were very fragile, and both were found to be broken at the end of the subject's first testing day. The thin transducer wiring of the sensor broke due to tensile stress and inadequate protection. The thin wires mostly likely broke when the subject moved his fingers during the tasks and stretched the wires. However, while the sensors were working, the data showed information that correlated with the appropriate atmospheric pressure at sea level (14.7 psia). The

sensor readings would show a spike if force was applied on the sensor however, such as during the Hand Grip and Fingerpad Pinch tasks. Larger spikes in pressure were seen in the gloved condition than in the ungloved condition, possibly due to the extra constriction within a glove that put more pressure on the hand as it moves. For the most part, the pattern of spikes in pressure would follow the pattern of force applied by the hand during the repetitive tasks. The pattern was clearer for the grip tasks than the pinch tasks because the finger on which the sensor was placed was more active during the grip tasks.

The barometric pressure sensors were placed between the base layer and the cover layer of the SCG, and the sensors' thin wires ran over the ring finger joints and along the length of the finger. Providing a housing that prevents mechanical pressure from the glove to affect the sensor itself and allows room for the sensor's wires to extend as the fingers move may allow consistent readings and prevent the sensor from failing regardless of hand movement.

The primary intent of evaluating barometric pressure, which was theoretical localized or transient increased pressure during dynamic tasks, is lost in a glovebox evaluation due to the fact that the sensor is open to the ambient atmosphere and not enclosed within a space suit. However, the objective was to evaluate the accuracy and durability of the sensor for future studies where measuring inside an enclosed space suit would be possible.

Temperature and Relative Humidity

Both the thermocouple (temperature) and the humidity sensors performed well together by showing how the temperature on the skin and the humidity within the glove changes over time and how it differs between ungloved and gloved conditions. General subjective discomfort has been shown to result from skin temperatures greater than 94° F or less than 91° F for light work conditions. Increased workloads require lower skin temperatures (< 86° F) for comfort (Chengalur et al., 2004). However, these temperatures are not specific to the hand, which may have slightly different ranges for comfort than the skin near the core. Additionally, only temperature changes of 3.6° F or greater are perceivable for human skin within the range of 64.4 - 107.6° F (Kroemer et al., 2001). Most of the temperature readings from the sensors were within this range, especially during the gloved conditions. All conditions saw an increase in temperature with ungloved having an average increase of 4° F and gloved 8° F. Depending on the subject, the Series 4000 had higher (Subject 1) or lower (Subject 2) temperatures. Two temperature sensors were known to fail during testing and investigators believe that it was during the egress effort of the Glove Box.

Changes in humidity can also cause discomfort while doing work. For example, the feeling of discomfort increases when raising the humidity from 50 to 90% at 79° F (Chengalur et al., 2004). Humidity varied little (1-2%) during the ungloved condition whereas glove conditions on average showed close to a 30% increase over time. None of the humidity sensors suffered damage or irregular behavior during tasks of the study.

A prior EVA related study by Jones et al. (2008) on glove ventilation duct tubing placement changes found that removing ventilation tubing that extended to the wrist created higher levels of moisture on the hands. Results of this study confirm that at least with a Glove Box environment, EVA gloves put more stress on the hands and do not allow as much ventilation of the skin as in an ungloved condition. These factors lead to an increase in heat and moisture within the gloves. Evidence was found of high relative humidity levels causing the nails to be wet and lead to high nail moisture absorption may cause the properties of fingernails to change and possibly split between the layering of the nail (Farran et al., 2008). One additional study did show that the combination of physical fingernail trauma and wet nails (in addition to soap detergent exposure), led to onycholysis for women performing physical hand scrubbing of clothing using wash boards (Sharquie et al., 2005). How moisture relates to hand related injury is still yet to be fully understood though, but anecdotal evidence to moisture as a cause was noted by flight doctors evaluating an onycholysis fingernail injury data during the data mining study of the High Performance EVA Glove (HPEG) investigation for EVA glove-hand injuries conducted during FY13 and FY14.

