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Refinement of Optimal Work Envelope for Extra-Vehicular Activity (EVA) Suit Operations

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Figures

Table

Acronyms

ABF	Anthropometry and Biomechanics Facility
ANSUR	Anthropometry Survey of U.S. Army Personnel
APFR	Articulating Portable Foot Restraint
EMU	Extravehicular Mobility Unit
DCM	display and control module
NTSC	National Television System Committee
NSTS	National Space Transportation System
PABF	Precision Air Bearing Facility
SSR	suit support rig

1 Introduction

1.1 Background

The purpose of the Extravehicular Mobility Unit (EMU) Work Envelope study is to determine and revise the work envelope defined in NSTS 07700 "System Description and Design Data – Extravehicular Activities" [1], arising from an action item as a result of the Shoulder Injury Tiger Team findings. The aim of this study is to determine a common work envelope that will encompass a majority of the crew population while minimizing the possibility of shoulder and upper arm injuries.

There will be approximately two phases of testing: arm sweep analysis to be performed in the Anthropometry and Biomechanics Facility (ABF), and torso lean testing to be performed on the Precision Air Bearing Facility (PABF). NSTS 07700 defines the preferred work envelope arm reach in terms of maximum reach, and defines the preferred work envelope torso flexibility of a crewmember to be a net 45 degree backwards lean [1]. This test served two functions: to investigate the validity of the standard discussed in NSTS 07700, and to provide recommendations to update this standard if necessary.

2 Methodology

2.1 Phase I

For Phase I of this study, three-dimensional work envelopes were measured for twelve crewmembers while they were wearing the pressurized (4.3 psi) EMU. The maximum work envelopes and preferred work envelopes were determined relative to a reference location on the display and control module (DCM), as well as a reference location relative to the midpoint between each crew member's left and right heel as positioned on the donning stand.

A reach envelope is the region in three-dimensional space that a crewmember is able to reach. The work envelope is a subset of the reach envelope, representing the volume in which the crewmember can work without persistent discomfort [2]. Each crewmember was asked to perform different tasks to acquire a maximum work (reach) envelope and a preferred work envelope for both one-handed and two-handed grasping tasks. Each crewmember was asked to perform three trials of each test, with a one-minute rest interval between each trial. The one-handed task was performed with the right hand, due to the fact that bilateral symmetry was assumed. To begin capturing the sweeping arm motion with the Vicon motion capture system, the crewmember was instructed to grasp a standard non-flight class III handrail and start with the elbow fully extended. The crewmembers then performed a sequence of mediolateral sweeps at incrementally increasing levels of shoulder circumduction. The inner and outer boundaries of the work envelope were defined by the most medial and lateral positions attained, respectively. The two-handed work envelopes were determined using both hands and performed using this same motion pattern. Two separate conditions were included in the two-hand task trials: two-hand close grip (the hands were placed touching each other while holding onto the handrail), and two-hand far grip (the hands were placed on opposite ends of the handrail). A reflective marker was placed on the right hand and bilateral symmetry was again assumed.

2.1.1 Facilities and Equipment

Testing for phase I of this study was performed under 1-g conditions in the motion capture laboratory of the ABF in Building 15. The crewmembers' work envelopes were measured using a 10-camera Vicon motion capture system capable of measuring the 3-dimensional positions of reflective markers with an accuracy of approximately 1mm. Four reflective markers were attached to crewmembers' left and right upper and lower corners of the DCM. One extra marker was added to the chest for asymmetry, and the marker used for determining the work envelope was attached to the dorsal side of the hand. A donning stand was used to support the EMU space suit in an upright position (Figure 1). The EMU was stationary throughout the duration of the trial, with the work envelopes being defined relative to a reference location at the center of the DCM. Vicon Nexus was then used to mark the boundaries along the work envelope for further analysis into the dimensions of the work envelope. Vicon Workstation software was used to export the events that were made into a text file. These text files were run through custom Matlab code to analyze the data and create tables and graphs from the results.

Figure 1. Photograph of a crewmember in the donning stand with the retro reflective markers on the DCM and the right hand.

2.2 Phase II

For Phase II of this study, subjects were chosen based on two factors: overall leg length and EVA experience. Current crewmembers having EVA experience were identified and placed into a pool of likely test candidates. These subjects were then divided into three groups based on various leg lengths: short (96-100 cm), average (101-105 cm), or long (106-110 cm). This subject grouping was selected to test the hypothesis that leg length would correlate with preferred torso lean.

2.2.1 Facilities and Equipment

All testing for Phase II took place at the Space Vehicle Mockup Facility's Precision Air Bearing Floor (PABF) located in building 9. This facility was chosen due to the ability to allow a suited subject to perform 2D translation and 1D rotations under simulated microgravity due to the near frictionless air cushion provided from the air bearings on the floor. After donning the suit, subjects were hoisted onto their side by crane and attached to the suit support rig (SSR). This rig was then moved such that the subject's feet could be placed securely in the Articulating Portable Foot Restraint (APFR) as seen in Figure 2.

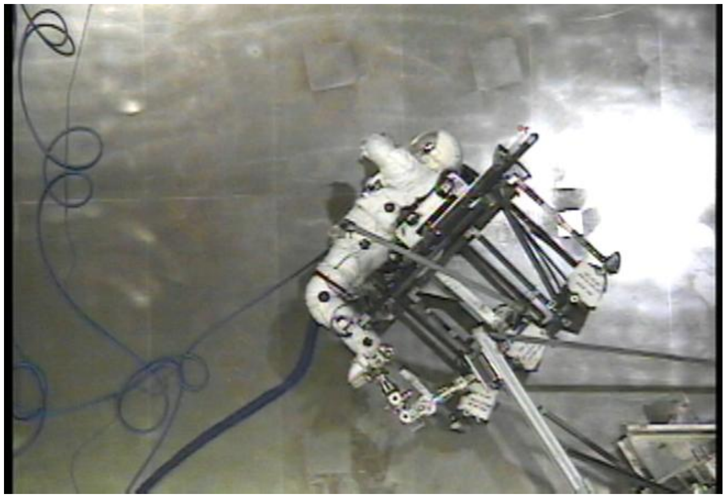


Figure 2. Overhead view of the crewmember secured to the SSR on the PABF.

Two motion capture systems were used to determine the segment angles of the lower kinematic chain of the body. An overhead NTSC closed-circuit video camera provided primary motion capture. The use of a Visualeyez Phoenix motion system provided secondary motion capture support in the event that the overhead camera became disabled. Markers consisting of a 2” diameter circle of black duct tape were placed along the joint centers of the lower kinematic chain, beginning with the APFR pivot point and ending at the bustpoint level of each crew member. Active near-infrared LED markers were then placed on top of these tape circles to capture data for the redundant system.

3. Results

3.1 Phase I Results

As described in the methodology section, work envelopes were defined relative to the front of the DCM on the HUT and also relative to the midpoint between each crewmember’s left and right heel as they are positioned on the donning stand. Arm length data for each subject was retrieved from the ABF anthropometric database and used to group the crewmembers into categories to be used for comparison.

Initial analysis of DCM height vs. subject anthropometrics showed a correlation between acromion height and DCM height. After examining the subject pool, it was discovered that the subject sizes spanned from 5th percentile to 80th percentile male, as determined by the 1998 Anthropometry Survey of U.S. Army Personnel (ANSUR).

Due to an insufficient sample size of subjects, two-handed (close) work envelopes were not analyzed for the purpose of this report. However, future analysis may be performed if it is deemed necessary to report this information. Subjective comments from test subjects suggested that the two-handed (far) work envelopes most accurately covered the most amount of prospective two-handed tasks required for a typical EVA.

Sample results of the suited data are shown below. Work envelopes are displayed relative to a laser scan of an actual EMU in Figure 3. The images below reflect the real EMU preferred work envelope capabilities defined for the long-armed crewmembers. Test data confirmed predictions that the subjective nature of a ‘preferred’ work envelope resulted in large variation in preferred work envelope dimensions, which were uncorrelated with arm length. As a result, it was decided not to attempt prediction of subjectively defined preferred work envelopes during subsequent data collections, or extrapolation of preferred work envelopes to 95th percentile male populations.

