CHAPTER XX

Comparative Ergonomic Evaluation of Spacesuit and Space Vehicle Design

Scott England[1], *Elizabeth Benson*[1], *Matthew Cowley*[2], *Lauren Harvill*[2], *Christopher Blackledge*[1], *Esau Perez*[2], *Sudhakar Rajulu*[3]

[1]MEI Technologies Inc.
2525 Bay Area Blvd. Suite 300
Houston, TX 77058, USA

[2]Lockheed Martin
1300 Hercules
Houston, TX 77058, USA

[3]National Aeronautics Space Association (NASA)
Anthropometry and Biomechanics Facility
NASA, Johnson Space Center
Houston, TX 77058, USA

ABSTRACT

With the advent of the latest human spaceflight objectives, a series of prototype architectures for a new launch and reentry spacesuit that would be suited to the new mission goals. Four prototype suits were evaluated to compare their performance and enable the selection of the preferred suit components and designs. A consolidated approach to testing was taken: concurrently collecting suit mobility data, seat-suit-vehicle interface clearances, and qualitative assessments of suit performance within the volume of a Multi-Purpose Crew Vehicle mockup.

It was necessary to maintain high fidelity in a mockup and use advanced motion-capture technologies in order to achieve the objectives of the study. These seemingly mutually exclusive goals were accommodated with the construction of an optically transparent and fully adjustable frame mockup. The construction of the mockup was such that it could be dimensionally validated rapidly with the motion-capture system. This paper describes the method used to create a space vehicle mockup compatible with use of an optical motion-capture system, the consolidated approach for evaluating spacesuits in action, and a way to use the complex data set resulting from a limited number of test subjects to generate hardware requirements for an entire population.

Kinematics, hardware clearance, anthropometry (suited and unsuited), and subjective feedback data were recorded on 15 unsuited and 5 suited subjects. Unsuited subjects were selected chiefly based on their anthropometry in an attempt to find subjects who fell within predefined criteria for medium male, large male, and small female subjects. The suited subjects were selected as a subset of the unsuited medium male subjects and were tested in both unpressurized and pressurized conditions. The prototype spacesuits were each fabricated in a single size to accommodate an approximately average-sized male, so select findings from the suit testing were systematically extrapolated to the extremes of the population to anticipate likely problem areas. This extrapolation was achieved by first comparing suited subjects' performance with their unsuited performance, and then applying the results to the entire range of the population.

The use of a transparent space vehicle mockup enabled the collection of large amounts of data during human-in-the-loop testing. Mobility data revealed that most of the tested spacesuits had sufficient ranges of motion for the selected tasks to be performed successfully. A suited subject's inability to perform a task most often stemmed from a combination of poor field of view in a seated position, poor dexterity of the pressurized gloves, or from suit/vehicle interface issues. Seat ingress and egress testing showed that problems with anthropometric accommodation did not exclusively occur with the largest or smallest subjects, but also with specific combinations of measurements that led to narrower seat ingress/egress clearance.

Keywords: Spacesuits, Ergonomics, Biomechanics, Human System Integration, NASA

1 INTRODUCTION

The next generation space vehicle being designed at the National Aeronautics and Space Administration (NASA) is required to accommodate a large range of crewmember anthropometry while enabling suited operations at a variety of pressures and permitting all safety hardware to be used in all planned contingencies. The Human-System Integration Requirements (CxP 70024) specify these various human factors constraints including critical anthropometric dimensions that must be accommodated by any spacesuits and space vehicles and the mobility and strength required of crewmembers wearing spacesuits. These conflicting design objectives necessitate a consolidated approach to testing and quantitative hardware evaluation, bringing multiple groups together to investigate integration issues. However, historically hardware testing has focused on qualitative evaluation of a single major hardware system at a time. One such test, labeled Functional Mobility Testing (England 2010), was conducted to determine the mobility requirements for the new generation of spacesuits. This testing became the corner stone for MPCV suited mobility requirements, despite relatively immature operational concepts and lack of a high fidelity test environment. As vehicle, operations, and suit concepts became more mature over several years, a consolidated test was envisioned to evaluate the integrated performance of the resulting spacesuits and the latest vehicle design.