Laser Doppler Perfusion Monitor (LDPM)

The LDPM was placed on the index finger of the left hand to monitor blood perfusion levels during testing. The LDPM showed identifiable spikes of hyperperfusion, then sudden dips of hypoperfusion, then blood resupply of reperfusion in the finger tissue underneath. This was the typical trend that occurred during finger motion activities that required pressing of the fingertip and fingerpad that induced changes in blood supply as it went from

unobstructed to obstructed back to unobstructed. Similar perfusion patterns are noted to occur during post occlusive reactive hyperemia medical tests where skin surface tissue perfusion is monitored while a blood pressure cuff on the upper arm or ankle induces the occlusion and then removes it. These types of tests are typically used for microvascular functional assessments by medical practitioners.

Higher PU levels were generally noticed in the ungloved states although in some cases Subject 1 showed higher levels in the gloved states. Between the gloved conditions, Phase VI generally was higher in PU values for all of the isolated static and dynamic tasks. This essentially is showing higher blood perfusion available to the two subjects' fingertip tissue for Phase VI than the Series 4000. As long as the sensor remained aligned correctly and in good contact with the skin of the finger, the perfusion sensor performed according to specifications. It was also reliable for durability and was not damaged during any of the testing. Future studies may try to find a sensor of smaller dimensions as subjects noted that the size of the sensor was uncomfortable and may have led to decreased performance during their dynamic testing tasks.

A previous LDPM study by Ansari et al. (2009) discussed differences found between hand and finger force pressures and changes in perfusion levels at the finger. Analogous to the trends of this study, Ansari et al. revealed that a clear relationship existed between increasing force on the finger and decreasing blood perfusion levels. It is yet to be understood how blood perfusion levels may change during EVA ground and flight activities as well as if low perfusion levels are continuously present during them. It can be hypothesized though that if a low enough perfusion level is present, ischemic conditions may take place in the finger such as reduction in normal tissue oxygenation, nutrient supply, and metabolic waste disposal. This negative affect may lead to tissue damage or associated signs and symptoms of the condition over prolonged periods of exposure such as onycholysis (Cabanillas et al., 2011), paresthesia, and finger blanching of the fingers similar to Raynaud's syndrome (Cooke and Marshall, 2005; Kroemer et al., 2001). Future work should continue to investigate this potential risk to crew.

Galvanic Skin Response (GSR)

During testing it was found that the GSR was not useful for short duration or minimal trial tasks. However, when assessed over time it was found that skin conduction increased with continuous conditional test exposure. Between condition comparisons for both subjects revealed that Subject 1 had lower μ Siemens than gloved and Subject 2 having the opposite. When comparing between EVA gloved conditions only, this non-consensus between subjects was also seen as Subject 1 had higher Series 4000 levels and Subject 2 had higher Phase VI levels.

Aside from its performance, durability of the sensor was noted to be high as even though it was placed on the fingerpads, the sensor did not fail during any of the tests. Subjects found the sensor bulky though as it was noticeable by them during all of the dynamic testing activities that required hand grip which they felt was uncomfortable and may have affected their performance.

Results of the GSR are subject to both mental and physical stressors perceived by the individual being tested. While the exact results may not be repeatable, long term usage of the sensor during testing will show increases in conductance due to moisture on the fingerpads. Further study with more subjects and longer duration could possibly lead to a clearer conclusion.

Like that of relative humidity, GSR was another sensor that was integrated into the test environment to assess the moisture content. Skin conductance is inversely related to skin impedance, which is known to decrease as one perspires (Brauer, 2006; Fish and Geddes, 2009). As a result, skin conductance should increase with increasing perspiration on the skin. Onycholysis of the fingernail is the only crew related injury that is known to possibly be at risk from moisture around the fingernail. Refer back to the end of the Temperature and Relative Humidity section of the Conclusion above to read further information on studies relative to moisture as a potential risk variable.

