

Publications

7-16-2016

Suitability Testing for PoSSUM Scientist-Astronaut Candidates using the Suborbital Space Flight Simulator with an IVA Spacesuit

Pedro J. Llanos

Embry-Riddle Aeronautical University, llanosp@erau.edu

Erik Seedhouse

Embry-Riddle Aeronautical University, seedhou@erau.edu

Ryan L. Kobrick

Embry-Riddle Aeronautical University, kobrickr@erau.edu

Follow this and additional works at: <https://commons.erau.edu/publication>



Part of the [Aerospace Engineering Commons](#)

Scholarly Commons Citation

Llanos, P. J., Seedhouse, E., & Kobrick, R. L. (2016). Suitability Testing for PoSSUM Scientist-Astronaut Candidates using the Suborbital Space Flight Simulator with an IVA Spacesuit. (). Retrieved from <https://commons.erau.edu/publication/1437>

This Conference Proceeding is brought to you for free and open access by Scholarly Commons. It has been accepted for inclusion in Publications by an authorized administrator of Scholarly Commons. For more information, please contact commons@erau.edu.

Suitability Testing for PoSSUM Scientist-Astronaut Candidates using the Suborbital Space Flight Simulator with an IVA Spacesuit

Pedro J. Llanos, Ph.D.¹, Victor Kitmanyen², Erik Seedhouse, Ph.D.³ and Ryan L. Kobrick, Ph.D.⁴
Embry-Riddle Aeronautical University, Daytona Beach, Florida, 32114

This paper evaluates key functional data parameters that must be considered for suborbital spaceflight participants wearing pressurized suits for intravehicular activity (IVA). Data parameters of an analog spacesuit worn in an analog flight environment were obtained from 40 civilian participants using the Suborbital Space Flight Simulator (SSFS) at Embry-Riddle Aeronautical University (ERAU) while donning Final Frontier Design's (FFD) fully pressurized third-generation spacesuit as part of their training for Project PoSSUM (the Polar Suborbital Science in the Upper Mesosphere Project). The physiological data collected included: blood pressure, electrocardiograms, heart rate, grip strength, and skin temperature. These parameters were measured using a blood pressure monitor, a Zephyr Bioharness, and a BioRadio respectively. Other data collected include participants' motion sickness, discomfort and mobility, and stress and workload. These parameters were self-assessed using the Simulator Sickness Questionnaire (SSQ), the Modified Cooper Harper Rating Scale, and the NASA-Task Load Index (TLX) respectively. Preliminary results show that 29% of the participants experienced basic spacesuit donning discomfort, while 17% of the participants showed some doffing discomfort. Feet, shoulders, neck, arms, and ankles were the most sensitive parts in this process and throughout their use of the suit. Our results also indicate that the spacesuit limited participants by approximately 24% of their normal cross-body reach range of motion. Nevertheless, the operational capability of this suit is currently being evaluated as a viable option for supporting future suborbital, orbital, and exploration missions. This research will enhance the functionality of the suit, standardize suit testing procedures, aid in identifying key parameters for reducing physiological deconditioning in the use of emerging spacesuit technologies, and provide comparative analysis reference for future studies.

Nomenclature

<i>AAS</i>	= Applied Aviation Sciences
<i>ERAU</i>	= Embry-Riddle Aeronautical University
<i>FFD</i>	= Final Frontiers Design
<i>IVA</i>	= Intravehicular Activity
<i>PoSSUM</i>	= Polar Suborbital Science in the Upper Mesosphere
<i>ROM</i>	= Range Of Motion
<i>SAC</i>	= Scientist-Astronaut Candidate
<i>SSFS</i>	= Suborbital Space Flight Simulator
<i>SSQ</i>	= Simulator Sickness Questionnaire
<i>TLX</i>	= Task Load Index

¹ Assistant Professor of Spaceflight Operations, Applied Aviation Sciences Department, College of Aviation, COA 316.

² Undergraduate student, Commercial Space Operations, Applied Aviation Sciences, College of Aviation.

³ Assistant Professor, Applied Aviation Sciences Department, College of Aviation, COA 314.

⁴ Assistant Professor of Spaceflight Operations, Applied Aviation Sciences Department, College of Aviation, COA 330.

I. Introduction

THIS study, proposed by Embry-Riddle Aeronautical University (ERAU) researchers, was based on data collected during the regularly scheduled Polar Suborbital Science in the Upper Mesosphere (PoSSUM) training platform on Daytona Beach campus. Variance in physiological and psychological responses among the participants was analyzed throughout three training phases: Phase one: Hypobaric chamber training; phase two: Suborbital Space Flight Simulator (SSFS) training, and phase three: aerobic training.

This paper examines how the participants responded to Phase Two during training classes in October 2015 and April 2016. Research associated with the other platforms will be presented in future papers. Using the data from Phase Two, the researchers assessed participants' adaptability in operating the scientific instrumentation within the SSFS while wearing a pressurized spacesuit. The ability to perform these tasks was rated using the Modified Cooper Harper Scale (from 1-Excellent to 10-Major Deficiencies).

II. Suborbital Space Flight Simulator and IVA Suit

This study represents the first time research was conducted on participants using the SSFS since its installation in the Summer of 2015 at the Space Operations Laboratory at ERAU's Applied Aviation Sciences (AAS) Department (Figure 1). Developed out of the shell of a Cessna cockpit that was previously used as an Airplane Flight Training Device (FTD), the SSFS is a stationary simulator capable of modeling the flagship vehicles of prominent commercial space companies such as XCOR's Lynx, and Scaled Composites' SpaceShipTwo. With several such companies planning on sending private citizens to space (some with payloads) at a frequency of 3-4 flights per week within the next 3-5 years, this research will help identify any risks associated with training commercial astronauts by providing a comprehensive human factors data set.

Project PoSSUM aims at certifying citizen scientist-astronauts capable of collecting data on noctilucent clouds during suborbital flight. Accordingly, the SSFS at ERAU provides an ideal mockup for what these scientist-astronaut candidates (SAC) can expect. Phase Two of SAC's training naturally helps identify and assess human/medical factors, external/environmental variables, and flight control complications (i.e., mission profiles, and contingency management issues) on suborbital flights.

The researchers assessed the interactions between the SAC and the vehicle during each simulation at three different stages: ingress, inflight, and egress. In each simulation, the SAC egressed the cockpit with the IVA suit unpressurized. The IVA suit was then pressurized and inflight operations were performed by the SAC during a suborbital profile simulation run while seated on the right (passenger) side of the cockpit. After inflight tasks were completed, the IVA suit was unpressurized and the SAC egressed the cockpit (Figure 1). Observing the SACs during these three phases generated pertinent information about the safe operation of the SSFS and addressed operational capabilities and tolerance levels that will help lead the FAA-approval for the simulator to be used to train future suborbital commercial astronauts.

The SAC's mobility data while in the pressurized suit and operating the scientific instrumentation (camera) was not directly obtained nor quantified, but different range of motions (ROM) inside the cockpit were observed and suggested limitations to movement (Figure 1a). It was observed in egress procedures that the SAC was unable to quickly extricate due to limited space and mobility restrictions imposed by the the spacesuit and the placement of the scientific camera. SACs (5 feet to 6.4 feet) had sufficient (ROM) to operate the camera, although at times with some degree of difficulty. Occasionally, the SAC would need to grab the camera handle from the very bottom as they were unable to reach the top, soft part of the handle (chin level to face level depending on SAC height). On the other hand, each SAC was able to easily access the 6 instrumentation controls and operate the two concentric knobs, zoom, and iris control. The instrumentation controls could be reached at chest level, indicated by the red and green switch lights displayed in Figure 1. These were operated by the left arm of the SAC. The zoom control was used to enlarge a micro feature of the noctilucent cloud, and the iris control was used to control the amount of light. The zoom and iris control were operated with the right arm of the SAC. In this preliminary study, each SAC performed single-handed tasks, but in future studies, the SAC will perform two-handed tasks to assess the performance of the work envelope.

Some payloads onboard commercial flights may require operators to be highly attentive and physically functional despite imminent spaceflight discomforts (i.e., cabin noise, vibration, weightlessness, cardiovascular and neurovestibular effects, and motion sickness). It is currently undetermined how these commercial astronauts will respond to flying several times per day.

This research will improve future pre-flight medical considerations to better accommodate astronauts on suborbital flights. The subjective workload data is intended to assist with next generation spacesuit design recommendations and spacesuit training operational procedures. The sequence of pictures depicted in Figure 2

demonstrates partial donning procedures for the IVA suit^{1,2}. The FFD pressurized garment is a 3 layered 3G (third generation) space suit made of nylon, dyneema (high molecular weight polyethylene with better strength-to-weight ratio than nylon), and flame retardant fabric. The suit weighs 6.8 kg (15 lbs).



Figure 1. a)-b) Stationary Suborbital Space Flight Simulator in the AAS department at ERAU during a pressurized spacesuit dry run and instrumentation tests, showing limited range of motion by extension of arm to touch front screen. c) Limited range of motion by extension of arm to touch secondary screen in diagonal direction. d) SAC being helped by FFD personnel to egress the SSFS. e) SAC in pressurized IVA suit performing data collection samples with PoSSUM instrumentation during the 20-minute suborbital mission. f) Noctilucent cloud measurement obtained by SAC when passing through the mesosphere at 273,000 ft.