The primary goals of this study were to quantitatively evaluate the performance of a series of prototype spacesuit architectures in the completion of a simulated mission to the International Space Station (ISS) and to estimate this performance for populations not currently accommodated by the prototype spacesuits. To accurately simulate performance of the tasks, a high fidelity mockup of the Orion Multi-Purpose Crew Vehicle (MPCV) was needed. However, quantitative analysis of spacesuit performance required extensive visual access for the motion capture cameras. These conflicting objectives were resolved with the construction of an optically transparent and fully adjustable vehicle frame mockup.

2 METHOD

Once the objectives of this test were defined, personnel in NASA's Anthropometry and Biomechanics Facility (ABF) immediately began resolving what operational concepts must be performed to evaluate the prototype spacesuits. It quickly became obvious that, in order to accurately represent a mission-similar environment, a high fidelity mockup of the MPCV would be required. The primary challenge was that the internal volume of the MPCV is too small for an adequate motion capture volume and existing vehicle mockups were fully enclosed. To resolve these problems, ABF personnel began designing a fully adjustable mockup of the vehicles critical work areas with as little solid structure as possible. The adjustability of the mockup was critical as the MPCV's design was still evolving. A stress analysis of the resulting mockup was performed to verify that it was safe for the ensuing test subjects. Commercially available bird netting wrapped around the structure created a sense of the internal crew areas while permitting the use of an optical motion capture system (Vicon, Oxford, UK). The ensuing mockup frame (Figure 1) was constructed chiefly out of extruded aluminum beams (80/20 Inc., Columbia City, Indiana).

Figure 1: Modeled drawing of reconfigurable mockup

A Vicon capture volume was constructed around the perimeter of the mockup such that subjects could be tracked while translating from the vehicle hatch to either recumbent seat in either position shown in Figure 1. The Vicon system was also used to validate the dimensions of the mockup against a computer aided design (CAD) drawing of the relevant iteration of the MPCV by quickly enabling the calculation of distances between key points.

Fifteen unsuited and five suited subjects participated in this study. Unsuited test subjects were selected chiefly based on anthropometry, in an attempt to find subjects who fit within defined categories for a medium male, large male and small female. Suited test subjects were selected for their ability to adequately fit multiple prototype suits and also were required to complete the test in the unsuited state.

Test subjects were fully instrumented with a set of retroreflective markers positioned to enable the calculation of all major joint angles. Once instrumented subjects completed an array of functional tasks representative of major tasks performed in a mission to the International Space Station (ISS) as kinematic data was recorded at 100 Hz (Figure 2). In addition to kinematic data; hardware clearance, suited anthropometry and subjective feedback were recorded at key instances throughout the test. Relevant operational tasks were performed while with both seat positions and with suited subjects at each of three pressure states; unpressurized, vent pressure, and nominal pressure. Suited anthropometry was recorded for critical dimensions at each pressure. Hardware clearance was recorded for hardware interference issues relevant to suited ingress and egress of the recumbent seats (Figure 2).

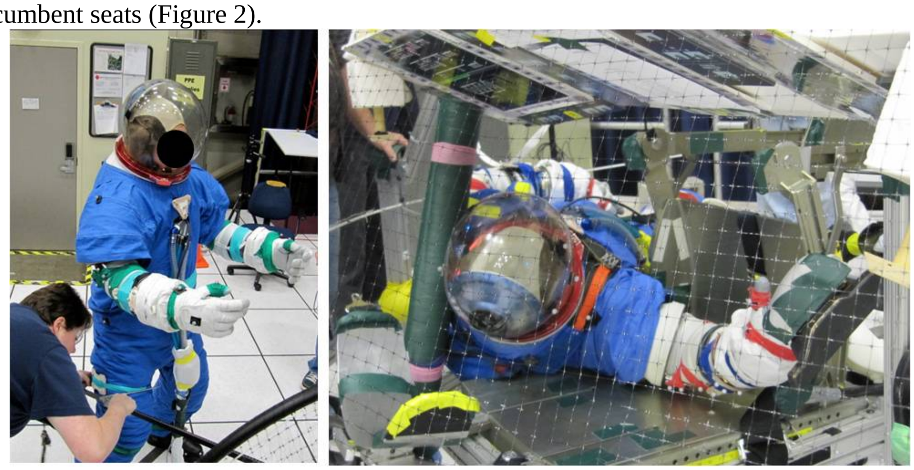


Figure 2: Left – Suited anthropometry being collected in a suit at vent pressure, Right – Kinematic data, hardware clearance and subjective feedback being recorded