Piezoresistance

The intent of using piezoresistance sensors was as an alternative method to gathering force related data along the fingerpads and MCP knuckles of the dorsum of the hand. Although meticulous effort was exerted at the beginning of this study by investigators, the effectiveness of the piezoresistance sensor was limited to that of a binary switch with

an on or off state. The sensor was generally considered unreliable for quantifying all of the force related tasks. Resulting force values were shown to be either extremely low or extremely high in magnitude.

To improve the reliability of the sensor, it is suggested that during the calibration process a large number of iterations be taken from both within and between sensor samples. This highly meticulous evaluation is normally done by manufacturers for products that are produced such as the FSR sensors. Due to time and budget constraints, investigators were not able to accomplish this. It may be possible for future investigators to ideally map the variability of the sensor, but due to the soft fabric material of the sensor, repeatable fabric deformation will be difficult.

Two of the piezoresistance sensors were damaged during testing and required replacement. They were damaged at the leads of the sensors likely due to high tension on the wiring during subject hand and finger movement. Better stress relief of the wiring may help prevent this for future work.

Vapometer & MoistSense Meter

The Vapometer and MoistSense Meter were two moisture sensors that were evaluated using a pre- and post-test method. Both were used on the test subjects' hands outside of the Glove Box test environment. For both sensors and both subjects, the palm area of the hand was shown to have higher levels of moisture and conversely the fingernails the least. Generally across the subjects, ungloved conditions were lower in moisture levels than gloved conditions. Subject 1 showed a higher level of moisture in the Series 4000 and Subject 2 showed higher levels in the Phase VI. This trend was consistent between both sensor types.

Due to these sensors being outside of the Glove Box, there was not a physical exposure that threatened their reliability or durability. The order of starting hand and hand measurement location data capture should be standardized for future tests as the hand moisture levels dry after being removed from the Glove Box and the EVA gloves. Additionally, this would mean leaving the non-assessed hand remaining in the Glove Box until needed.

IV. Conclusion

This EVA Glove Sensor Feasibility II study evaluated 10 types of sensors on both hands (40 sensors integrated to the gloves and 3 external to the glove) of two subjects for three study conditions (ungloved, Series 4000, and Phase VI) over 28 static and dynamic hand tasks. This data collection took place over two test days and collected approximately six hours of data.

Going forward, future feasibility testing should look to take sensors that are known to be accurate, reliable, and durable and test them with a larger population to get a better understanding of the changes that were shown to result from this test in order to verify their outcome. Additionally, the Glove Box condition is just the beginning of any EVA related feasibility testing. Testing methods will need to evolve to include a self-contained system capable of being integrated into an EVA suit and then tested in a laboratory setting prior to a NBL one where a large number of training injuries are known to occur.

Table below summarizes the performance of each sensor type in terms of accuracy, durability and repeatability.

Table 2: Overall sensor performance in terms of accuracy, durability, and repeatability

Sensor Type	Accuracy	Durability	Repeatability
FSR	pass	pass	pass
Strain Gauge	pass	pass	pass
LDPM	pass	pass	fail
Piezoresistance	fail	fail	fail
Baro. Pressure	pass	fail	pass
Temperature	pass	fail	pass
Humidity	pass	pass	pass
GSR	pass	pass	pass
Vapometer	pass	pass	pass
MoistSense Meter	pass	pass	pass

Force Sensitive Resistor (FSR)

Force Sensitive Resistor (FSR) tip sensors while calibrated correctly were shown to have low levels of force feedback compared to what was being generated on the load cells of the test equipment. Highest force levels for tips sensors for example were noted to be approximately 2 lbs during Fingertip Button Presses with a 10 lb force exerted by subjects on the force plates. Fingerpad sensors were shown to give more appropriate magnitudes of feedback when aligned correctly with the applied force direction. Overall, these sensors may still need to be evaluated further as they may have been mis-aligned during the press activities and they also may have suffered from force dispersion through the multiple layers of the Sensor Carrier Glove (SCG) and EVA gloves. Bare skin Fingertip and Fingerpad Button Presses from future testing would be a final confirmation as to their potential future usage. Additional training to test subjects regarding perpendicular alignment with the sensor may also be necessary during these skin tests.