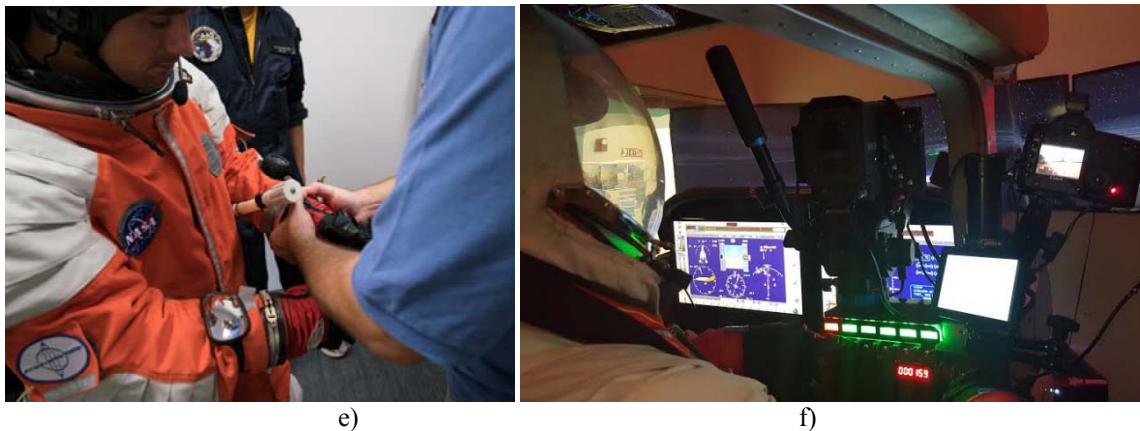
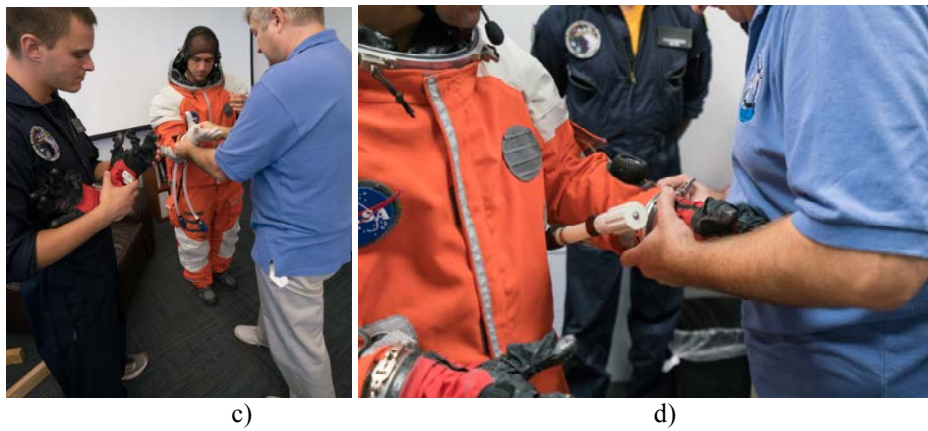
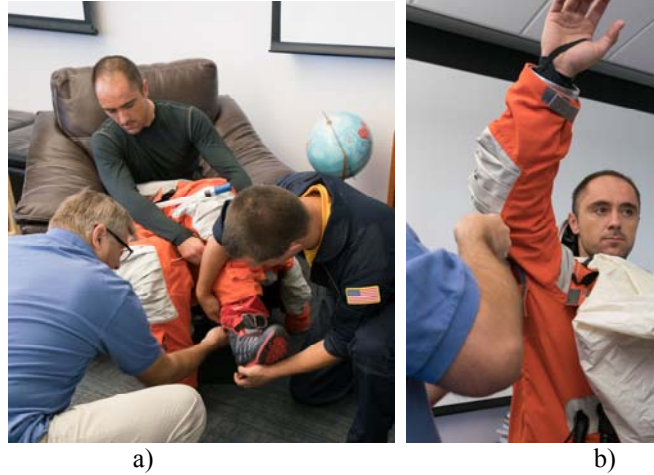


Figure 2. Selected permitted (proprietary issues) steps of IVA suit donning demonstration during a test dry run before putting SACs in the SSFS. a) Putting on booties after undergarments. b) Adjusting arms after integrating upper torso of IVA suit, fixing pulls and stirrups in the armpit, and connecting waist restraint adjustments. c) Putting on thin gloves d) After adjusting visor latches and pulls and communication cap, and integrating gloves. e) Connecting and latching the gloves onto the suit. f) SAC in the pressurized IVA suit operating the instrumentation inside the SSFS.

Because of proprietary issues, limited visual suit operations have been reported in this paper. ERAU's team was able to observe some of the IVA donning process. Figure 2a shows a candidate sliding his legs into the bottom part of the IVA suit. Assistance was required by at least one other person. Shoes would be donned following suit donning. The candidate stands up and holds the mid part of the suit to pull it up. The SAC places the arms one at a time into the

suit (see Figure 2b) while the FFD team aided with fixing the pulls and stirrups in the armpits. At this point the white material in front of the suit (see Figure 2b) was gathered and wrapped around with two rubber bands to seal it to hold the pressure inside the suit. Next, the SAC donned the communication headset and plugged the microphone, power connector, cables and sensors. Donning took 20-25 minutes.

III. Bioinstrumentation and Data Collection Analysis

During Phase Two/SSFS Training portion of the research, the Zephyr BioHarness and BioRadio instrumentation was used to collect biometric response data from the participants as they performed their duties. The biometric data was time stamped and thereby synchronized with events from each of the training platforms. The biometric responses can therefore be correlated across each training platform.

A. Zephyr BioHarness

The Zephyr BioHarness consists of several sensors fixed to a chest strap as depicted in Figure 3. This system has been used by NASA and in published peer-reviewed studies. It was used in this study to collect physiological data, such as heart rate, breathing rate, estimated core temperature, posture, as well as the accelerations and ECGs experienced by the participant during aerobatic flights as part of the same research study.³

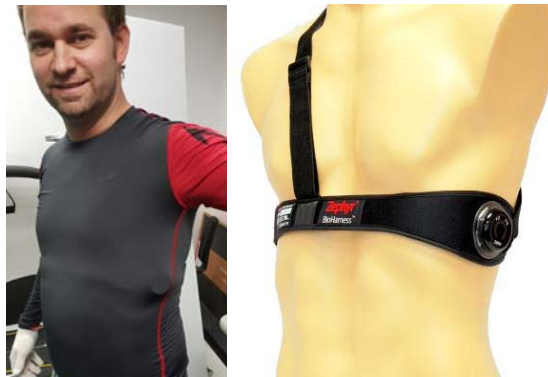


Figure 3. Participant wearing a Zephyr BioHarness sensor and chest strap.

B. BioRadio Instrumentation

The BioRadio Instrumentation (see Figure 4a) was used during SSFS training to obtain measurements of skin conductance (using the surface temperature sensor) and grip strength (using the hand dynamometer). This device also provided spirometry data during the aerobatic flights research phase platform.³

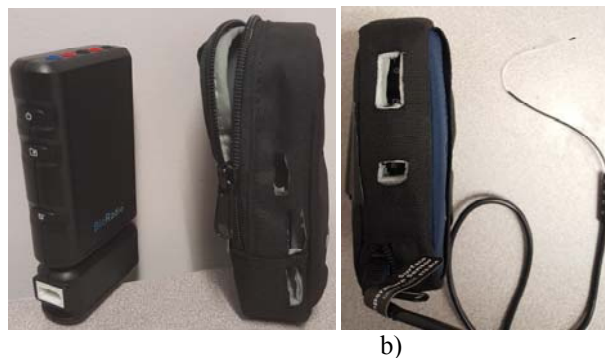


Figure 4. a) BioRadio Instrumentation with a camera-pouch adapted for the Bio Radio instrumentation. b) Surface temperature sensor with probe sensor. c) Hand dynamometer sensor.

C. Bioinstrumentation Measurements

The following measurements were obtained using the aforementioned bioinstrumentation:

1. To measure skin temperature variation, a skin conductance (surface temperature) sensor (see Figure 4b) from the BioRadio instrumentation was used to measure the participant's skin temperature five minutes after suit doffing. Each candidate was asked to place the temperature probe sensor on the collar bone of the neck. The probe sensor was taped to the skin using surgical tape to minimize movement and false readings. In the future, the intent is to characterize the temperature gradient inside the pressurized spacesuit and correlate it to mission tasks. For this, a small thermometer affixed to the inside of the suit may be needed.
2. To measure tension, a hand dynamometer (Figure 4c) was used. For this, each participant was asked to hold the device just as they held the camera instrumentation inside of the SSFS (see Figure 1), and perform similar operational movements to mimic the grip strength and pinch strength when using the camera. These grip strength measurements were obtained without gloves (bare hand). In the future, participants will wear the gloves to obtain more accurate grip strength measurements and to assess the range of manual dexterity permitted by the glove from the pressurized suit.
3. Basic physiological measurements, such as height and weight were obtained for each SAC.
4. Range of motion and subjective workload associated with wearing the pressure suit was measured using the Modified Cooper Harper Scale⁵ and the NASA TLX respectively. Each SAC was asked to perform a series of range of motions prior to ingress/pressurization and with the visor up (Figure 5). Each SAC rated the overall comfort level (1 = excellent, 10 = very uncomfortable) for each ROM. The first ROM test required the SAC to reach across their body to touch the opposite side of their hip. The SAC then raised their arm and touched the opposite shoulder. Next, the SAC extended their arm above and outward from the helmet. The SAC then reached behind to touch the back of the helmet. Lastly, the SAC returned to the relaxed, neutral position.