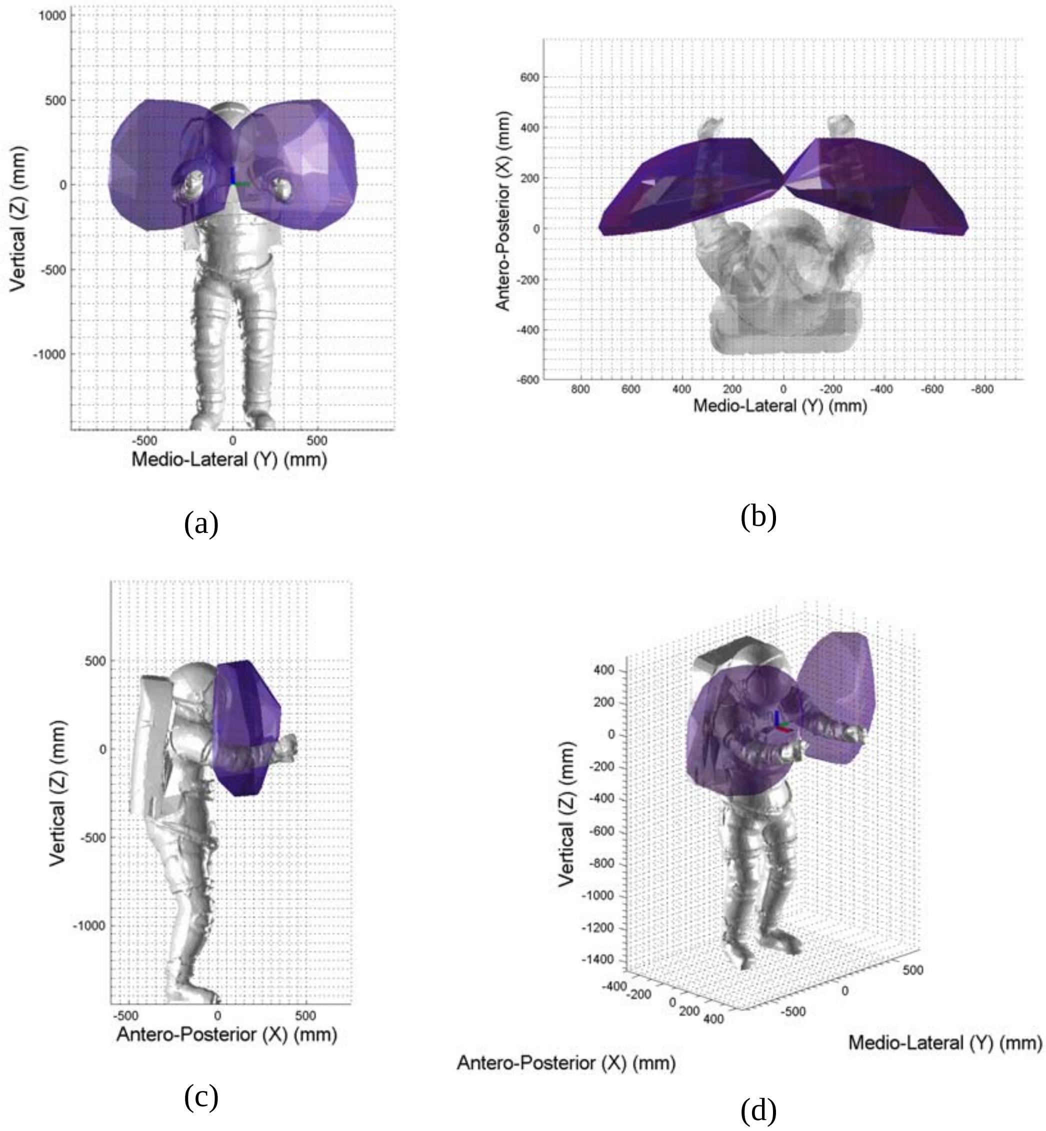
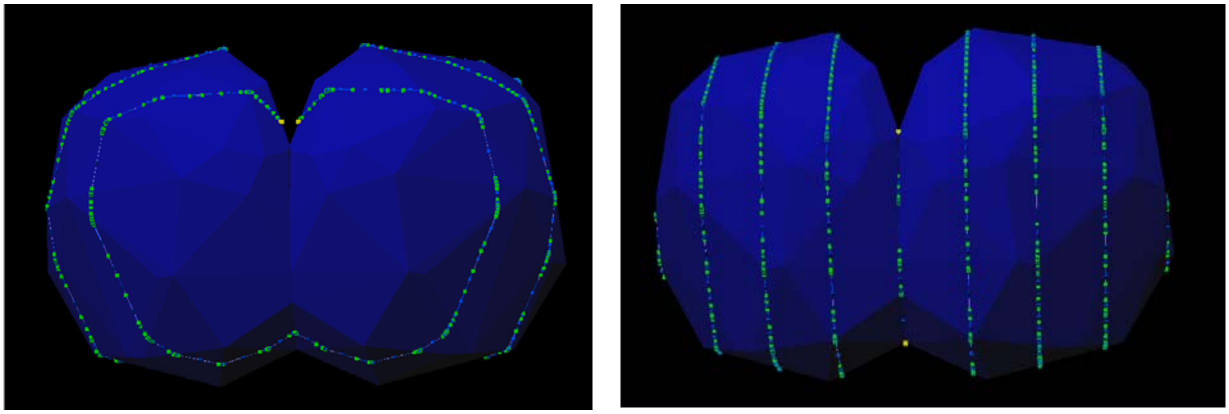


Figure 3. Common preferred work envelope for long armed (61-64 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) Isometric view.

The preferred work envelope was further analyzed in Polyworks by creating cross sections at 5.1 cm (2 in) intervals. The frontal slices began at the front face of the DCM while the sagittal slices started at the midline relative to the work envelope for each crewmember as shown in Figure 4. Frontal and sagittal cross sections were taken for the three groups (short, medium and long arm) in order to compare to the requirements that are listed in the NSTS 007700.



(a) (b)

Figure 4. Polyworks example of (a) frontal and (b) sagittal slices taken from a crewmembers work envelope.

While evaluating each subject groups reach capability in the EMU comparisons were made between the captured data and NSTS 07700 definitions. NSTS 07700 defines only a maximum reach for EVA instead of a comfortable, user-preferred reach that would be able to be maintained and reduce fatigue during an EVA activity. Figure 5 illustrates the preferred 1-handed reach for short, medium, and long armed crewmembers. The resulting cross sections shown in figure 5 are the actual work envelope slices representative for each group. The small arm length is representative of a 5th percentile male; the medium arm length is representative 60th percentile male while the long arm length is 80th percentile male. The centerpoint heights of each work envelope have been adjusted to the approximate acromion height of 5th, 60th, and 80th percentile male, respectively. All data for all cross-sections, as well as data for 2-handed (far) tasks can be found in appendix A.

When comparing this study to the current NSTS 07700, Plane A-A is closet to 5.1cm (4 in) from the DCM. The long arm preferred work envelope in this study reaches approximately 80 cm laterally from the origin. The max reach for a 95th percentile crewmember represented in NSTS 07700 reaches approximately 120 cm laterally. This represents an approximate 40 cm difference between the current max work envelope and the calculated preferred work envelope. The short arm preferred work envelope reaches approximately 50 cm laterally while the reported maximum reach for a 5th percentile male crewmember reaches approximately 105 cm laterally, resulting in a 55 cm difference between the two.

Figure 5(b) is the closet to Plane B-B in the NSTS 07700 at 15.3 cm (6 in). This figure shows the calculated long arm preferred work envelope to be approximately 65 cm laterally. The max reach for a 95th percentile crewmember defined in NSTS 07700 is approximately 120 cm laterally, resulting in a 55 cm difference. The short arm preferred work envelope is calculated to be 45 cm laterally, while NSTS 07700 records the max reach for a 5th percentile male crewmember to be approximately 80 cm laterally, an approximate 35 cm difference.

Figure 5(c) is close to NSTS 07700 Plane C-C at 25.4 cm (10 in). This slice shows the calculated long arm preferred work envelope is approximately 60 cm laterally. The max reach for a 95th percentile male crewmember is defined in NSTS 07700 at 105 cm laterally, resulting in a 45 cm difference. It is important to note that the short arm preferred work envelope did not reach the 25.4 cm mark for this task. The max reach for a 5th percentile crewmember as defined in NSTS 07700 at this plane is approximately 50 cm laterally.

The preferred reach envelope for all crewmembers are much smaller than the max reach that has been set in NSTS 07700. The preferred reach for the C-C plane for the 5th percentile crewmembers were nonexistent, showing a need to redefine the limits of the crewmembers' work envelope in the NSTS paper. The ABF recommends updating NSTS 07700 to include the preferred work envelopes calculated as the result of this project.

