An Ergonomic Evaluation of the Extravehicular Mobility Unit (EMU) Space Suit Hard Upper Torso (HUT) Size Effect on Metabolic, Mobility, and Strength Performance

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Introduction: The objective of this project was to assess the performance differences between a nominally sized Extravehicular Mobility Unit (EMU) space suit and a nominal +1 (plus) sized EMU. **Method:** This study evaluated suit size conditions by using metabolic cost, arm mobility, and arm strength as performance metrics. **Results:** Differences between the suit sizes were found only in shoulder extension strength being 15.8% greater for the plus size. **Discussion**: While this study was able to identify motions and activities that were considered to be practically or statistically different, it does not signify that use of a plus sized suit should be prohibited. Further testing would be required that either pertained to a particular mission critical task or better simulates a microgravity environment that the EMU suit was designed to work in.

INTRODUCTION

Current Extravehicular activity (EVA) suit designs are an improvement over older EVA suits, but injuries, discomfort, fatigue, and other performance degradation issues still remain. Additionally, there have been occasions during flight when astronauts have had to utilize a larger EVA suit than their nominal size. It is generally recognized among the EVA community that proper suit fit is extremely important to help reduce the negative results of pressurized suited work.

This project assisted the National Aeronautics and Space Administration (NASA) EVA Project Office at Johnson Space Center (JSC) by identifying possible performance effects of off-nominal sized hard upper torsos (HUTs) of the Planar Extravehicular Mobility Unit (EMU) space suit. Performance metrics for this study included metabolic cost, arm mobility (isolated range of motion), and arm strength. Supporting data was also collected to help better understand the differences in results between sizing conditions. These data included: 3D whole body laser scans and HUT scans for assessing body anthropometry and suit size, FARO 3D points for assessing suit clearance, and suit-body interaction assessments using pressure mats and subjective surveys. This document will discuss the methods and results of the performance metrics for the subjects tested.

METHOD

Eight subjects were chosen from the JSC Human Test Subject Facility based on their nominal EMU suit sizing and pressurized suit testing experience. All subjects were familiar with pressurized suited testing, having passed a U.S. Air Force Class III physical and having been test subjects in past pressurized suited projects. Two of the eight subjects had no previous experience with testing in the EMU. Prior to testing, subjects were informed of the nature of the study and signed all related informed consent documents approved by the JSC Institutional Review Board (IRB).

Based on their individual anthropometry, half of the test group was nominally sized for medium Planar HUTs and the other half for large Planar HUTs. Based on their nominal HUT size, subjects' nominal +1 (plus) condition was either a large or an extra-large HUT size.

The study included three females and five males. Mean age of subjects during testing was 32.5 years (standard deviation [sd] of ±6 years). The occupations of the subjects included six engineers, one scientist, and one suit technician.

Testing Equipment

EMU Spacesuit. Subjects wore the Planar EMU while performing suited tasks. The two suited size conditions for comparison throughout the study were nominally suited and plus sized suited. Subjects also performed tasks while unsuited, standing upright, without leaning or bracing against a structure. For relative comparisons unsuited results were collected in the study, but will not be discussed in this paper due to this paper focusing on HUT sizing differences. Subjects were sized and fitted to their suits by qualified NASA EMU suit technicians. Each suited condition was tested pressurized at 29.6 kPa differential (4.3 psid) and unpressurized with the arm and shoulder components removed to allow suit-body interaction investigation. This "sleeveless testing" kept the retaining ring for the shoulder component in place to more closely resemble the inner perimeter of the shoulder of the EMU during the suited pressurized condition. The thermal micrometeorite garments were removed from the HUT and arms for all testing to allow better observation of suit joint articulation.

Underneath the EMU, subjects wore long sleeved full length Thermal Comfort Undergarments (TCU) as the base layer near the skin. Above this, the standard liquid cooling and ventilation garment (LCVG) was worn to keep subjects cool during suited testing.

EMU Suit Stand. The HUT of the EMU was affixed to a suit stand during testing. This relieved subjects from bearing the full weight of the EMU suit during testing, which is great-

er than 100 kg. The stand allowed subjects freedom to move their arms, but restricted any suit torso mobility.