The SACs subjective workload was also assessed while performing the following tasks:

1. Each SAC walked 200 feet from the room where they donned their IVA suit to the SSFS and while completing safety briefings and preparation checklists.
2. Ingress into the SSFS required step up onto a 7 in-flat stool before stepping up into the right seat of the SSFS, 33 inches above the flat stool. This motion required raising the left leg up and squeezing their body in between the camera mount to place themselves into the right seat of the SSFS.
3. After seated, the SAC latched the helmet and started the pressurization of the IVA suit. Inflight operations using the instrumentation described commenced thereafter for a duration of 20-25 minutes. SACs of shorter stature felt their upper torso dropped and leaned into the suit, consequently losing field of view through the helmet. It was difficult for these SACs to rearrange their position inside the suit since it was pressurized. This restriction may affect the position of the SAC in the seat of the SSFS and may also limit the field of view while performing a task (in the future, the position will be subject to further scrutiny and measured with the BioHarness to assess the work envelope of the SAC).
4. After the mission was completed, the suit was depressurized, and the SAC unlatched the helmet and then egressed the SSFS with the help of a suit technician (see Figure 1d). The SAC had to step down from the right seat of the simulator onto the 7-in flat stool, then walked back 200 feet to the donning/doffing room before doffing the IVA suit aided by the FFD team.

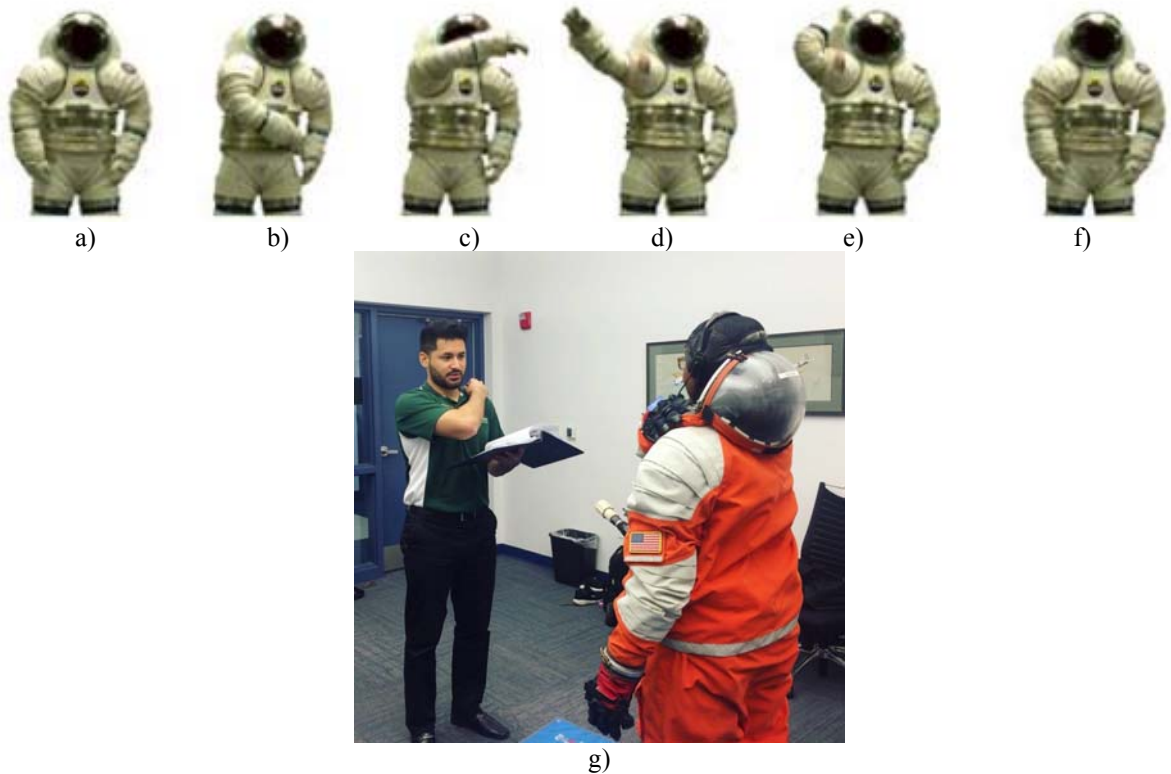


Figure 5. a)-f) Range of motions⁴ performed by each of the participants. g) Undergraduate student collecting range of motion data from one of the SACs in the AAS department at ERAU.

5. Self-assessed magnitude of simulator sickness in response to the three training platforms was measured using the Simulator Sickness Questionnaire⁶ (SSQ).
6. Instrumenting each astronaut scientist when performing SSFS operations took approximately 15 minutes.
7. It took approximately 10 minutes to remove instrumentation for each of the three phases (hypobaric chamber, SSFS, aerobic).
8. Individuals completed a self-reported survey regarding SSFS training in approximately 5 minutes.
9. On average, it took a total of 30 minutes for SSFS training phase pre-donning and post-doffing operations.

Note: not all the measurements were gathered due to time and scheduling constraints between ERAU and FFD duties when some IVA suit operations took place.

D. SSFS Training Risks

This section describes risks associated with the study.

Overheating (low risk): To relieve the astronaut from overheating or sweating inside the pressurized during specific mission tasks, one of the manifolds (tubes) connected to the pressurized (2.0 psid or pounds per square inch differential) IVA suit was routed through a vessel containing iced water for cooling purposes. This manifold is split into two other manifolds used to ventilate different parts of the IVA suit, such as arms and legs, and head. This system worked successfully. Note: in this preliminary study, no attempt was made to quantify externally-applied cooling, such as air temperature into and out of the suit, and flow rates, but this will be analyzed in future studies. Furthermore, the participants were hydrated with water or Gatorade before entering the SSFS.

Air deficiency (low risk): To avoid air deprivation (air flows through a second manifold), the helmet of the astronaut could easily be unlocked by one of the nearby spacesuit technicians. This procedure was managed by FFD and was not actively combined with dynamics pulse oximetry and CO₂ measurements. This procedure will be conducted in future studies. None of the participants experienced any air deprivation, so there was no need to perform this operation.

Depressurization (low risk): In case of pressurization failure, the compressor could be disconnected and the participant could be brought out of the pressurized suit after having opened the helmet. An extra compressor was onsite in case of main compressor failure.

IV. Results

Presented in this section are the results for several of the parameter assessments conducted in this study including: the skin temperature and grip strength analyses, the Modified Cooper Harper Scale assessment, the NASA TLX analysis, and the simulator sickness questionnaire.

E. Skin Temperature Analysis

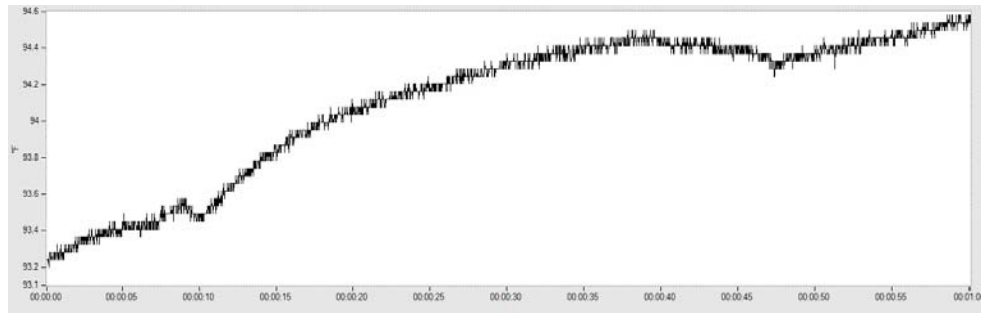
This measurement was recorded for 28 of the 40 participants while training in the SSFS for about 25 minutes as displayed in Figure 7. Time and schedule constraints prevented skin temperature measurements for all 40 participants. Figure 7a to Figure 7h represent 8 of these 28 temperature profiles. The temperature measurement was the first measurement recorded from each participant within ten minutes of having doffed the pressure suit. Participants were seated (as mentioned in section IV) while this measurement was recorded by the BioRadio Instrumentation (see Figure 4b) for 60 seconds. Due to proprietary issues with the IVA suit, temperature measurements inside the IVA suit could not be obtained by placing a temperature sensor inside the IVA suit.

Participants wore a pressurized (2.0 psid) IVA suit with proper ventilation flow while training in the SSFS. 25% of participants experienced slight sweating, while 10% experienced moderate sweating. On a scale from one to ten, slight sweating accounted for 1-3, and moderate sweating was described by 4-6. All of the skin temperature profiles (with full set of data) displayed in Figure 7 have a general trend of increasing skin temperature and can be approximated as a linear fit for analysis purposes. This slight increase in temperature in most of these participants may be understood as possible heat storage in their bodies even while in the ventilated pressurized IVA suit. So when the pressurization and ventilation stopped, evaporative heat losses from sweat took place. Note that the heat stored in each of these astronaut-scientist participants is a function of their individual body surface area, weight, and the change in body temperature. The body heat storage (in kcal/m²) was computed using the Eq (1).