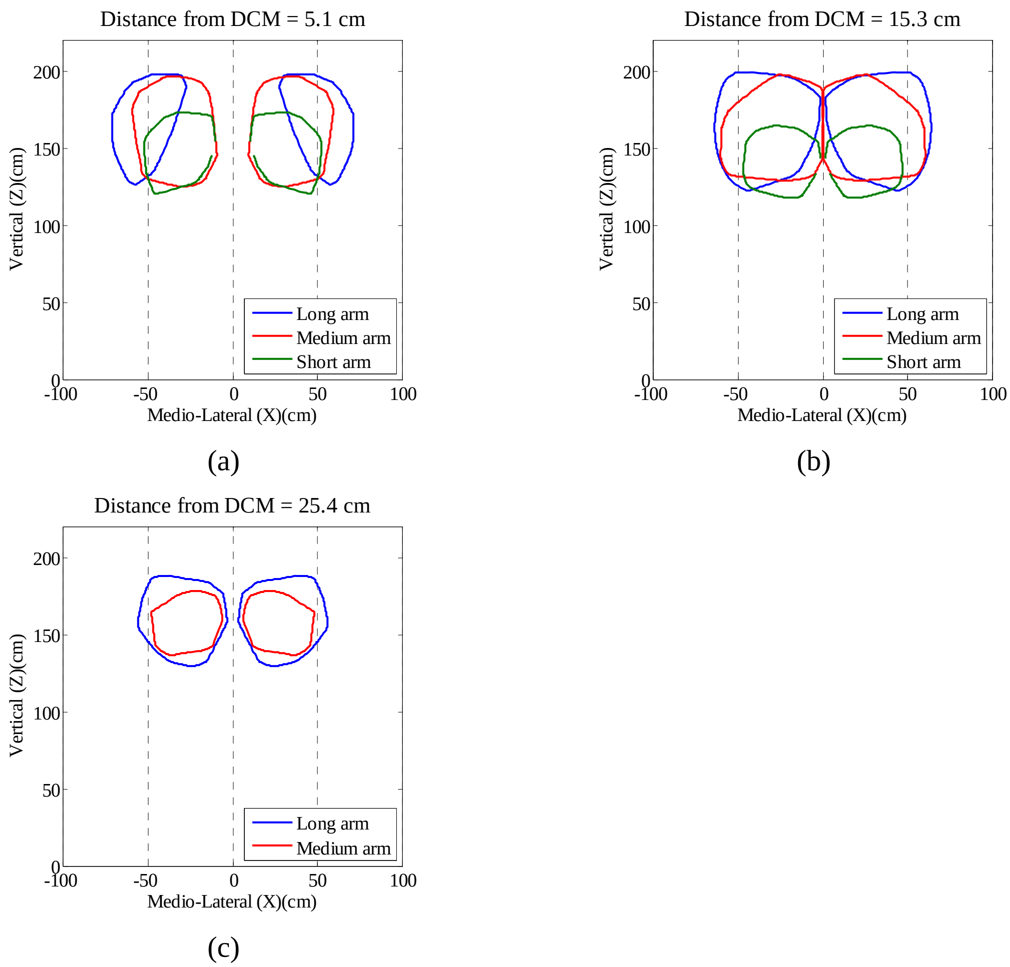


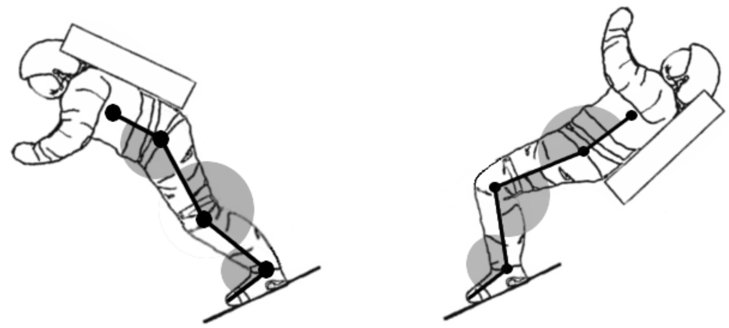
Figure 5. Matlab graphs showing the frontal slices for (a) 5.1 cm (b) 15.3 cm and (c) 25.4 cm from the front of the DCM.

3.2 Phase II Results

The overall goal of Phase II for this study is to examine and compare current requirements within NSTS 07700 to the results found from this study. Initial analysis of the crewmember runs was concerned with determining the net torso forward/backward lean of a subject for both maximum reach and preferred working area. This differs from NSTS 07700 because only the backward lean is explicitly defined as a requirement so the forward lean will be valuable information for EVA planning.

For Phase II, the translation of the work envelopes were defined relative to a reference location on the APFR. This reference point was determined by assuming a 25-degree plate tilt from the horizontal of the APFR footplate (Figure 6). To compare directly with NSTS 07700, the angle defined by the midpoint of the torso relative to the reference point was examined and reported. After examining each individual's work envelope, a common work envelope that can accommodate all crewmembers was generated.

Using Dartfish software, the net torso angle as well as the joint angles of the lower kinematic chain was calculated as shown in Figure 6 (a) and (b). As there were no problems with the overhead video camera during testing, data obtained by the Phoenix motion capture system was not used.



(a) (b)

Figure 6 Example illustration of a crewmember lean (a) forward and (b) back with the marker placement and joint angles that were analyzed.

NSTS 07700 refers to a lean back of 45 degrees, not specifying if this is a maximum lean back or preferred lean back. Table 1 contains the maximum and preferred lean back along with lean forward grouped by categories dependent on leg length.

After analysis, it was determined that the 89 degrees reported by the ‘short’ crewmember was potentially an outlier. Examination of all of the values recorded suggests that a common torso lean work envelope can be defined that encompasses all subject sizes. Therefore, the ABF recommends setting the preferred torso lean (forward) to approximately 48 degrees and preferred torso lean (backward) to 53 degrees. As the subjects were instructed to denote the maximum boundary of their preferred boundary, these points will fall within any common preferred work envelope. If a worksite requires a torso lean outside of this boundary, it is suggested that the APFR footplate be rotated and adjusted to ensure the maximum torso lean falls within these values.

Table 1 Results for maximum/preferred for lean back and lean forward trials.

	Maximum Lean Forward	Maximum Lean Backward	Preferred Lean Forward	Preferred Lean Backward
Short	**100**	**67**	**89**	**53**
Medium	**86**	**68**	**49**	**55**
Long	**82**	**82**	**48**	**59**

4. Discussion / Conclusions

4.1 Common Arm Reach Work Envelope

The common work envelope is a region in three-dimensional space in which a person can comfortably work for extended periods of time. While planning EVAs and designing the EVA work areas, it is crucial to determine in advance whether a crew member can comfortably reach a work site and maintain that position from the available foot restraints. The work envelope currently used for these analyses is a cylindrical volume centered on the body centerline, which was determined from experiments with suited test subjects. Later experiments have shown that the current work envelope may be conservative in some regions, while other areas of the current work envelope are probably not visible or safely attainable to the suited person. In addition, the experimentally-determined work envelope cannot be extrapolated to the outside boundaries of the prospective population due to the lack of correlation between anthropometric measurement(s) and preferred work envelope.

4.2 Preferred Torso Lean Work Envelope Boundary

At first glance the subjective nature of this test tended to yield varying results for the work envelope lean forward/backward range of motion. It is interesting to note that the crewmembers with the longest leg length yielded nearly the same preferred backward torso lean values as crewmembers with shorter leg lengths. Also the crewmembers with the shortest leg lengths are consistently more comfortable leaning forward to reach worksite locations then the longer legged crewmembers, verified by the objective data collected as well as subjective data and comments recorded during testing. However, the recommendation was made to be conservative in defining the torso lean work envelope in order to accommodate all potential crewmembers, with the idea that a smaller number by default lays within the envelope of all tested subjects.

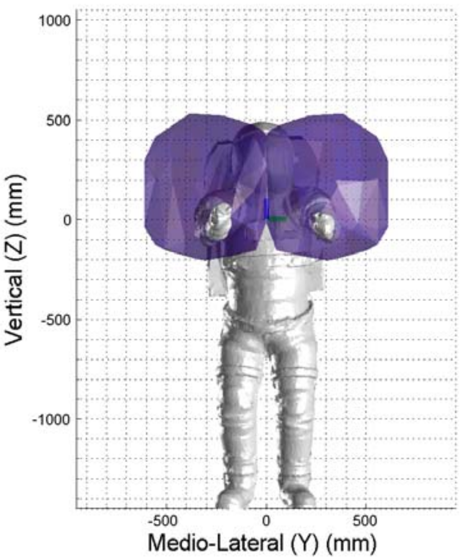
5. References

1. NASA. System Description and Design Data – Extravehicular Activities, Technical Report NSTS 0770, Volume XIV, Appendix 7, Revision K, NASA report, September 2000.

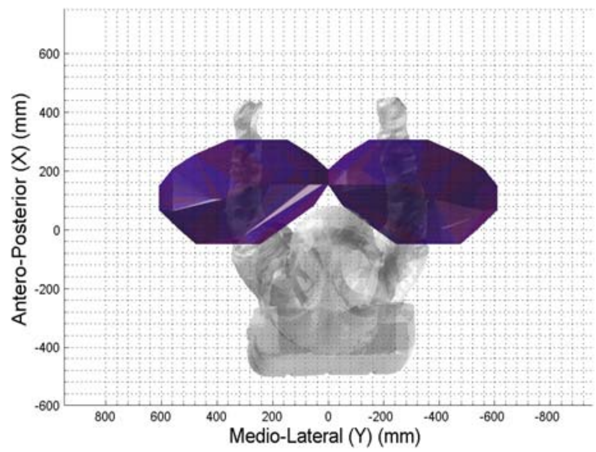
2. Schmidt, P.B. (2001). *An investigation of space suit mobility with applications to EVA operations.* PhD Thesis, Massachusetts Institute of Technology-Boston, MA.

Appendix A

The results of the suited data are shown below for the one-hand task preferred envelope short-armed and medium-armed crewmembers. Also shown below are the two-hand task preferred work envelopes for the short, medium and long armed crewmembers. The images reflect the real EMU preferred work envelope capabilities for both the one-handed and two-handed tasks that were performed.



(a)



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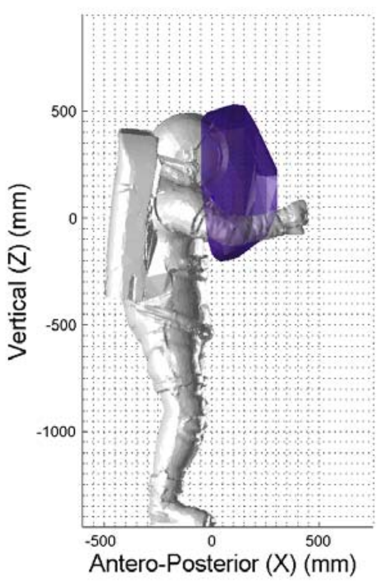
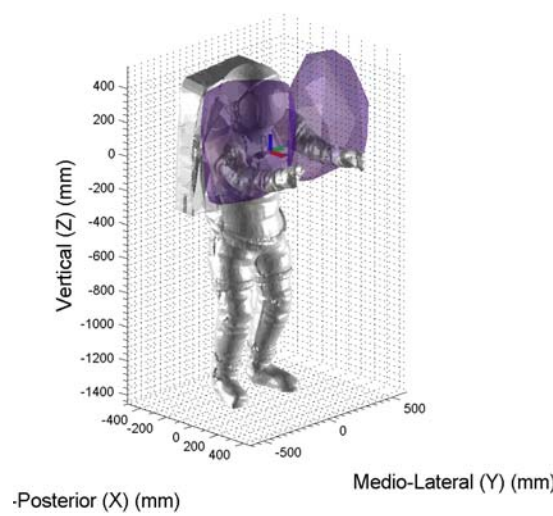


(c)



(d)

Figure A1. Common preferred work envelope for one-handed medium-armed (57-60 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) isometric view.