Metabolic Data Collection

One metric commonly used to measure human performance in a spacesuit is energy expenditure. If a subject can complete the same amount of work while using less energy, then that is considered improved performance. Subjects were tasked with performing two motions similar to that used during EVAs. Horizontal and vertical translations were simulated using the PrimusRS (BTE Technologies Inc., Hanover, MD). The Primus provided a constant resistance for ten minutes during each task while the subject rotated the apparatus at a prescribed rate of 60 pulls per minute. The arm range of motion per pull was not prescribed and was freely chosen by the subject. For the horizontal translation, the subject could change direction at any point to compensate for muscular fatigue.

The rate of carbon dioxide (CO_2) production (VCO_2) was based on measured suit ventilation rate, expired CO_2 concentration in the exhaust umbilical (CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, Penn.). A constant respiratory exchange ratio of 0.85 was assumed as an estimate of the rate of oxygen consumption (VO_2. These values were then entered into the Weir equation ([Weir, 1949](#)) and converted to the rate of kilocalories (kcal) expended, which were converted to BTU/hr.

Due to the small subject pool size, a pre-defined level of practical significance equivalent to 3.5 ml/min/kg for metabolic comparisons was used, which has been used for other suited human performance studies ([Norcross et. al, 2009, 2010](#)).

Subjects were asked to rate their perceived level of exertion using the Borg Rate of Perceived Exertion (RPE) 15 point scale ([Borg, 1990](#)). This scale ranges from 6 (no exertion at all) to 20 (maximal exertion) and was designed to follow the general heart rate of a healthy adult. A paired t-test with a 95% confidence level was used to assess for statistical differences between the two suited conditions for each of the functional activities.

Mobility Data Collection

Motion capture data was collected for twenty tasks of each subject's right arm. These included strength, isolated Range of Motion (ROM), functional activities, and FARO measurement trials. Motion capture data was collected using a Vicon optical based system (Vicon, Oxford, UK).

For the kinematic portions of the testing, the subjects performed standard maximum isolated ROM movements of shoulder flexion/extension, shoulder abduction/adduction, shoulder internal transverse rotation, and elbow flexion/extension about anatomical planes as defined by NASA Human System Integration Requirements (HSIR) ([NASA, 2012](#)).

In order to compare the configurations, two methods were used in parallel to determine "significant" performance differences. The first method determined a "practical" difference, or the minimal difference needed to connote a change in perfor-

mance. The second method used repeated measures Analysis of Variance (ANOVA) with a 95% confidence level to statistically compare the groups.

To determine practical significance, the two or conditions were compared. The overall subject mean per condition and the range of the results per condition were found. A ten degree limit of practicality was chosen to identify a change in performance between conditions. If there was a ten degree or greater difference between the maximum of one condition and the minimum of the other, it was determined that these two groups were practically different. If the magnitude of the difference between the two groups was less than ten degrees then it was termed as a "non-practical" difference.

Strength Data Collection

All subjects completed a strength evaluation for right arm shoulder flexion/extension, shoulder internal/external transverse rotation, and elbow flexion/ extension. The subjects were set up for maximal strength assessments using the PrimusRS (BTE Technologies Inc., Hanover, MD) system in an isokinetic configuration for the right arm. For flexion/ extension exertions, the dynamometer head was aligned with the center of rotation of the shoulder or elbow. For transverse shoulder rotation, subjects pulled a cable internally through the transverse plane. The necessity of using a cable for internal transverse rotation meant that external transverse rotation had to be performed as an eccentric contraction as opposed to concentric like the other five strength measures being captured. For this reason, shoulder external transverse rotation was not included with the rest of the kinetic analyses.

Subjects completed four cycles of each exertion at 60 degrees per second, in each of three conditions: unsuited, pressurized in their nominal HUT, and pressurized in the plus HUT size. Trials were repeated if the coefficient of variation (CV) of repetitions 2, 3, and 4 was above 10 % for unsuited trials or 15 % for suited trials.

The strength analysis looked for both a practical and statistical significance for differences between the conditions. Practical significance was set to differences of greater than 15% and a statistical analysis using repeated measures ANOVAs set to 95% confidence levels was used to identify statistical differences between the conditions.

HUT Fit Data Collection

The HUT Fit Analysis utilized a 3D whole body scanner (VITUS XL™, Vitronic GmbH, Wiesbaden, Germany) to collect subject anthropometry, and the FARO Edge Scan Arm (FARO Technologies Inc., Lake Mary, FL) to collect internal and external scans of the three HUT sizes used in this study. The FARO arm probe (FARO Technologies Inc., Lake Mary, FL) was used to collect position data on the shoulder scye bearing interaction while the subject was suited unpressurized with the right arm removed.