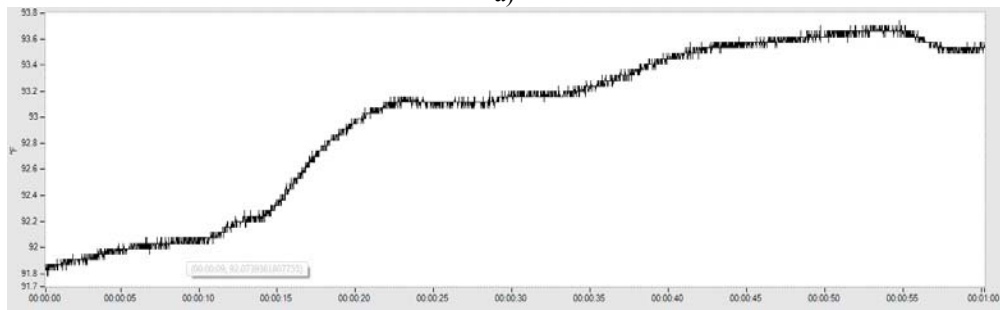
$$Q_{stored} \text{ (kcal / m}^2\text{)} = \frac{0.831 \left(\frac{\text{kcal}}{\text{kg} \cdot ^\circ\text{C}} \right) \cdot \Delta T \text{ (}^\circ\text{C)} \cdot \text{Weight (kg)}}{A_{participant} \text{ (m}^2\text{)}} \quad (1)$$

The change in body temperature, ΔT (degrees Celcius), was measured over approximately 60 seconds, which corresponds with the recording time of the skin temperature for each participant. The body surface area of each participant was computed assuming the Mosteller formula.⁸ Figure 9, depicts body heat stored by each of the 28 participants. 68% of the participants (19 participants) showed body heat storage levels lower than the average, and 32% of the participants (9 participants) experienced large body heat storage levels. Of these 9 participants, 6 participants experienced body heat storage levels between 600 kcal/m² and about 1,000 kcal/m².

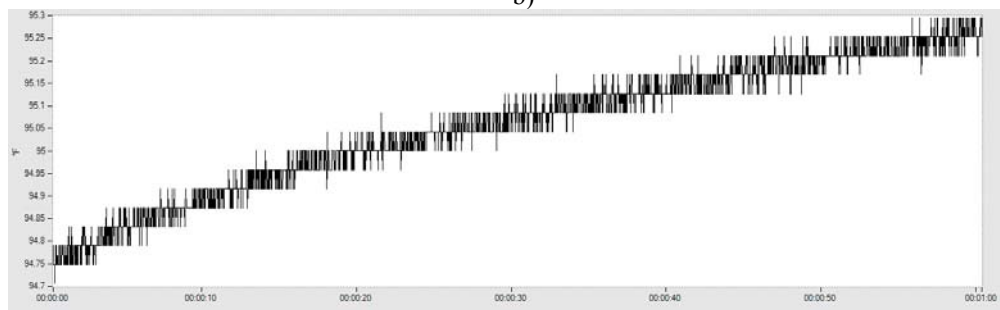
Minimum skin temperatures measured with the BioRadio device ranged from 87.8 °F to 95.5 °F with an average of 92.3°F. Maximum skin temperatures ranged from 86.6 °F to about 95.6 °F with an average value of 92.5 °F. The standard deviation for the maximum and minimum temperatures were 2.2 °F and 2.3 °F, respectively. Individual skin temperature profiles are shown in Figure 6a to Figure 6e and Figure 7a to Figure 7c. In Figure 7d, minimum temperatures are shown in orange squares, maximum temperatures are displayed in blue rhombus. The orange line represents the linear fit for the maximum temperatures, and the blue line represents the linear fit for the minimum temperatures.



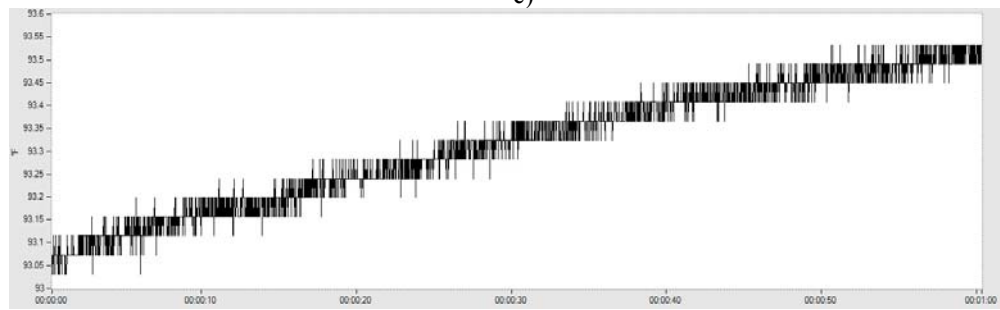
a)



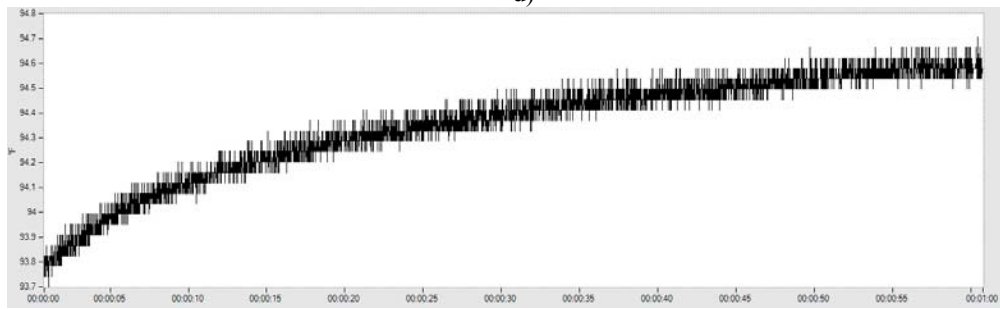
b)



c)

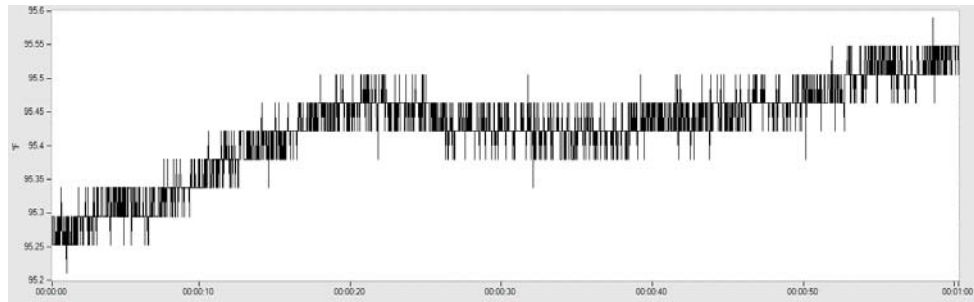


d)

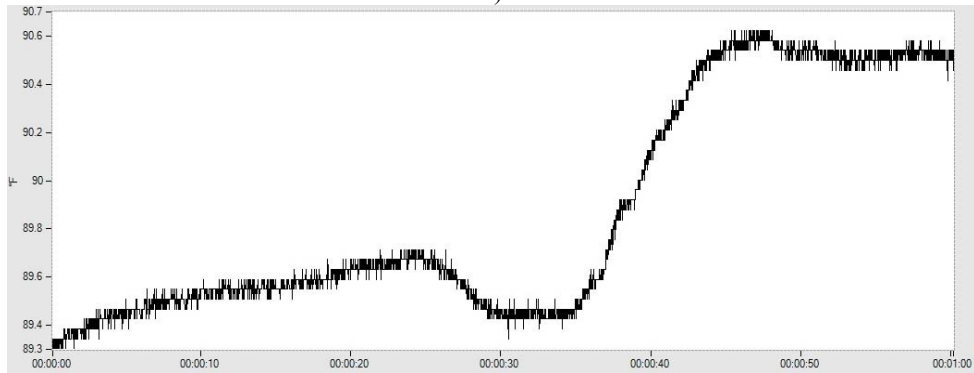


e)

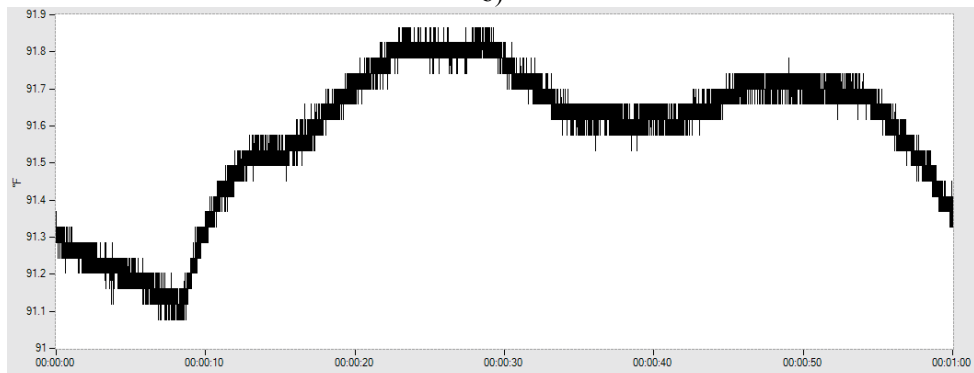
Figure 6. a)-e) Individual skin temperature profiles of some participants.