Four prototype spacesuit concepts were evaluated in this study including the Pathfinder 1, Pathfinder 2, Demonstrator Suit, and Zipper Entry ILC suit (ZEI). These suits had multiple designs for helmets, mobility components and sizing adjustments, and had varying pressurization strategies. Typically when fabricating a new suit design concept, a single prototype is constructed for initial evaluation. These prototypes are generally fabricated in a single size to accommodate an approximately average sized male. Because the suits only accommodated a narrow band of the potential population, findings from the suit testing were systematically extrapolated to the extremes of the required anthropometry for crewmembers. This analysis into accommodated populations was performed by first comparing the suited test subjects' performance with their unsuited performance and then applying this relative performance ratio to the entire range of the population.

3 RESULTS

3.1 Mockup for Motion Capture

The optically transparent mockup was a success in enabling the use of motion capture technology while performing high fidelity tasks. Figure 3 shows an unsuited test subject reaching for the Displays and Controls (D&C) panel in Vicon and in video. Calculation of joint angles requires the reflective marker sets comprising body segments on either side of a joint to be fully visible. Figure 3 illustrates that the upper body for the test subject was fully captured by the Vicon cameras enabling calculation of all key joint angles for this task. Ranges of motion (ROM) were then calculated for each joint by determining the maximum joint mobility necessary for each task performed.

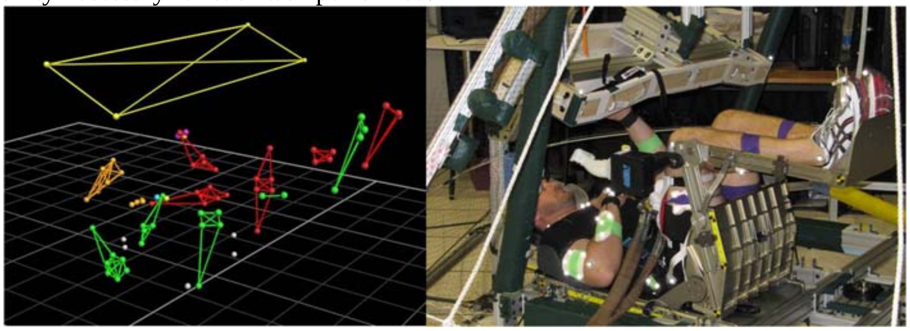


Figure 3: Large, unsuited test subject touching the Display and Controls Panel in Vicon (LEFT) and on video (RIGHT)

The fidelity of the mockup was such that, for any critical dimension, the reconfigurable mockup was never more than one inch from the dimensions in the official CAD file and was often substantially less. This could rapidly be verified by placing Vicon markers on key landmarks of the MPCV mockup and taking a short data capture (Figure 4). Once landmarks of the physical mockup were recorded in Vicon, they could be exported into a spreadsheet where distances between markers were calculated and compared to the intended design of the vehicle.

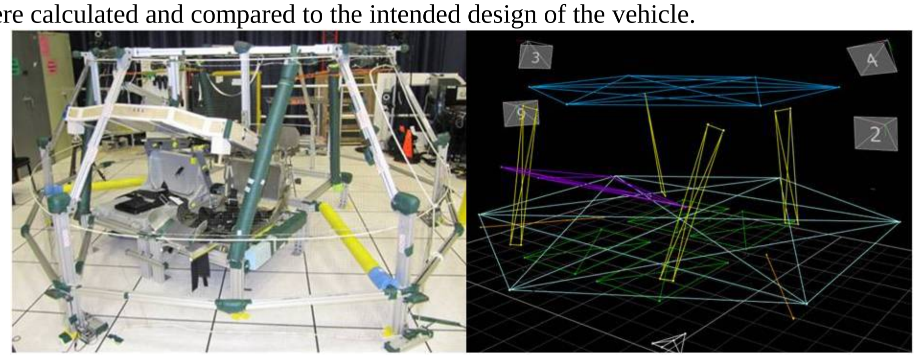
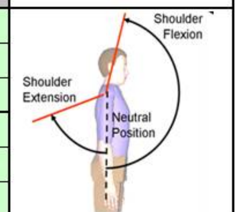