FSR crotch and MCP sensors were also shown to have minimal levels of force magnitude. This may likely be because the sensors were either experiencing minimal forces due to subjects' loose or large glove fit in the crotch areas (particularly to finger crotch sensors) or due to the sensors being normal force sensors and the sensors needed may be shear force ones. This latter point is specifically regarding the MCP sensors which were placed there to understand any EVA glove pressure points or abrasions at those locations. Finger crotch FSRs were placed on the dorsum aspect of the finger crotch webbing. Having a sensor ideally placed on the leading edge of that webbing may aid in better capturing the applied force. A different FSR may be needed if that is the case, one that could fold across the leading edge from dorsum to palmar side.

Strain Gauge

Strain gauges performed ideally for the circumstances that they were exposed to. Only one strain gauge failed during testing out of the 20 used and it only lost one of its directional attributes. These were noted to be the best performers of all of the sensors tested and gave the most return in information across multiple tasks. Further work should be done to further strain relieve the wire leads and routing to create a more protective environment for the sensor.

Laser Doppler Perfusion Monitor (LDPM)

The Laser Doppler Perfusion Monitor (LDPM) was shown to be remarkably useful and reliable regardless of condition. Future use with it would need to take care to ensure that a solid contact interface is made between the sensor and the skin to prevent any movement and mis-alignment that would produce erroneous data. Additionally, if further sensor size miniaturization could take place, that would prove ideal so that subjects, would be less perceptible to its presence on their fingerpads. The sensor size itself was a negative factor in how tight the glove felt on subjects and the rating that they gave it towards influencing their performance.

Piezoresistance

Sensors that were shown to have extremely unreliable performance across the three attributes were the piezoresistive sensors. These sensors results were showing values that were not within logical means of actually being experienced during the test (such as ranges between 3,000 and 5×10^9 lbs of force). If used in future testing, meticulous calibration techniques similarly done in a sensor manufacturing setting would need to be performed to improve its performance. Preference should be given to the FSR sensors though if force is to be collected.

Barometric Pressure

The barometric pressure sensor although accurate and repeatable outside of the gloved condition, was greatly affected once in. If the same sensor is to be used in future studies, the sensor would need to be inserted into a protective housing to prevent its results from being influenced by mechanical forces of the glove and also prevent it from being damaged.

Thermocouple

The thermocouples were excellent at being minimally perceptible by subjects, but itself was susceptible to mechanical damage. Although not as fragile as the barometric sensor, possible housing or application method may need to be adapted to assist its longevity through testing.

Humidity

The humidity sensor was another fairly flawless performer. Minimal notice was given to it by subjects and the data recorded was useful especially when combined with temperature and other moisture sensor readings like GSR, Vapometer, and MoistSense Meter.

Galvanic Skin Response (GSR)

Galvanic Skin Response (GSR) sensors performed well. It was found from tests that the GSR should not be assessed by individual task, but instead similar to temperature or humidity, over the longitudinal approach of accumulated tasks through time. Similar to LDPM, the GSR was a bulky sensor, so further work should be conducted to try to minimize its size so that it is less perceptible to subjects.

Vapometer and MoistSense Meter

The two pre- and post-test sensors used were the Vapometer and MoistSense Meter. Both were highly useful to investigators and helped confirm what the humidity and GSR sensors were reporting. Although slow in data collection, the Vapometer gave actual moisture levels on the hand ($\text{g/m}^2\text{h}$) whereas in contrast the MoistSense Meter was a quick turnaround between readings but only gave arbitrary results on a 100 point moisture scale. An order of starting hand preference and hand measurement location should also be established for the measures, as the measurements from the hand locations take time and this can cause the skin and nail surfaces to dry. Additionally, leaving the non-measured second hand in the Glove Box will allow more of the moisture to be preserved until the hand is ready to be measured.

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The authors wish to thank Mark Schaeffbauer, Kase Urban, and Phong Do in the JSC EC2 soft goods lab, as well as Vic Untalan for EC2's support of this effort, related efforts and ongoing help in integrating sensors, associated electronics and softgoods.

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