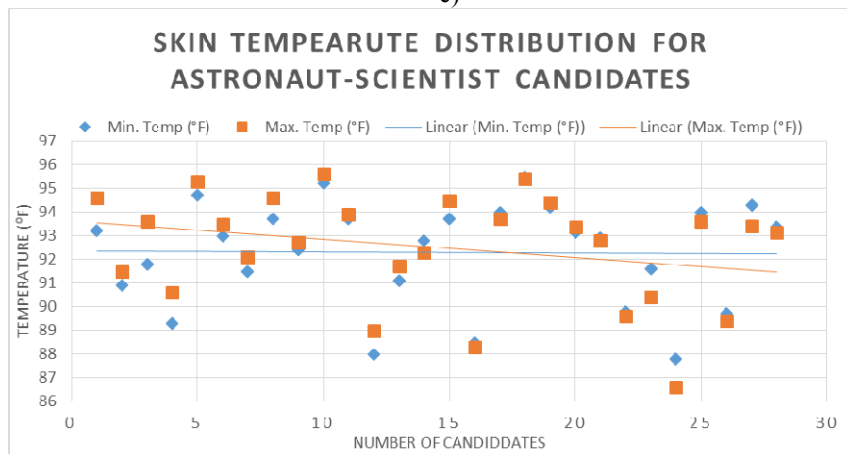
a)



b)



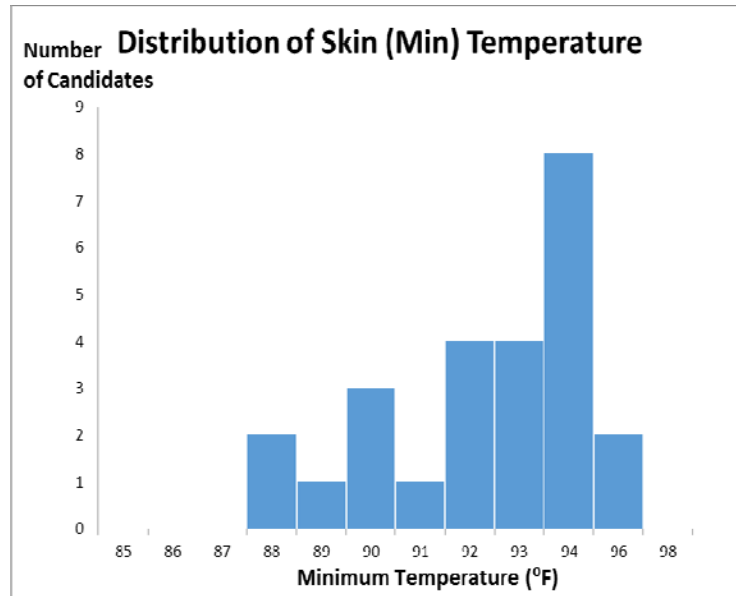
c)



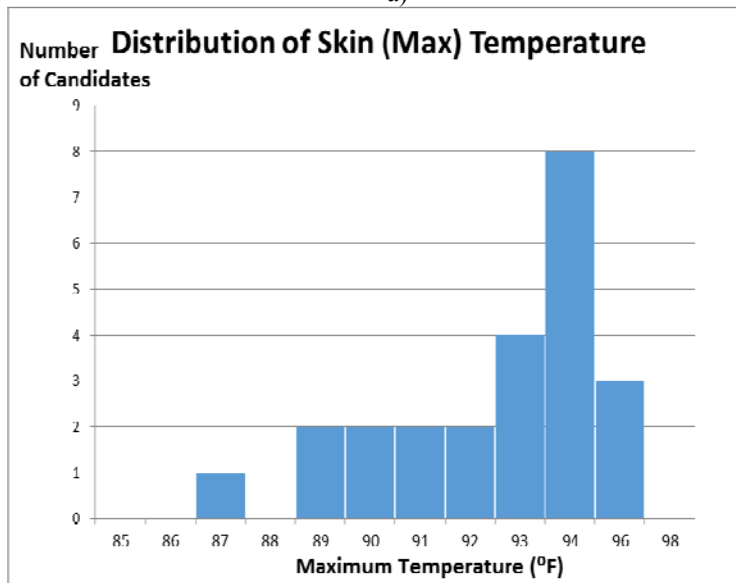
d)

Figure 7. a)-b) Individual skin temperature profiles of some participants. Skin surface temperature for 28 scientist-astronaut candidates.

Figure 8 depicts the distribution for the skin temperature data collected. 20 participants have a skin temperature that fall under one standard deviation (Figure 8a) and the rest have a skin temperature with standard deviation greater than 2.2. 18 participants have skin temperatures with a standard deviation less than 2.2 (Figure 8b) and the rest have skin temperatures with greater standard deviations.

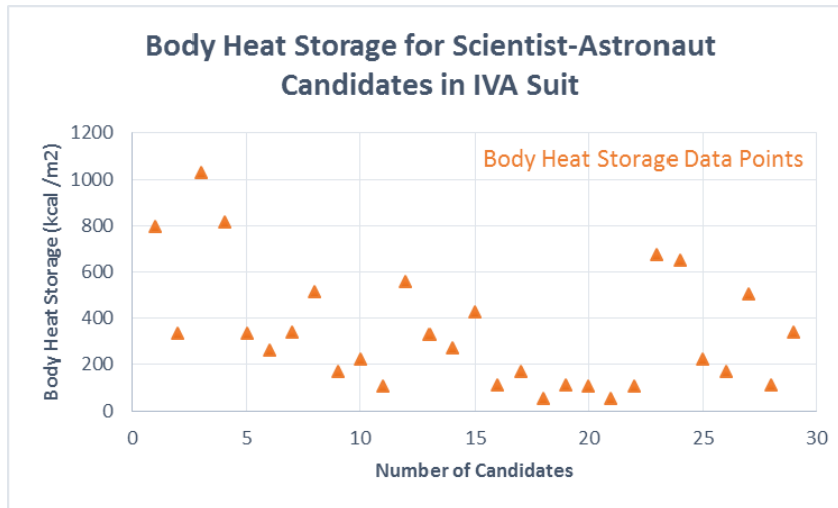


a)

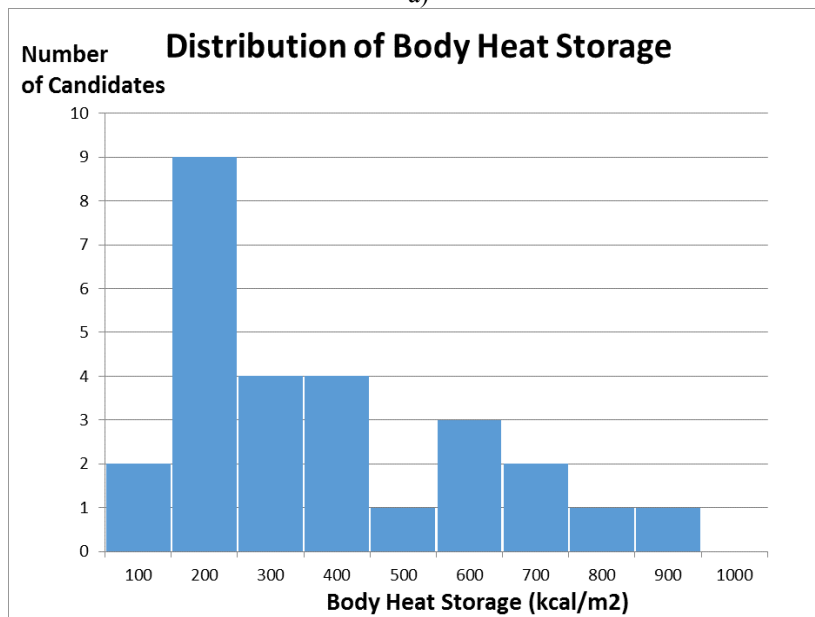


b)

Figure 8. a) Distribution of skin (minimum) temperature measurements. b) Distribution of skin (maximum) temperature measurements.



a)



b)

Figure 9. a) Body heat storage for each participant. b) Distribution of body heat storage for each SAC.

F. Modified Cooper Harper Scale Analysis

The workload of each participant was self-assessed using the Modified Cooper Harper Rating Scale (see Table 1) and NASA-TLX questionnaires.

Table 1: Modified Cooper Harper Scale

1	Excellent- Highly Desirable	Operator compensation not a factor for desired performance, desired performance is easily achieved.
2	Good- Negligible Deficiencies	Operator compensation not a factor for desired performance.
3	Fair- Some Mildly Unpleasant Deficiencies	Minimal operator compensation required for desired performance.

4	Minor but Annoying Difficulty	Desired performance requires moderate operator compensation.
5	Moderately Objectionable Difficulty	Adequate performance requires considerable operator compensation.
6	Very Objectionable but Tolerable Deficiencies	Adequate performance requires high operator compensation.
7	Major Deficiencies	Adequate performance not attainable with maximum tolerable operator compensation
8	Major Deficiencies	Considerable operator compensation is required to accomplish tasks with moderate errors.
9	Major Deficiencies	Intense operator compensation is required to accomplish tasks with numerous errors.
10	Major Deficiencies	Unlikely to perform perform the tasks without high levels of discomfort.

Figure 10 depicts the number of participants as a function of the discomfort level for each ROM that participants were asked to perform. The discomfort level ranges between 1 (excellent) to 10 (major deficiency) based on the Modified Cooper Harper Scale shown in Table 1. A series of images of the NASA JSC Mk. III suit⁴ with different ROMs are superimposed in Figure 10 for reference. Figure 10a corresponds to the relaxed state of each participant and shows that 77% of the participants experienced some kind of negligible to minor discomfort without conducting movement outside of a neutral position. For cross hip reach in Figure 10b, 45% of the participants encountered minor to moderate discomfort. When the participants were asked to touch their opposite shoulder, 55% commented that the shoulder and armpit areas of the reaching arm restricted them from performing such a motion to a minor degree (see Figure 10c). Of most concern among these motions is the extended reach above and outward from the helmet; here, 65% of the participants experienced higher levels of discomfort (see Figure 10d). Similarly, 58% of the participants reported some unpleasant deficiencies, and 13% of the participants mentioned tolerable and major deficiencies when asked to reach behind and touch the back of their helmet (see Figure 10e). This suggests participants may have limited ROM when performing overhead activity. Overall, nearly 25% of the participants reported suit restrictions when performing normal cross-body reach ROM. This will be further investigated in the next study using more accurate metric standards such as using a grid screen behind the SAC to measure ROM more precisely. This analysis will help improve the characterization of mobility performance when SACs are asked to perform different tasks. In this preliminary study, it was not possible to obtain any video recording, motion capture, or accelerometer data due to PoSSUM schedule constraints. Thus, true ROM deficiency could not be quantified during pre- and post-range motion tests.