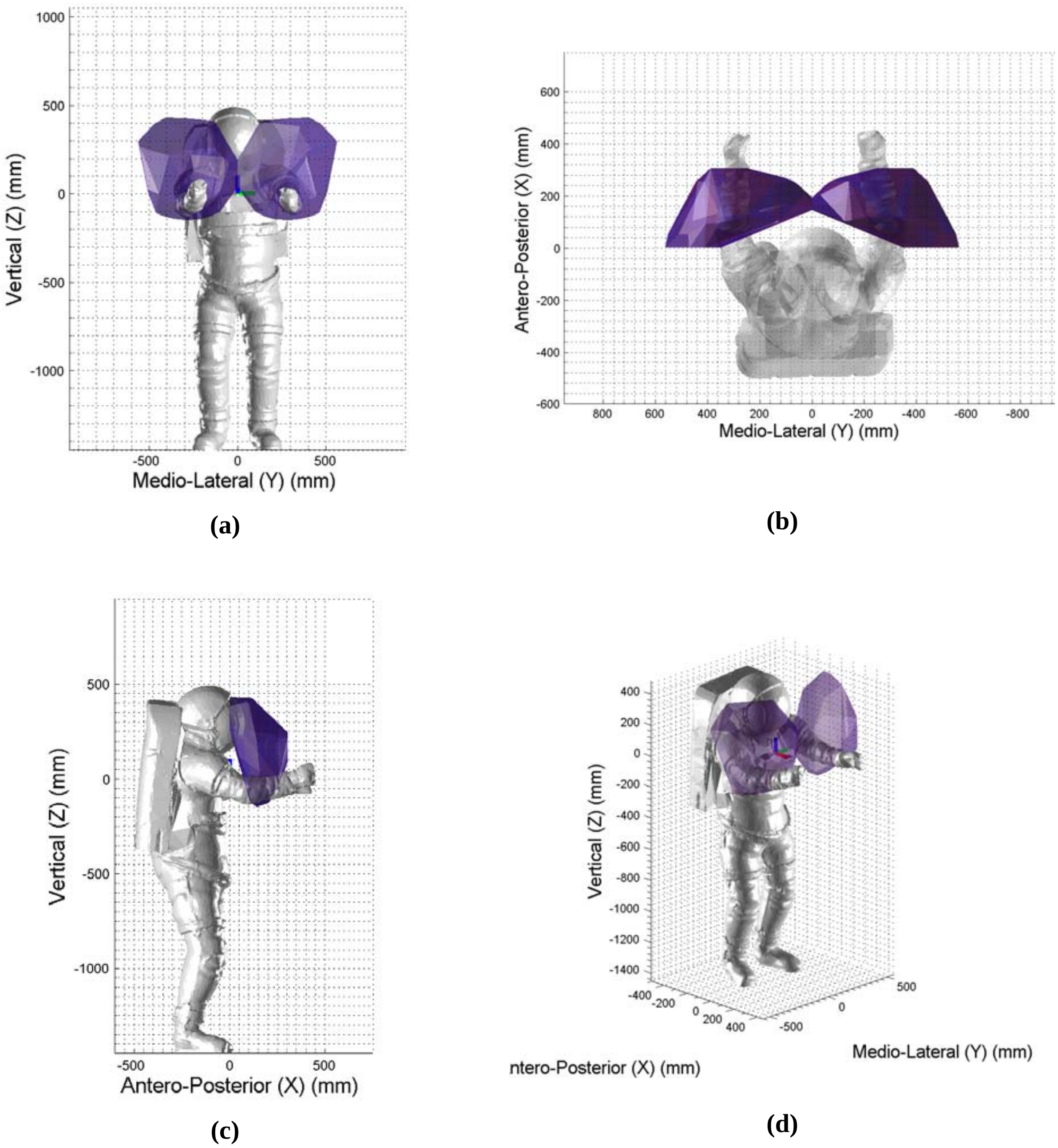


Figure A2. Common preferred work envelope for one-handed short-armed (53-56 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) isometric view.

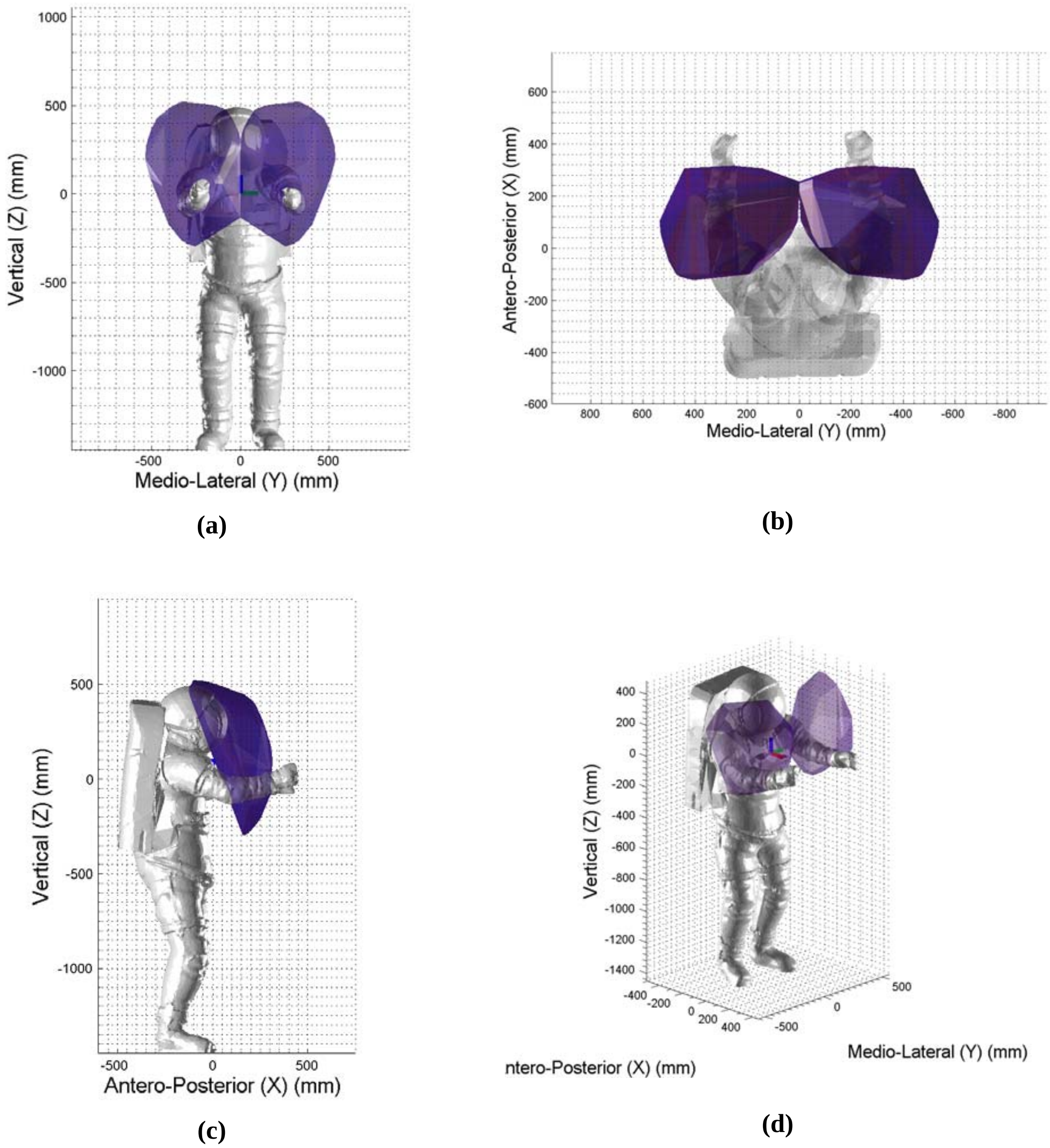


Figure A3. Common preferred work envelope for two-handed long-armed (61-64 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) isometric view.