Using the 3D whole body laser scanning protocol, data was collected from minimally clothed subjects in multiple postures. Measurements pertinent to HUT sizing were used for this study which included but not limited to stature, biacromial

breadth, mid-shoulder breadth, scye circumference, base of neck to acromion length, and suprasternale to acromion length.

Scans of the HUTs, captured using the FARO arm scanner, were used to view how the subjects were situated within the HUT. The HUT scans, nominal and plus size, were overlaid on the scan images of the subjects for two different arm positions: one in a neutral/relaxed standing pose and the other in a T-pose with arms at 90° of shoulder abduction.

The 3D laser scanning data was aligned using a 1-2 cm vertical clearance from the scye bearing to the shoulder, and the midlines of the subject and HUT images in the sagittal and frontal planes. The images were then adjusted using information from the pressure mapping and suit contact survey data. The 3D scan images do not account for the exact posture within the EMU or for the thickness of the cooling garments (TCUs and LCVG) and additional padding. The exact positioning of a subject within the EMU is very difficult to replicate, so the two standard postures were chosen based on the visual that was desired. The neutral scan position allows for observation of the top of the shoulder and is similar to the position in which FARO arm data was collected, and the T-pose allows for a visual of the shoulder within the HUT scye.

To evaluate actual clearances between the suit and the unsuited subject, investigators utilized the FARO arm digitizer probe to collect the 3D location of right-side anatomical landmarks and the HUT scye bearing, and the vertical clearance between the subject and the scye bearing. This data was used to calculate the suprasternale-to-acromion and base-of-neck-to-acromion distances. These lengths were then referenced to a point on the HUT, to determine the location of the HUT top of scye point relative to the $2/3^{rd}$ point along the shoulder. The $2/3^{rd}$ point on the shoulders is measured along the clavicle (collar bone) from the midline of the body (Williams & Johnson, 2003). Scye bearings that fall beyond this $2/3^{rd}$ shoulder point and which have less than 1-2cm of vertical (z-axis) clearance between the scye and body are more likely to cause scapulothorasic (shoulder) restriction when the shoulder is raised during flexion and particularly abduction motions.

Suit Body Interaction Data Collection

Subjective Survey. While holding each of the isolated postures for the right arm (neutral with arms at side, flexion/extension, abduction/adduction, and internal/external transverse), if the subject felt contact at any designated body locations along the torso and arms, such as the deltoid or shoulder, they were asked to rate the intensity level of contact (contact discomfort level) using the Borg CR10 (Borg, 1990). This scale's severity levels were modified with ranks in general categories such as light, moderate, and high contact levels, with a 12 point scale ranging in magnitude from 0 to 10.

For analyses at the overall body posture level and at the individual body location level, a paired t-test with a 95% confidence level was used to assess the differences between the two HUT sizes for both the number of contact locations and the mean contact intensity levels.

Pressure Mapping. Levels of pressure of suit-body contacts along subject's shoulders, chest and back were collected

with pressure mat technology. The XSENSOR (XSENSOR Technology Corporation, Calgary, Alberta, Canada) and Novel (Novel Electronics Inc., St. Paul, MN) pressure mapping systems measured the interface pressures between the two surfaces (suit interior and body surface) and transferred that information to a computer system. The pressure mats were placed between the LCVG and the TCUs within each subject's suited setup and were used for all of the isolated mobility and strength motions activities. No statistical analysis was performed for the pressure mapping results.

RESULTS

Metabolic Cost

Both metabolic functional activities achieved clear steady state levels for each suited condition. The suited conditions were also within a normal range of energy expenditure for microgravity EVA translation. Both activities required similar energy expenditures and subjects generally rated each activity at about the same RPE. However, more total work was done during the horizontal translation activity.

Although cadence of subjects was controlled, the ROM was not. This variation in ROM led to different workloads between subjects and within an individual subject across conditions. Workload was not originally recorded, so suited workload at both conditions was available only for seven of the eight subjects. Workload was provided as total workload across the activity in the units of kilo-joules (kJ). Energy expenditure per unit of work was calculated at BTU/kJ during the activity.

Vertical Translation Activity. There was no consistent trend noted for the suited data between HUT sizes as differences were seen in both the positive and negative directions with some subject's differences reaching "practical" significance for either the nominal or plus sized suit (nominal: mean of 85.9 ± 13.2 BTU/kJ; plus: mean of 94.3 ± 16.1 BTU/kJ). Additionally, statistical analysis did not reveal any differences between the two suited conditions due to low statistical power from the small sample size.