In terms of simply having the suit on, results show that 29% of the participants experienced a general, basic donning discomfort with the suit, and 17% of the participants showed similar doffing discomfort. Feet, shoulders, neck, arms, and ankles were the most sensitive parts (Figure 11). 38% of participants showed moderate levels of discomfort in the shoulders, and 28% of them showed negligible or some mild unpleasant deficiencies (Figure 11a). Another area of concern are the feet (see Figure 11f), where 48% of the participants (24 participants) reported varying levels of discomfort: 38% of these participants (15 participants) reported minor levels of deficiencies, and the other 23% of these participants reported tolerable and major deficiencies. The third major area of concern was the neck (see Figure 11b); 48% of the participants commented that they felt the helmet was pushing their head forward with fair to minor levels of discomfort. Similarly, the fourth area addressed (see Figure 11c) was the arms, where 35% of the participants indicated that they experienced fair to minor discomfort. The last area addressed corresponds to the ankles, where approximately 38% of the participants experienced minor to slight deficiencies (see Figure 11).

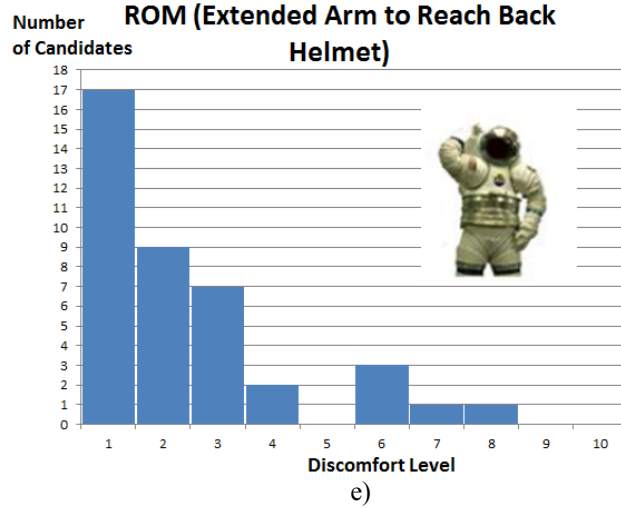
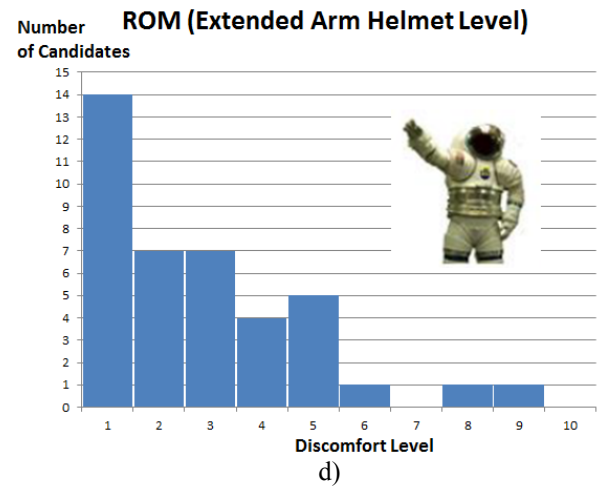
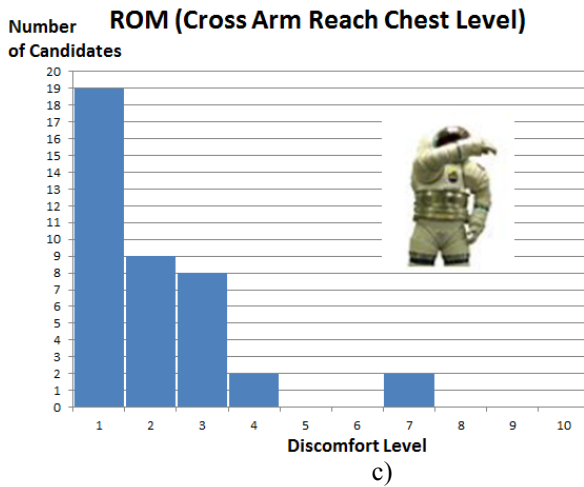
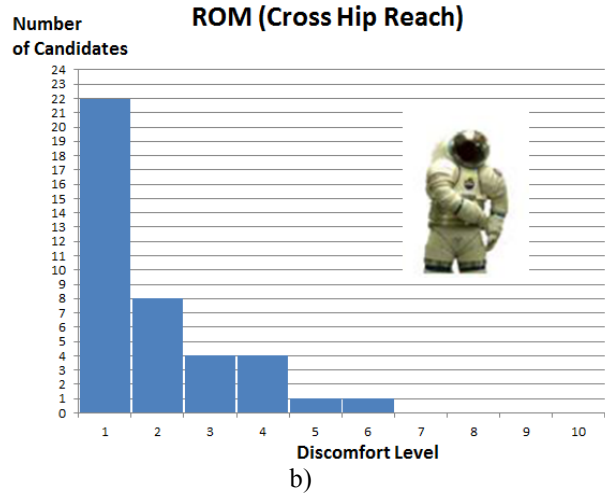
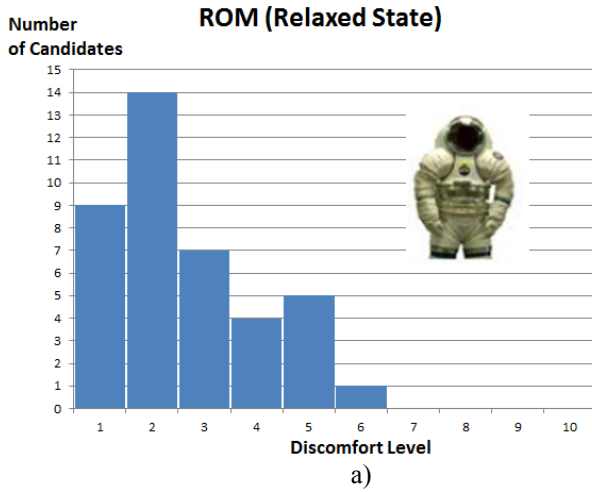


Figure 10. Range of Motion performed by participants unpressurized. Note: In this study, participants' visors were unlatched and pull back so as to rest above the neck and expose the head.

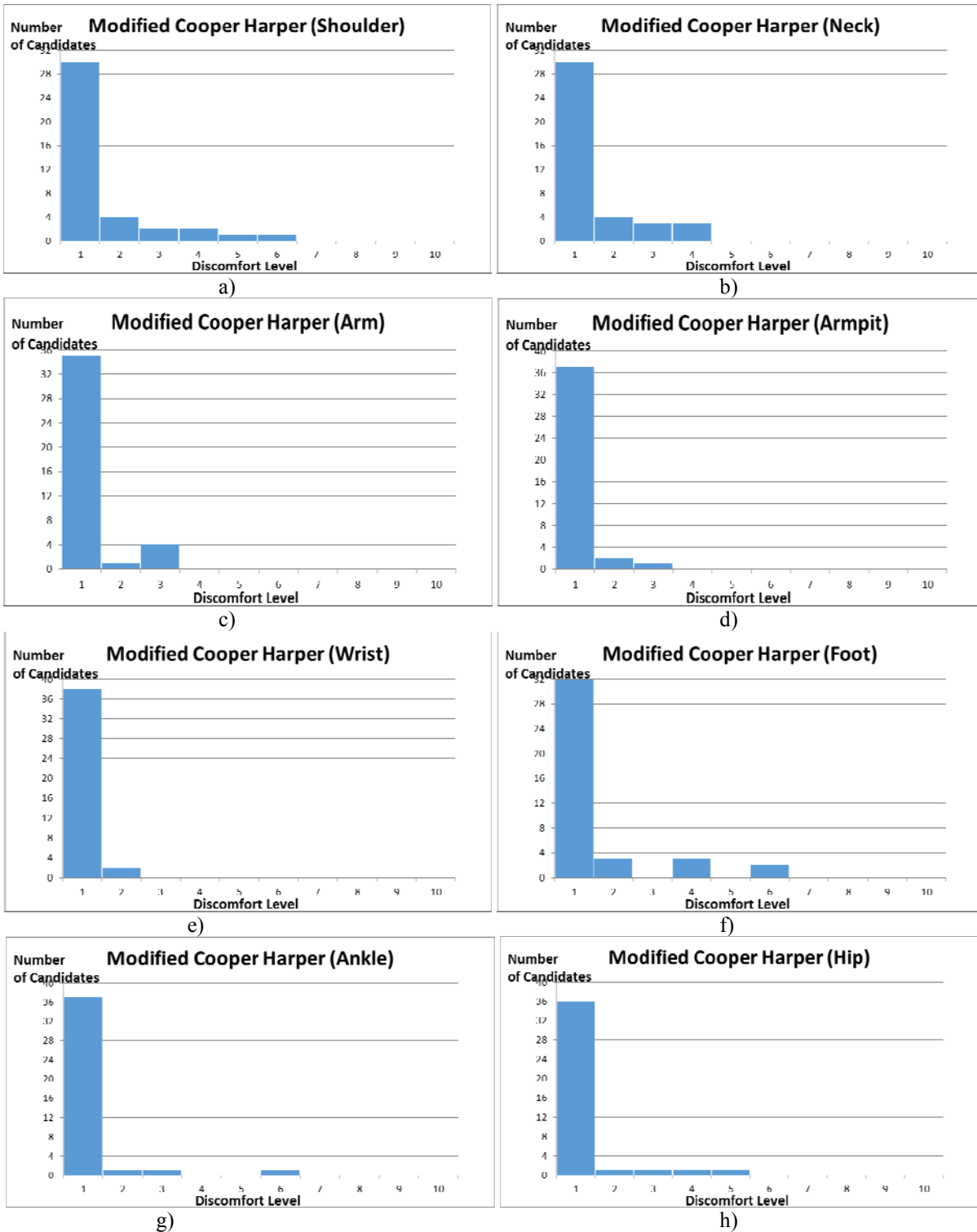


Figure 11. Modified Cooper Harper results of different body parts when donning the IVA suit.