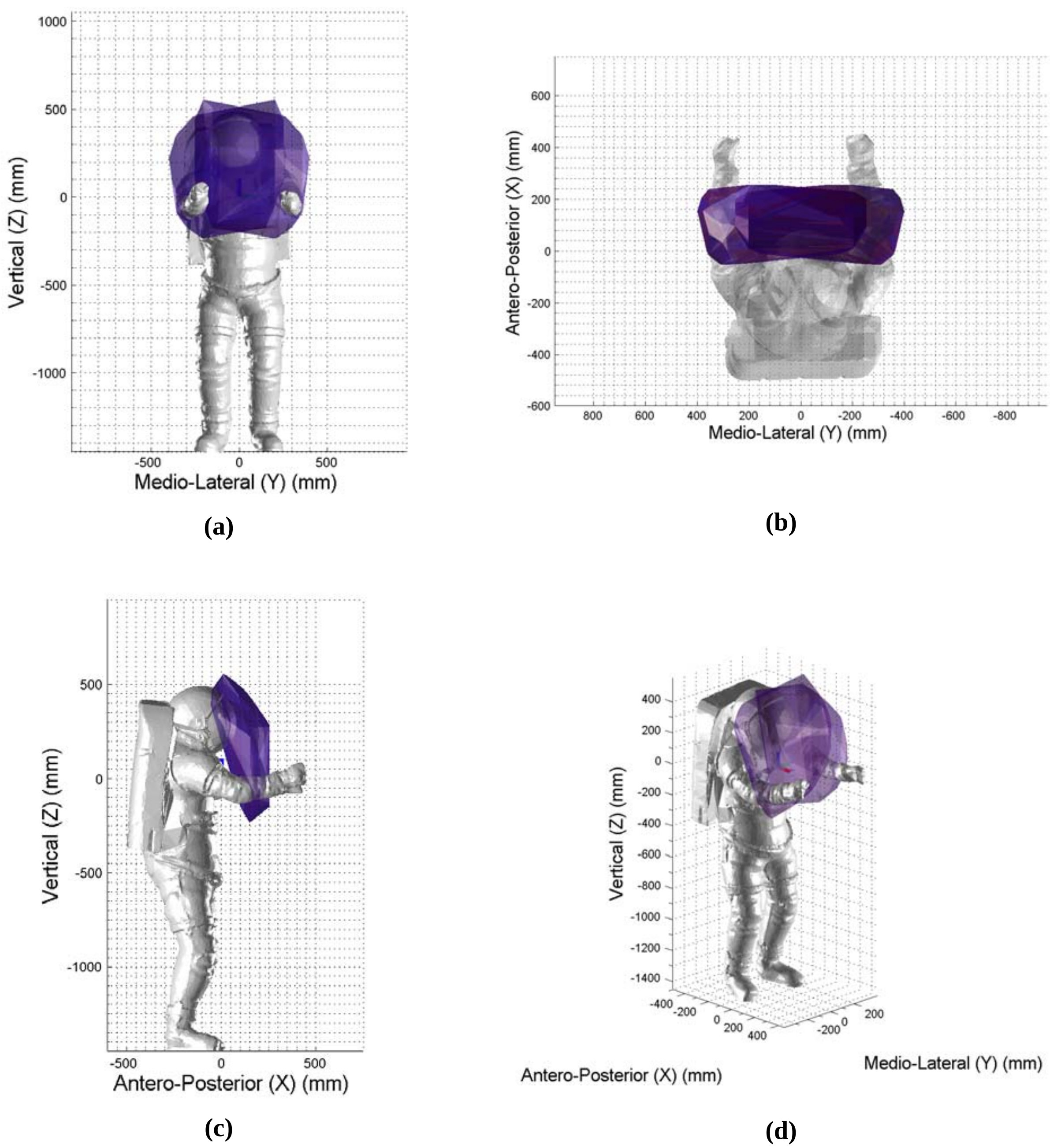


Figure A4. Common preferred work envelope for two-handed medium-armed (57-60 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) isometric view.

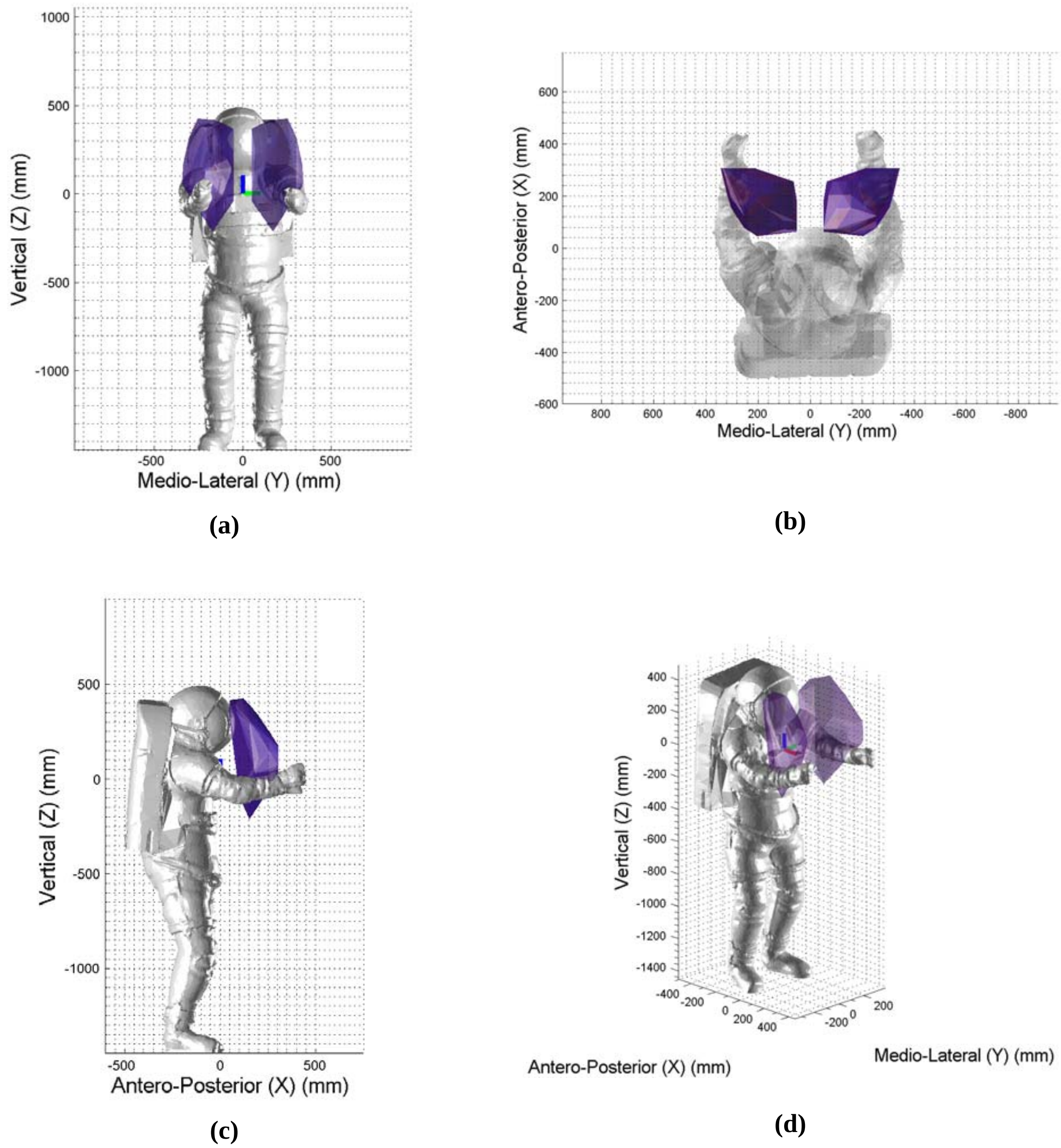
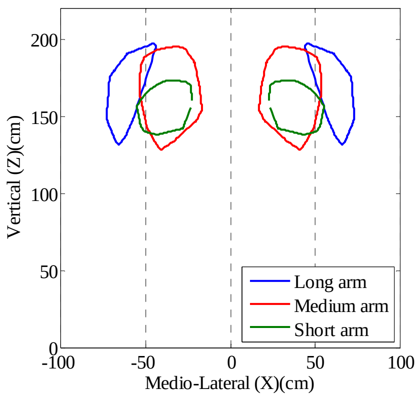


Figure A5. Common preferred work envelope for two-handed short-armed (53-56 cm) crewmembers. (a) front view, (b) top view, (c) right side view and (d) isometric view.

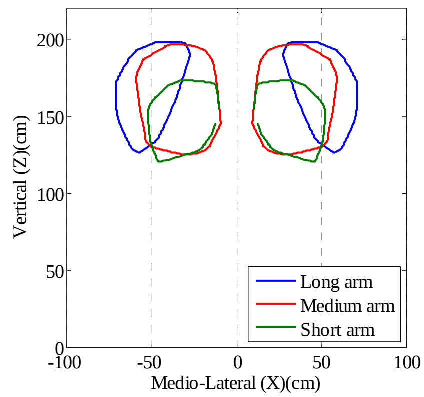
Appendix B

The results of the suited data shown below are for both the one-hand and two-hand task preferred envelope for long, medium- and short-armed crewmembers. The images reflect the real EMU preferred work envelope capabilities shown with frontal and sagittal slices.