Figure 4: Key landmarks from the reconfigurable mockup reconstructed in Vicon

3.2 Spacesuit Evaluation

The use of a transparent space vehicle mockup permitted large quantities of both quantitative and qualitative data to be collected with human-in-the-loop testing. While the intent of testing was to quantify the performance of the various spacesuit prototypes, obviously qualitative evaluation was a simple but necessary data point to paint a more comprehensive picture of how the suits performed. To that end, all suits were largely successful in having sufficient mobility to complete tasks required of them. Qualitatively, failures to complete a task were generally attributed to problems with suit-vehicle integration, poor pressurized glove dexterity and tactility, or field of view issues when seated rather than insufficient mobility from the new spacesuits. All collected data was consolidated when determining how to update the suit mobility requirements (Figure 5).

Joint Movement		Unpressurized	Vent Pressure	Nominal Pressure	Figure
SHOULDER		Range of Motion (°)			Figure
Flexion	Old Requirement	120	120	100	
	New Requirement	130	130	120	
	Δ ROM	10	10	20	
Extension	Old Requirement	55	55	10	
	New Requirement	50	45	25	
	Δ ROM	-5	-10	15	
Adduction	Old Requirement	20	20	0	
	New Requirement	40	30	20	
	Δ ROM	20	10	20	
Abduction	Old Requirement	100	100	90	
	New Requirement	100	100	70	
	Δ ROM	0	0	-20	



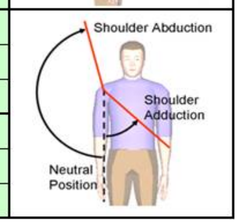


Figure 5: Pre and post-test mobility requirements for primary shoulder motions

3.3 Population Analysis

Observational data and feedback from suited test subjects indicated few challenges based on subject anthropometry within nominal operations of the suits. For example, of the four inspected suits, only in the Demonstrator suit did subjects indicate difficulty reaching any the upper-most controls on the D&C panel, representing insufficient shoulder flexion. However, extrapolating this finding to smaller subjects with shorter arms, it can be inferred that the suits would exacerbate this problem, potentially requiring more mobility than they are currently capable. For this reason, mobility requirements were buffered conservatively to produce newer suits with greater mobility than was minimally necessary.

Ingress and egress of the recumbent seats provided the greatest opportunity for problems to arise based on bulk of the suit and anthropometry of the test subjects. Subjects often attempted multiple techniques unsuccessfully before finding an approach that worked for them. These techniques included sliding into the seat facing down, facing up, squeezing the helmet between the seat and D&C console then laying down, hugging the strut, and more (Figure 6). Suited ingress of the recumbent seat was easily the most challenging task encountered in this test and it could potentially become more difficult with smaller test subjects. The smaller the test subject, the closer the seat pan must be adjusted toward the D&C panel to maintain proper eye alignment with the controls, which reduces the available ingress window. Small unsuited test subjects were able to ingress the seat without severe difficulty; however, comparison of suited anthropometry to unsuited anthropometry indicates that this will not be the case for small suited crewmembers.