G. NASA TLX Scale Analysis

This section addresses the NASA TLX measure for each participant. Participants were asked to express their mental state, physical state, temporal activity demand, effort demand and frustration demands on a scale from 0% (low

demand) to 100% (high demand) for each category; and performance level from 0% (failure) to 100% (perfect performance) as displayed in Figure 12d).

For the 40 SACs who operated the science instrumentation in the SSFS while wearing the pressurized IVA suit: the average mental state level was approximately 34%, the average physical level for the participants was 38%, and their average temporal demand for performing their activity was 37%. Their average performance level was reported as 75%. Participants were able to perform the activity with an average effort level of 41% and with an average frustration level of 18%. Out of the 40 participants, 28% reported mental demands higher than 50 (moderate difficulty), 30% experienced moderate to high physical demands, 35% encountered moderate temporal demands when performing their task, 75% felt they performed their tasks successfully, 40% felt moderate to high stress levels (beyond 50), and 20% of the participants had fair to minor frustration levels. This data does not provide conclusive results of the SAC's performance of tasks with the IVA suit in the simulator, but this data will be used as reference for future studies involving a more comprehensive test protocol. This protocol will involve performing the same tasks with the suit on and in shirtsleeves.

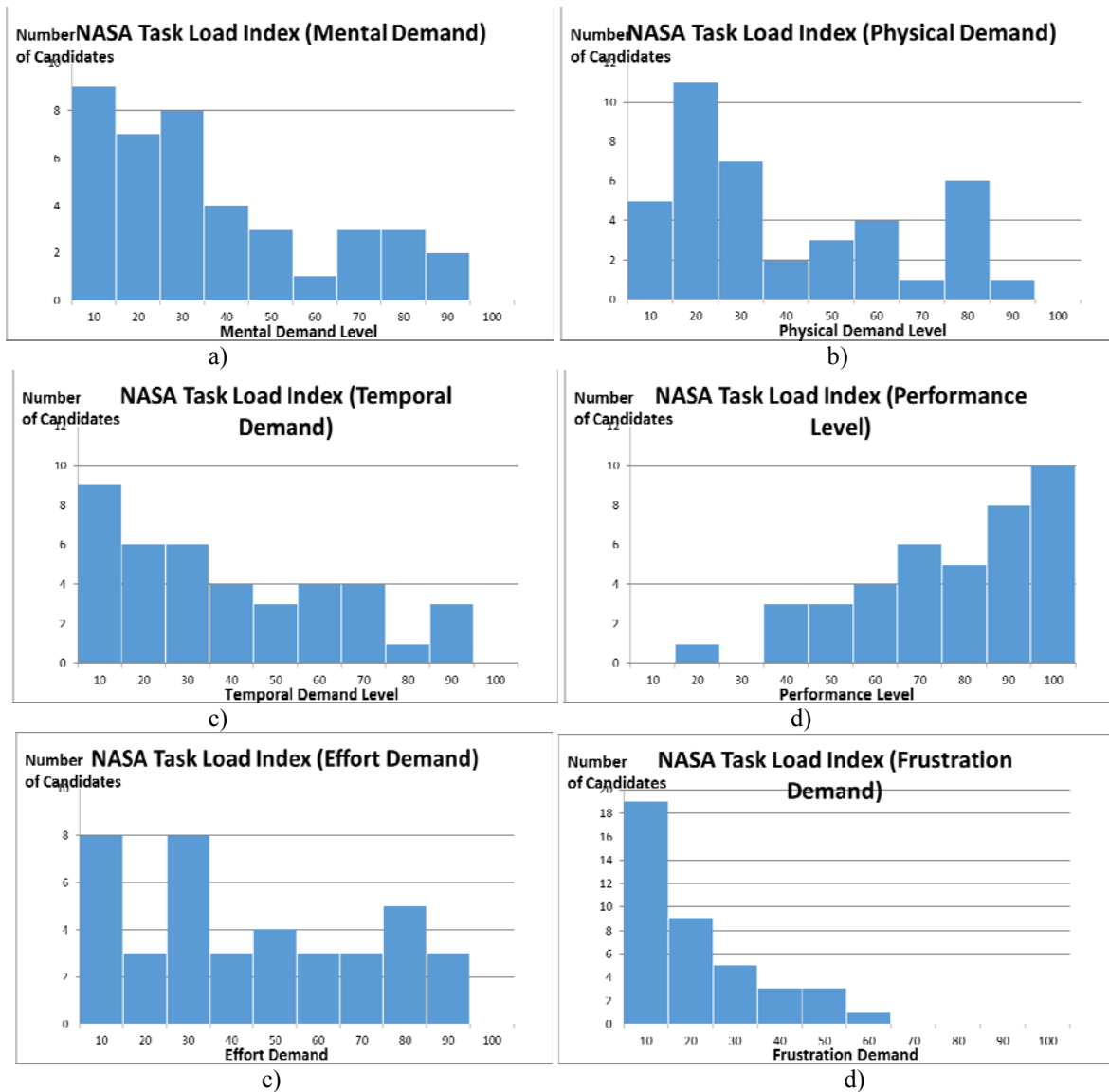
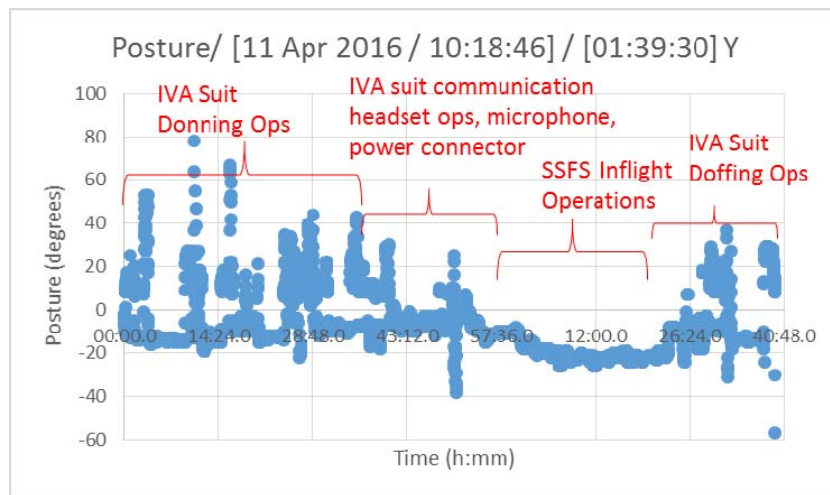


Figure 12. NASA Task Load Index distributions. a) Mental demand, b) Physical demand, c) Temporal demand, e) Performance Level, e) Effort demand, f) Frustration demand.

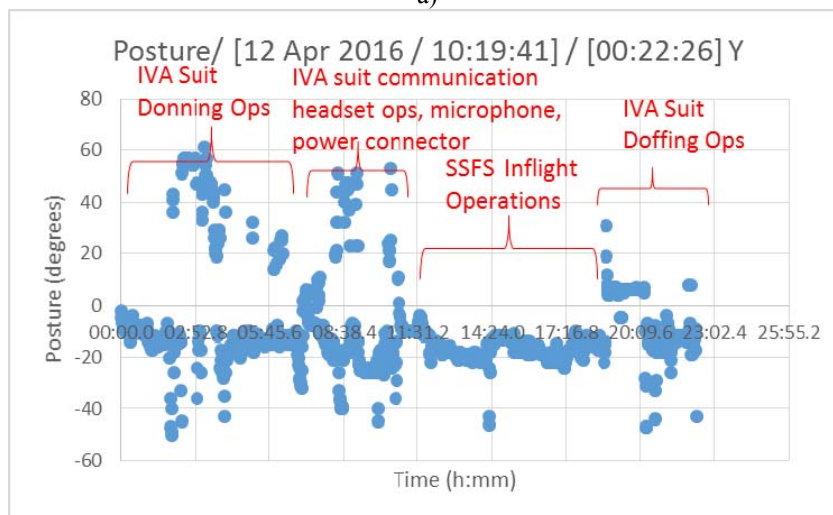
H. Simulator Sickness Questionnaire (SSQ) Analysis

Whenever a simulator is used in a study, there is a risk of simulator sickness, the effects of which may compromise study outcomes. To guard against this, the SSQ was administered to participants, who self-assessed the combined effects of using the simulator while suited in the IVA pressure suit.

During their simulation training, participants were tasked with operating a scientific camera mounted on the right side of the simulator (see Figure 1e). After the simulated flight, each participant completed the SSQ sheet (Appendix I), which included questions regarding: general discomfort, fatigue, headache, eye strain, difficulty focusing, salivation, sweating, nausea, difficulty concentrating, fullness of the head, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness, and burping. Among these symptoms, sweating was the most significant with 10% of the participants experiencing moderate sweating while in the IVA suit inside of the simulator. Additionally, 25% of the participants reported slight sweating. The second most significant factor was general discomfort: 10% of the participants commented on moderate discomfort levels while performing their tasks with the IVA suit inside of the simulator, and about 23% of the participants experienced slight general discomfort levels. The third most significant factor was fatigue: 18% of the participants claimed to have experienced slight fatigue during or after the simulation.