Horizontal Translation Activity. The horizontal translation activity had much less variability than the vertical translation activity between all conditions. There were no consistent differences between the suited conditions (nominal: mean of 42.1 ± 6.7 BTU/kJ; plus: mean of 41.6 ± 5.5 BTU/kJ). Additionally, statistical analysis did not reveal any differences between the two suited conditions due to low statistical power from the sample size.

Shoulder and Elbow Mobility

ROM data of all eight subjects were averaged and the overall ranges were found for each configuration. Comparing the two pressurized EMU HUT conditions showed that differences between the two HUT sizes were negligible. No practically significant differences were found between the nominal and plus size configurations although statistical differences were seen for shoulder adduction (nominal: mean of -41°± 4°; plus: mean of -44°± 4°) (p=0.02), shoulder extension (nomi-

nal: mean of 35°± 5°; plus: mean of 43°± 6°) (p=0.01), shoulder internal transverse rotation (nominal: mean of -9°± 5°; plus: mean of -14°± 4°) (p=0.01) and elbow extension (nominal: mean of 15°± 4°; plus: mean of 9°± 7°) (p=0.02). Since no practical differences for these were seen they were not considered as relevant differences to the mobility results.

The ROM data for each subject's suited conditions were also normalized using the unsuited data. The EMU suit reduced the ROM no matter the HUT size. Comparing the two suit configurations once again showed little if any difference in performance. On average, the normalized difference between the nominal and plus size ranges were below 5%, with the standard deviation ranging from zero to 12% of unsuited.

Shoulder and Elbow Strength

When comparing the three reps with the lowest coefficient of variation for each strength exertion, statistically (p=0.007) and practically significant differences were found between HUT sizes only for shoulder extension (nominal: mean of 100.5 ± 22.6 N; plus: mean of 116.5 ± 25.4 N). This strength result was greater for the plus sized configuration.

It is generally accepted that the presence of a spacesuit restricts the ability of a subject to exert force in a given direction; however experimental results were mixed, likely due to constraints of the test. While the suit provides a hindrance to motion, when docked in the suit stand, it also provides a rigid brace for strength testing, possibly enabling a subject to gain greater leverage. Furthermore, it was difficult to align the axis of the dynamometer head with the joint center of a subject inside the suit. The bulk of the suit may also allow a test subject to move out of proper alignment to get a mechanical advantage thereby artificially raising the apparent strength results for suited conditions.

HUT Fit

For the Nominal HUT, the distance between the HUT scye-to-scye openings was less than the subjects' mid-shoulder breadth. Therefore, the HUT size selected should not have caused any shoulder mobility issues in the EMU. For the plus size HUT, five subjects failed the mid-shoulder breadth check. Only one of those five subjects showed to have the possibility of the HUT scye bearing being located outside the 2/3rd point along their shoulder (by 1.05 cm) for the plus HUT size. This would indicate that the HUT size was too large for that individual and may impact shoulder performance.

The next portion of the HUT sizing analysis was to use the FARO digitized probe to gather anthropometric and HUT positional data from the actual suited testing environment. This data revealed that all nominal HUT size conditions for subjects were within the critical 2/3rd point along the right shoulder (the scye location was less than the 2/3rd suprasternale-acromion distance). However, this was not true for all of the plus HUT sized subjects. Three subjects were found to be laterally past this critical point. Additionally, all vertical measures from the top of the subject's shoulder to the inside of the HUT shoulder scye revealed that all subjects were at or greater than the 2 cm minimum clearance required for nominal suit sizing in this test.

Suit Body Interaction

Subjective Survey. Contact point distribution results from the survey noted that only two of the seven arm postures had any statistical significance. One of the body segments significantly different between configurations was the left shoulder for the neutral arm posture where more subjects noted contacted in the nominal HUT size (p=0.033). Another significant difference was for the right deltoid during shoulder extension, where the plus sized HUT affected six of eight subjects whereas the nominal sized HUT contacted none of the subjects for that body location (p=0.011).

The results of the mean grouped neutral posture assessment showed that there was a noticeable difference between the HUT sizes for the right and left shoulder intensity levels. Between these configurations, the nominal size had a higher intensity (mean of 2.2 for right and 2.1 for left) than that of the plus sized HUT (mean of 0.9 right and 0.8 left). Statistical significance was shown for the differences between the HUT sizes for the left shoulder only (p=0.036). This information supports the statistical significance data found for the left shoulder for the contact location distribution for neutral posture, where nominal sizing was shown to contact more people along the shoulder than in the plus sized configuration. Additionally, there were a number of higher maximum intensity levels for nominal size than there were for plus size, but there were no overall statistical significances found.