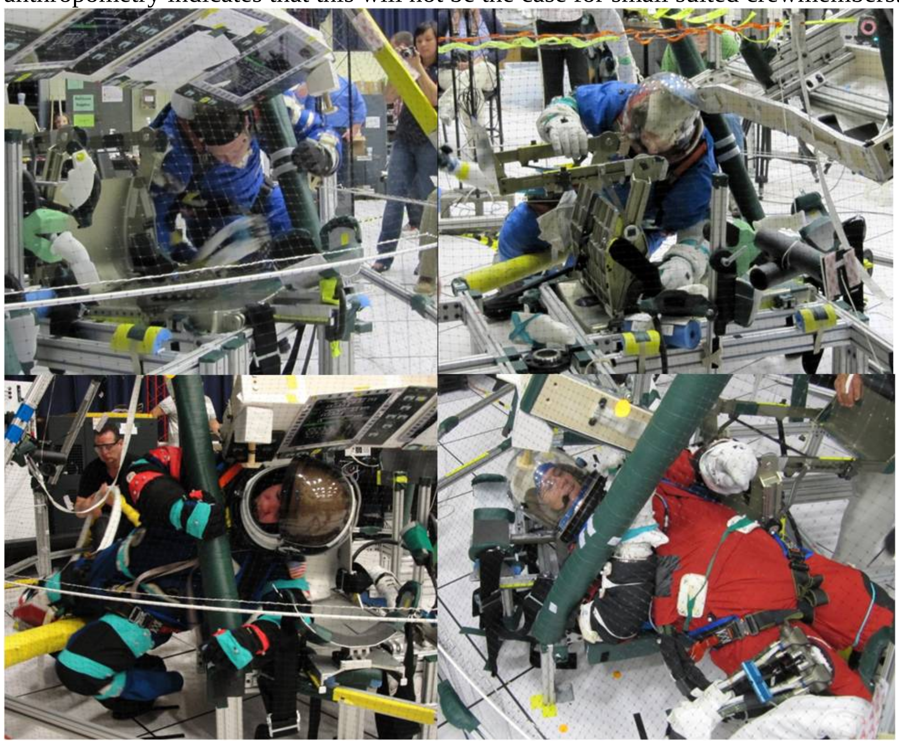


Figure 6: Multiple techniques were employed for ingressing/egressing the seat

4 DISCUSSION

The construction and use of a high fidelity mockup compatible with advanced motion capture technology was quite successful. The mockup was validated to be within acceptable tolerances of other high fidelity mockups of the Orion MPCV. Additionally, the mockup enabled suited ROMs to be quantified for all suits in all conditions as they completed the critical functional tasks. The update of mobility requirements evident in Figure 5 reflect varying needs and capabilities of the new prototype suits. For example, the requirements were updated to increase shoulder flexion and adduction, which reflects a more mature series of operational concepts in this round of tests and the need for greater arm mobility in a mission which now is geared towards microgravity IVA while unpressurized or at a low vent pressure. Previous mobility requirements included more significant operations for planetary EVA operations including fall recoveries, geological exploration, and habitat fabrication which all require much more significant lower body mobility.

Variation in subject anthropometry among unsuited subjects did not report any serious design accommodation issues; however, analysis of suited anthropometry and suited performance suggests that suited subject accommodation issues may exist when prototype spacesuits are developed for other sized crewmembers. While the seat ingress and egress evaluation of large and small unsuited test subjects did not produce any outright failures, it did reveal some difficulties that may arise when multiple circumstances coincide. The simplest example may be small subjects failing due to the small clearance window, but that may be over simplifying the issue. In practice, seated problems are more likely to occur for subjects with shorter torsos and longer legs or wider shoulders, which results in larger body segments needing to squeeze through smaller than normal access areas. Conditions may exist where specific subject anthropometry merged with additional suit bulk exceed hardware clearances. Care must be taken during crew selection and hardware verification to avoid creating excessive rates of failure for nominal mission operations.

5 CONCLUSION

Concurrent evaluation of prototype spacesuits in a vehicle mockup for multiple test subject anthropometries is a difficult task yet necessary to provide meaningful insight to hardware designers about spacesuit and space vehicle requirements verification. The creation of an optically transparent, fully adjustable vehicle mockup was challenging yet successful in practice. It enabled quantitative analysis of the spacesuit prototypes while allowing inspection by all variety of stakeholders in real time. This ability to observe the subjects in real time was secondary to the three dimensional kinematic data in initial test priority yet ended up being very useful for breaking down task completion beyond what is normally visible in a fully enclosed vehicle mockup. While the test was successful in completing its objectives, it must be acknowledged that this test had several key limitations including all operations being performed at full gravity and a single test subject completing tasks in an open mockup where at least two astronauts would be present in actuality. Despite those acknowledged limitations, this series of consolidated experiments still provided vast improvements in knowledge base for the data collectors and stakeholders the involved hardware systems.

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