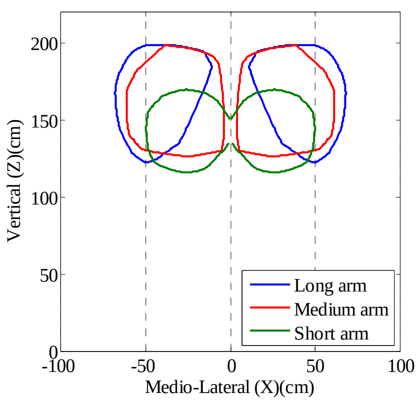
Distance from DCM = 0 cm



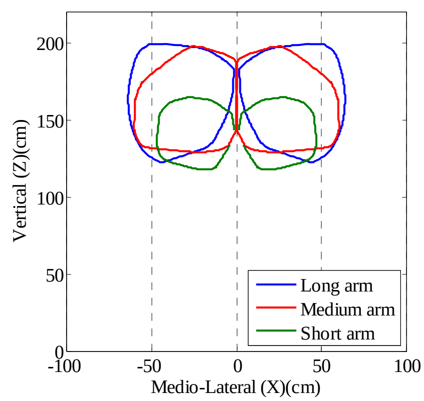
Distance from DCM = 5.1 cm



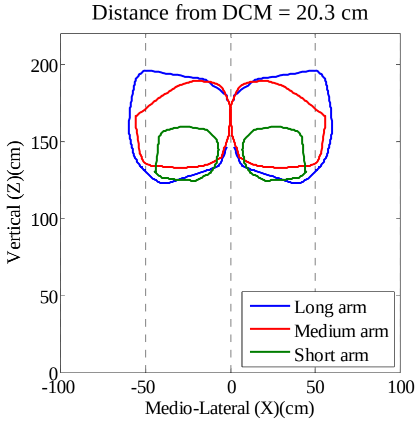
Distance from DCM = 10.2 cm



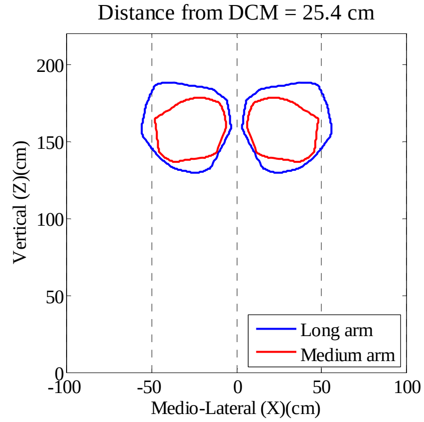
Distance from DCM = 15.3 cm



Distance from DCM = 20.3 cm



Distance from DCM = 25.4 cm



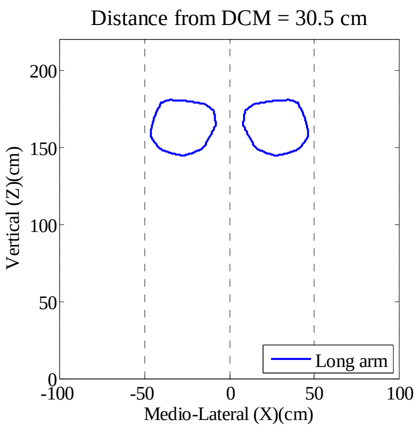
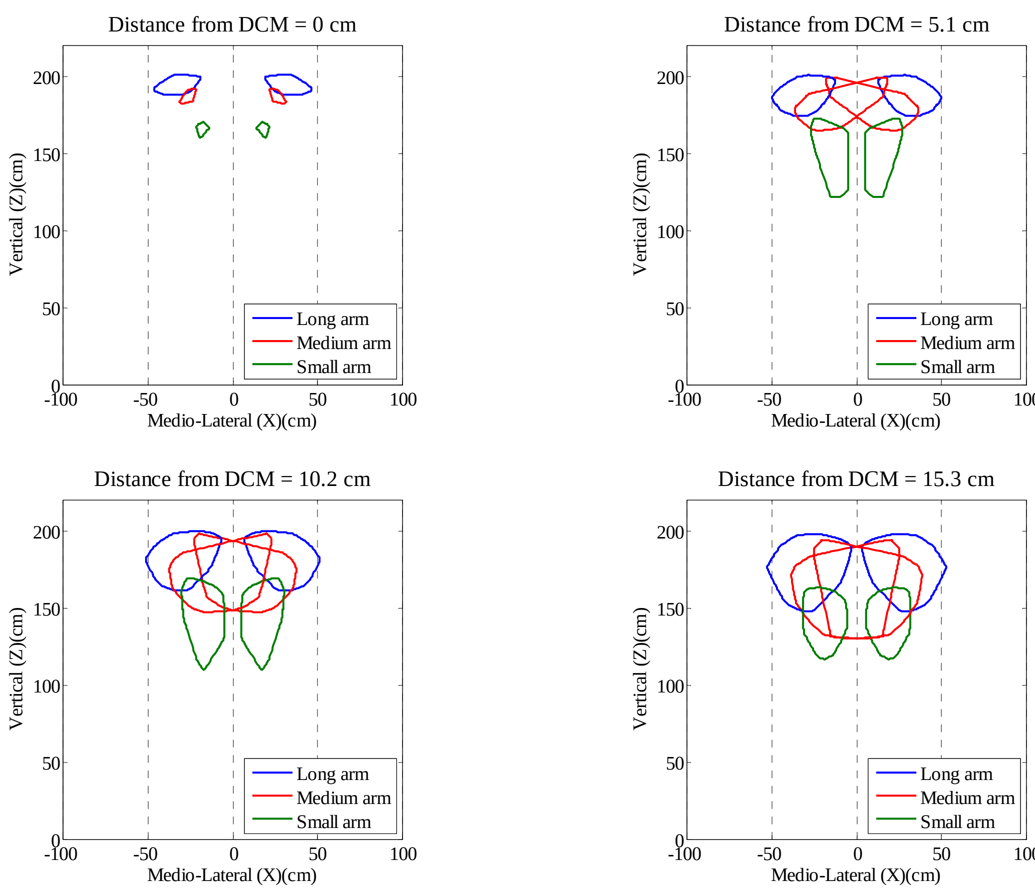


Figure B1. Frontal slices for crewmembers performing one-handed preferred-reach task.