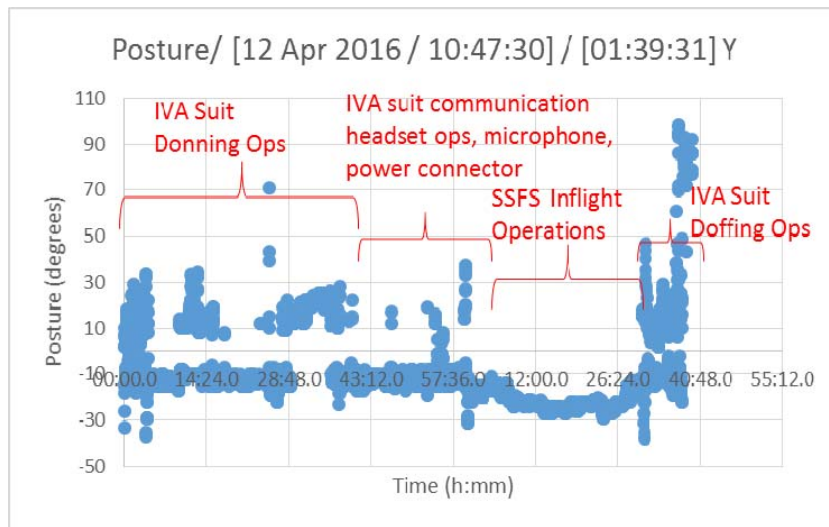
a)



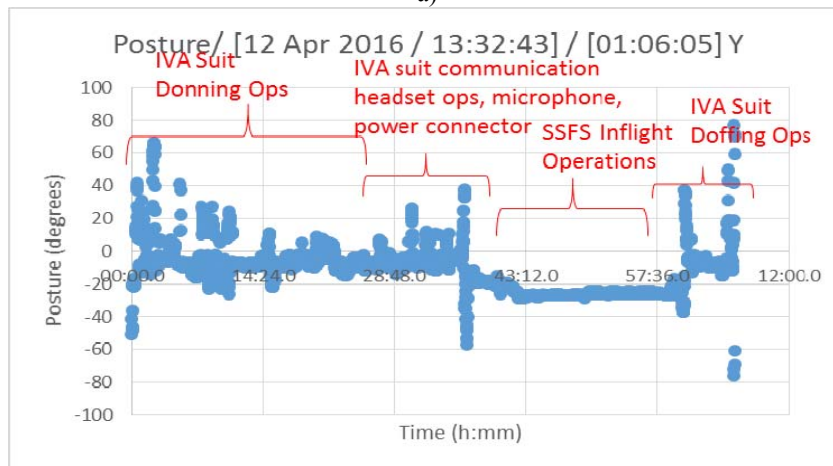
b)

Figure 13. a) Posture of one Scientist-Astronaut Candidate during IVA suit donning operations, SSFS operations, and IVA suit doffing operations. b) Posture of other SAC during IVA suit operations, SSFS operations, and IVA suit doffing operations.

Part of the discomfort and sweating symptoms for each SAC may have been partially attributed to their attempt to place themselves in a comfortable position inside the IVA suit through the donning, inflight, and doffing operations. The posture of each SAC was measured with the BioHarness device.



a)



b)

Figure 14. a) Posture of one Scientist-Astronaut Candidate during IVA suit donning operations, SSFS operations, and IVA suit doffing operations. b) Posture of other SAC during IVA suit operations, SSFS operations, and IVA suit doffing operations.

From the preliminary data extracted from the BioHarness on some of the SACs, it was observed that the posture of the SAC is relevant when performing tasks inside the cockpit of the SSFS. This specific data also provides information about the posture of some of the SACs during donning, inflight operations in the SSFS, and doffing procedures as observed in Figure 13 and Figure 14. Note that the posture is measured in degrees. The BioHarness device has a dynamic range of -180 degrees to +180 degrees. 180 degrees indicates that the subject anterior inclination is a positive value, and -180 degrees indicates that the subject posterior is negative.

1. IVA suit donning operations took about 30-35 minutes for each SAC.
2. IVA suit communications, head operations, microphone and power connector operations conducted on each SAC lasted approximately 15 minutes.
3. During the SSFS inflight operations (20-25 minutes), the SAC posture was about -25 degrees as depicted in Figure 13 and Figure 14.
4. IVA suit doffing operations took approximately 10 to 15 minutes.

V. Conclusion and Future Work

This research has revealed a better understanding of the architecture design of IVA suits for suborbital flights. The parameters of interest analyzed in this paper were the participants' skin temperature, donning and doffing discomfort levels, and range of motion for overhead activities in an unpressurized IVA suit, and a simulated suborbital spaceflight run while wearing a pressurized IVA suit.

Post-simulation readings reveal a slight increase in participants' skin temperature over a period of approximately 25 minutes during which they wore the IVA suit. During this time, participants experienced moderate to slight sweating, which added to the discomfort reported as they operated the instrumentation inside of the SSFS. During prelaunch operations for a real suborbital flight scenario, passengers/participants will be strapped to their seats for periods much longer than 25 minutes as they wait for takeoff. Thus, the suit's thermal control system must be able to maintain proper suit cooling levels, minimize odors resulting from sweat, and should allow for interior temperature control by the participant. Once in space, sweating may pose serious risks as a result of the microgravity or zero-G environments; sweat may affect radio communications if it builds up around the ears; it may also fog the helmet visor and reduce the participants' vision if it builds up around the forehead or eyes. At only the 38 minute mark of a planned 150 minute extravehicular activity (spacewalk), Gemini XI astronaut Gordon Cooper's sweat had begun accumulating at one of his eyes, and even after resting, the sweat would not evaporate⁷. Thus, the suit must be able to deal with the range of body heat generated across participants and across different workload levels.

In terms of spacesuit mobility and comfort, although the study shows that only 29% of the participants experienced discomfort in the neck and shoulder areas, this may be a concern when reaching for vehicle controls in an unpressurized suit, and even more so in a pressurized suit as limitations to ROM become more apparent. In future studies, different ROM when performing different tasks in an unpressurized and pressurized suit will be compared to characterize different work envelopes. Furthermore, the suit's restriction of nearly 25% of the participants' normal cross-body reach range-of-motion may play a significant safety concern particularly during off-nominal situations in which emergency controls are just out of range and the necessary movements are now limited. Thus, the suit should allow for greater flexibility in the upper-shoulder areas. Future work will be done also in a seated position (see Figure 2e) since the ROM may vary beyond the acceptable work envelope, and may affect the use of the instrumentation.

Due to the amount of data collected, some of this data will be analyzed in a future paper with more control variables. In future studies, participants will perform multiple tasks of varying workloads both while wearing a sweat sensor and while not wearing a sweat sensor in order to make a valid comparison and to measure the thermal load of the suit itself. Sensors inside the gloves will record gloved grip strength across various workloads, as well as other metrics (eg., pinch strength) to quantify workload performance and fatigue for unpressurized and pressurized scenarios. Furthermore, more thorough ROM will be performed to better understand the mobility issues of the suit. In the next study, the IVA suit will be analyzed using a multicompartment model, which involves placing sensors in the helmet, arms, gloves, upper torso, legs, and feet areas of the suit in order to measure interior thermal flow.

Acknowledgments

We would like to acknowledge Nikolay Moiseev, Virgil Calejesan and Ted Southern of Final Frontier Design, and Dr. Jason Reimuller of Integrated Spaceflight Services for supporting and facilitating the ERAU researchers in their collection of data. We would also like to thank all of the Project PoSSUM participants for their cooperation.

References

- ¹Southern, T.C., Moiseev, N.A., and Iturmendi, M. "Continued Development and Testing of a Commercial Intra Vehicular Activity Space Suit," *International Conference on Environmental Systems*, ICES-2016-50, Vienna, Austria, 10-14 July 2016.
- ²Southern, T.C., Moiseev, N.A., and Iturmendi, M. "Operational Testing of a Novel IVA Space Suit," *International Conference on Environmental Systems*, ICES-2015-132, Bellevue, Washington, 12-16 July 2015.
- ³Llanos, P.J., and Seedhouse, E., "Application of Bioinstrumentation in Developing a Pressure Suit for Suborbital Flight," *Computing in Cardiology*, Vancouver, September 2016.
- ⁴Anderson, A. "Understanding Human-Space Suit Interaction to Prevent Injury During Extravehicular Activity," Ph.D. Thesis in Aerospace Biomedical Engineering, MIT, June 2014.
- ⁵Rubio, S., Díaz, E., and Martín, J. "Evaluation of Subjective Mental Workload: A Comparison of SWAT, NASA-TLX, and Workload Profile Methods," *Applied Psychology: An International Review*, Madrid, Spain, Vol. 53, No. 1, 2004, pp., 61-86.
- ⁶Kennery, R.S., Lane, N.E., Berbaum, K.S., and Lilienthal, M.G. "Simulator Sickness Questionnaire: An Enhanced Method For Quantifying Simulator Sickness," *The International Journal of Aviation Psychology*, 3:3, 13 Nov. 2009, pp., 203-220.

⁷Gemini First Docking Turns to Wild Ride in Orbit, (Accessed March 3 2016), <https://www.nasa.gov/feature/geminis-first-docking-turns-to-wild-ride-in-orbit>, NASA's Kennedy Space Center, Florida.

⁸Mosteller, R.D. "Simplified Calculation of Body Surface Area", Letter, *New England Journal of Medicine*, 317 (17), 1987.