The HUT size increase affected the right deltoid negatively as the mean intensity was at 0 for the nominal size for all subjects and then became 2.3 for the plus size (p=0.017). Another significant difference was noted for the right shoulder although this time with a decrease in intensity for the plus HUT, reducing from 4.6 nominal to 2.5 plus (p=0.028). A similar decrease in the number of subjects contacted on the shoulder was also noted in the contact distribution data, although it was not statistically significant.

These two results show that both at a contact distribution level and at an intensity level, the right deltoid seems to have more intense contact levels for a majority of the group during right shoulder extension in the plus sized suit than it does for the nominal sized suit.

Pressure Mapping. There was only a minimal peak pressure difference between the nominal and plus conditions for the right shoulder for half of the subjects. For one subject, the plus sized condition saw a notable reduction in their right shoulder peak pressure levels. However, several subjects increased in peak pressure results along the right shoulder. Similarly, although overall body contact intensity levels decreased in the plus sized HUT from the survey data, it also identified that contact distributions and/or intensity levels for the plus suit increased in general as compared to the nominal suit for the shoulder, deltoid, and upper arm regions.

None of the subjects appeared to have consistent trends. In general, when moving from the nominal to the plus size, 30% of collected trials showed an increase in pressure, 20%

showed a decrease, and 50% stayed the same between suit sizes.

The most affected trial tended to be shoulder flexion/extension strength, where all but one subject saw a right-side shoulder increase in peak pressure in the plus size (this motion was completed with the right arm only). Similarly, isolated shoulder flexion/extension tended to increase or stay the same across subjects, with only two people seeing a decrease. The changes in shoulder/flexion extension peak pressures in the plus size suit may be a result of the scye rings moving farther out laterally on the shoulders, where they are more likely to contact bony prominences on the shoulder during motion.

Assumptions, Limitations and Constraints

There were several assumptions, limitations, and constraints that were applicable to this testing. (1) It was assumed that when suits were used, the suits were sized and configured properly for the subject. (2) It was assumed that the subjects performed in an unbiased and consistent manner and followed instructions. (3) It was assumed that subjects were standing fully upright during suited testing. (4) Pressure mapping data was collected on subjects' back and chest was not considered, due to interference from data collection equipment in the suit. (5) Results and conclusions drawn from this summary do not account for postural and performance changes due to microgravity or partial-gravity environments. (6) Kinematic testing for this study only looked at the extremes of the isolated motions. Additional testing would be needed to define and assess mission/task dependent motions or activities.

DISCUSSION

The primary goal of this project was to evaluate suited performance difference between suit HUT sizes. The first step to answering this was to assess the subjects as an entire group and to determine how each of the performance metrics varied. Over the entire group of eight subjects, there were no overall obvious trends.

The only task in which significant differences found was with the increase from nominal to plus size in shoulder extension strength. This significant difference indicated an increase of more than 15% (mean increase of 15.8%) for the plus size over the nominal condition. Review of the supporting metrics for this strength motion found that from the HUT fit analysis, there was no noted sizing problems found for the nominal HUT size. For the plus sized HUT, four subjects were outside the 2/3rd point cutoff for the HUT top of scye (one from the body scan method and three from the FARO method). HUT scye bearing proximity at or beyond this 2/3rd point may have a possible influence on the results of subjects in the plus sized suit, although further testing would be needed to confirm this.

Pressure mapping information noted an increase in contact pressures on both the left and right shoulders in the plus size suit, for shoulder flexion/extension isolated ROM. Additionally, although decreases were noted in subjective survey results for the shoulder contact intensities during shoulder extension, the deltoid contact distributions and intensity levels were found to increase for the plus size.

While this study was able to identify motions and activities that were considered to be practically or statistically different, it did not signify that use of a plus sized suit should be prohibited. Further testing would be required that either pertains to a particular mission critical task or as mentioned in the limitations section, better simulates a microgravity environment in which the EMU suit was designed to work in.

Evaluation methods and results developed for this study can apply towards future pressurized suited investigations to help determine optimal suit sizing/fit and HUT shape and bearing locations for specified tasks. They can also aid in a better understanding of the interaction between the suit and its human user, leading to better suit designs with aims to maximize performance and minimize discomfort and injury.

ACKNOWLEDGEMENTS

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