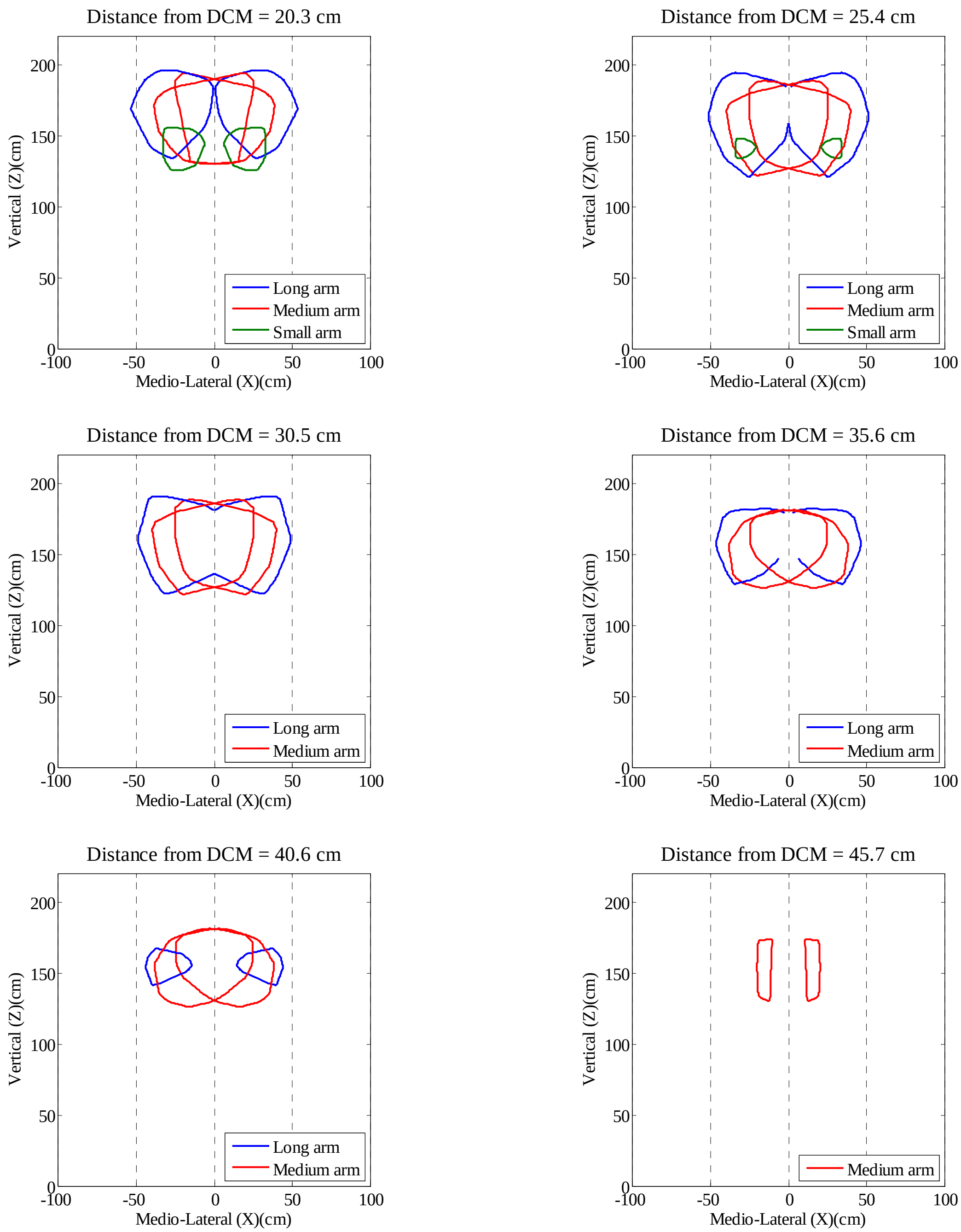
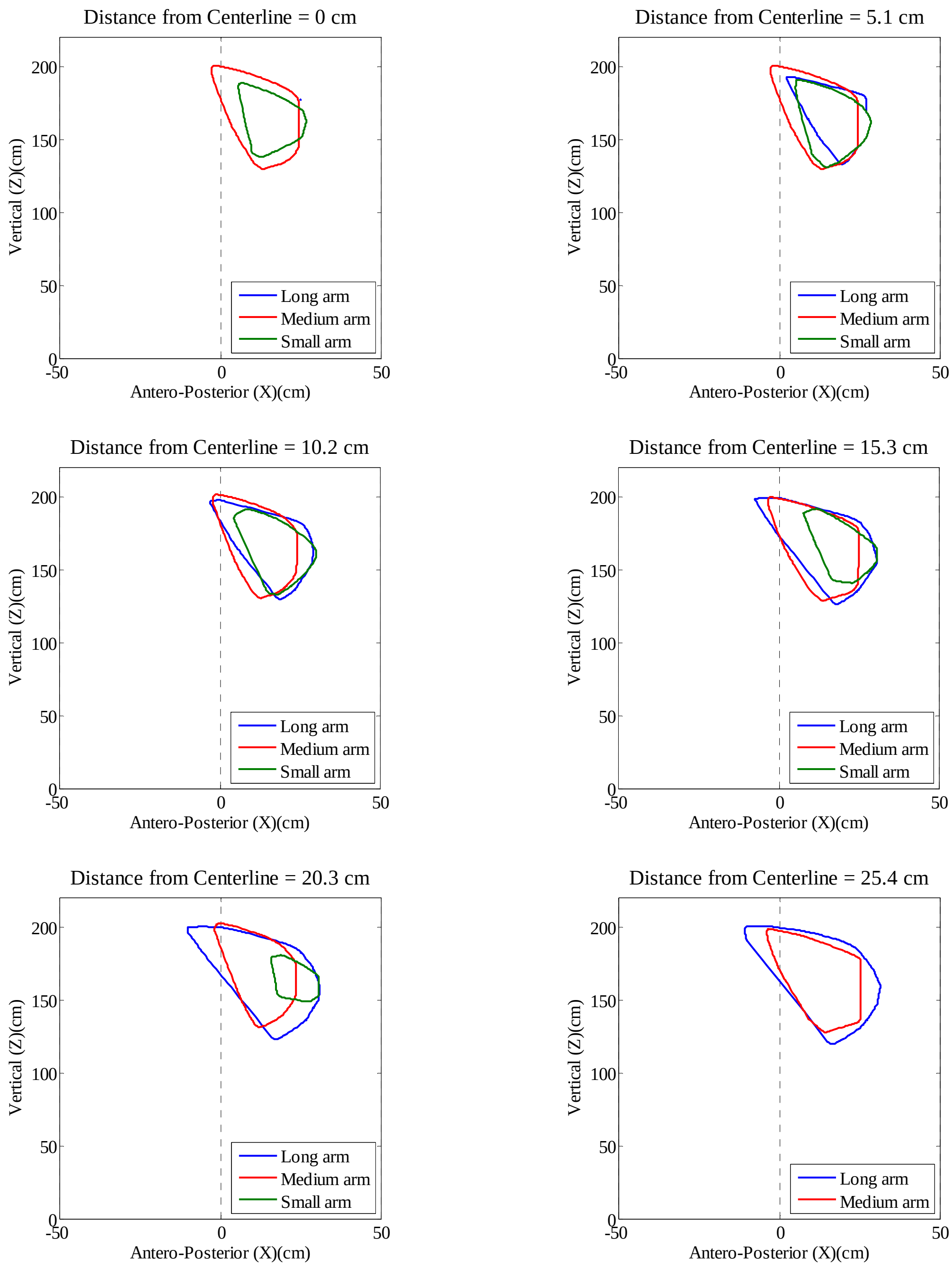
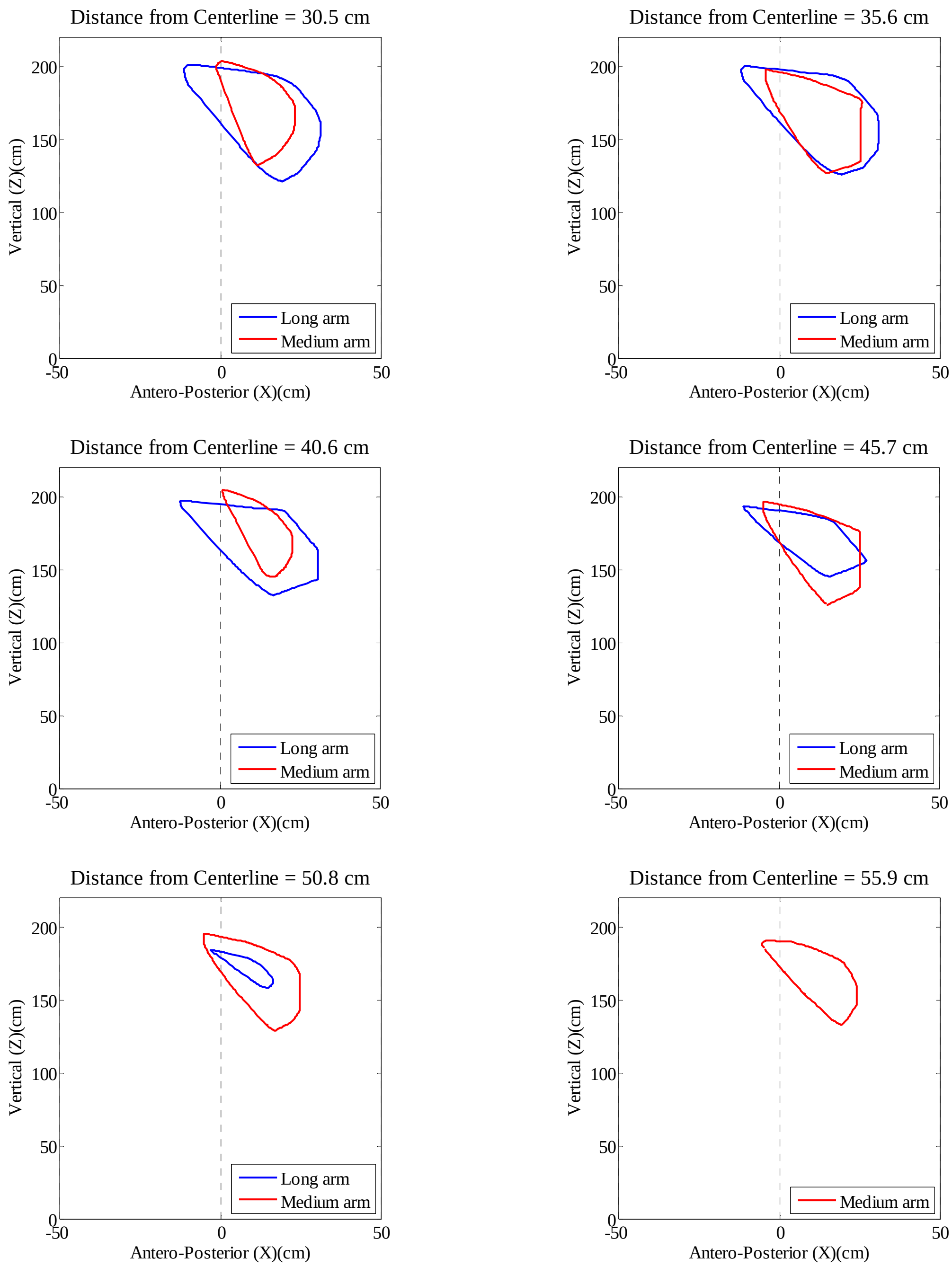


Figure B2. Frontal slices for crewmembers performing two-handed preferred-reach task.


Distance from Centerline = 0 cm
Distance from Centerline = 5.1 cm
Distance from Centerline = 10.2 cm
Distance from Centerline = 15.3 cm
Distance from Centerline = 20.3 cm
Distance from Centerline = 25.4 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Small arm
0
50
100
150
200
-50
0
50


Distance from Centerline = 30.5 cm
Distance from Centerline = 35.6 cm
Distance from Centerline = 40.6 cm
Distance from Centerline = 45.7 cm
Distance from Centerline = 50.8 cm
Distance from Centerline = 55.9 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
200
150
100
50
0
-50
0
50

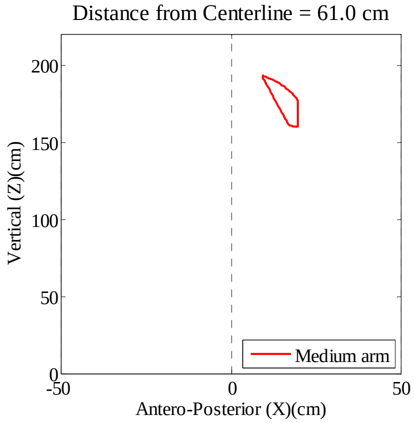
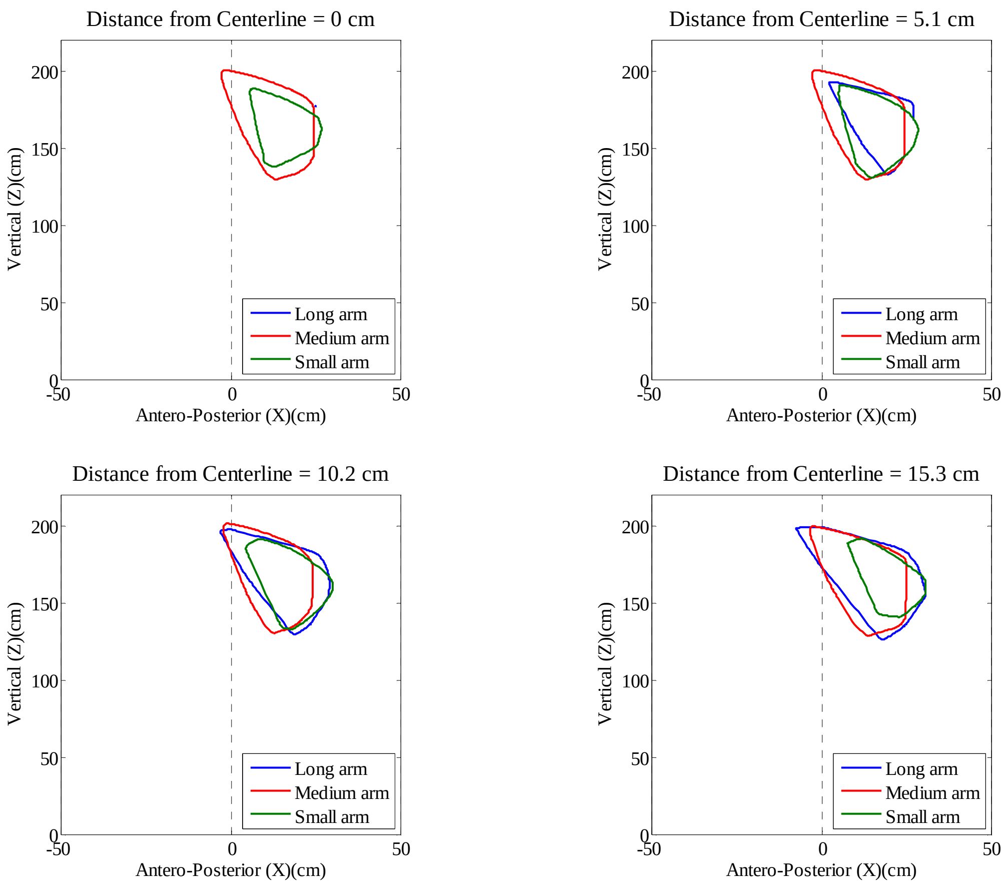
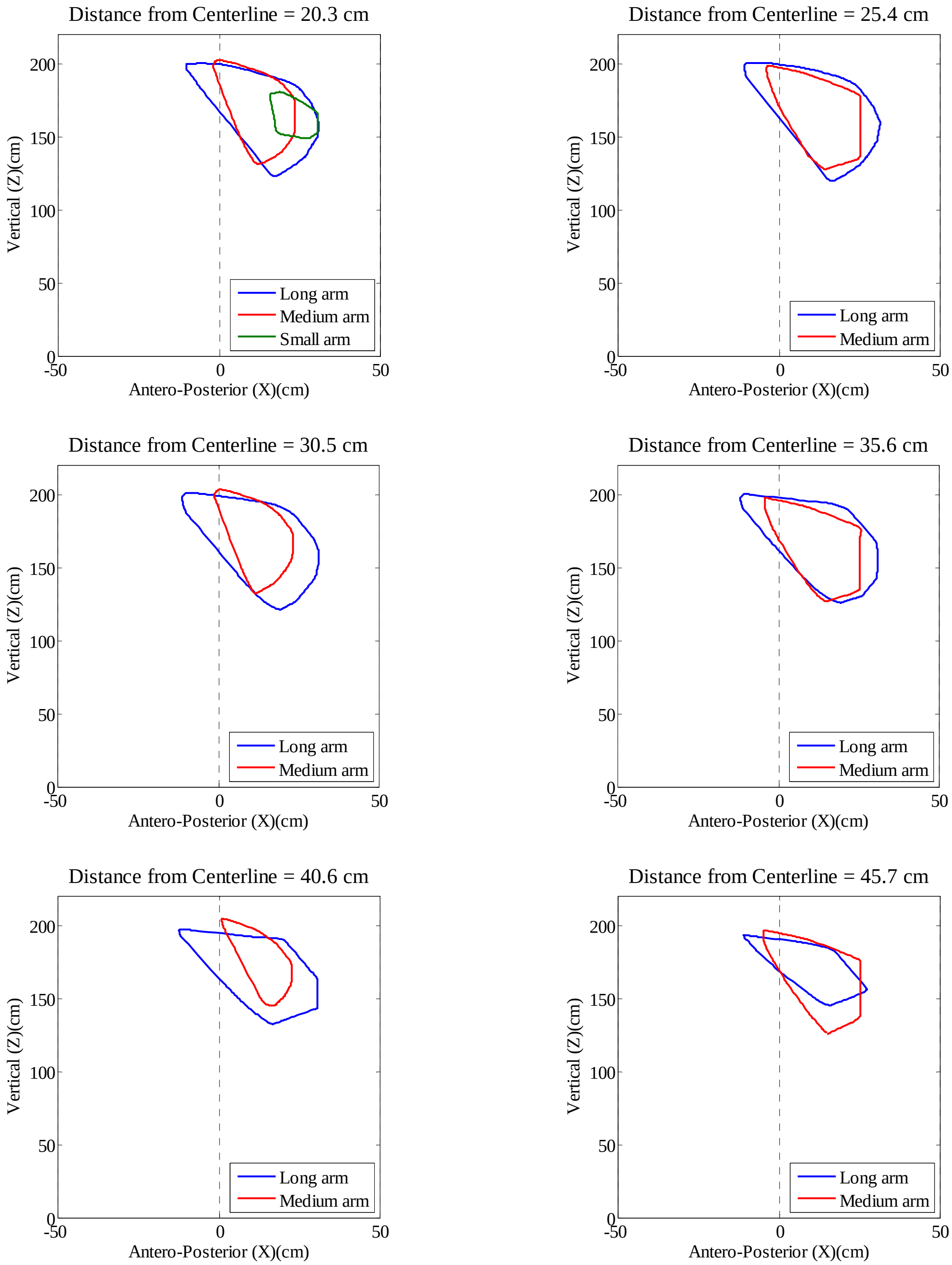


Figure B3. Sagittal slices for crewmembers performing one-handed preferred-reach task.





Distance from Centerline = 20.3 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Small arm
Distance from Centerline = 25.4 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Distance from Centerline = 30.5 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Distance from Centerline = 35.6 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Distance from Centerline = 40.6 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm
Distance from Centerline = 45.7 cm
Vertical (Z)(cm)
Antero-Posterior (X)(cm)
Long arm
Medium arm

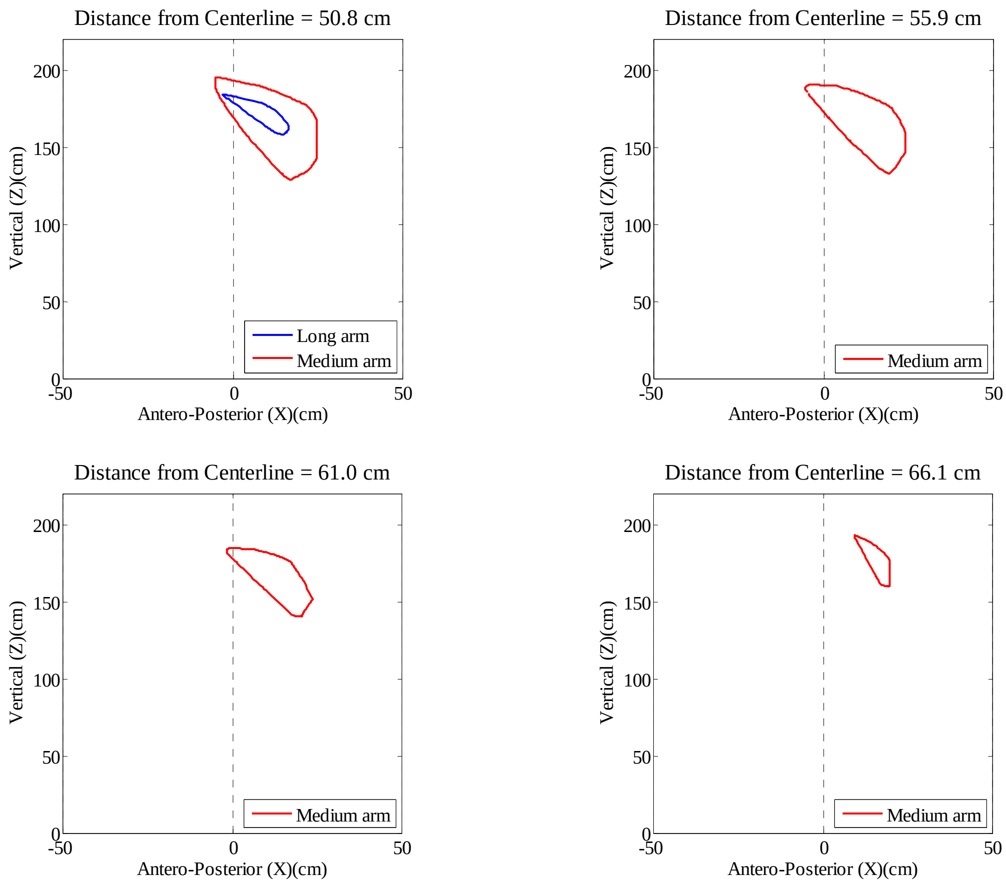


Figure B4. Sagittal slices for crewmembers performing two-handed preferred-reach task.