NASA/TM—2020-220149

# Cross-cutting Computational Modeling Project: Exploration Medical Station Analysis

*Christopher A. Gallo, Jonathan M. Goodman, Beth E. Lewandowski, and William K. Thompson*
*Glenn Research Center, Cleveland, Ohio*

May 2020

# NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., "quick-release" reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Fax your question to the NASA STI Information Desk at 757-864-6500

- Telephone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Program
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM—2020-220149

# Cross-cutting Computational Modeling Project: Exploration Medical Station Analysis

*Christopher A. Gallo, Jonathan M. Goodman, Beth E. Lewandowski, and William K. Thompson*
*Glenn Research Center, Cleveland, Ohio*

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

May 2020

*Level of Review*: This material has been technically reviewed by technical management.

Available from

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

# Contents

# Cross-cutting Computational Modeling Project: Exploration Medical Station Analysis

Christopher A. Gallo, Jonathan M. Goodman, Beth E. Lewandowski, and William K. Thompson
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Summary

Astronauts will be away from Earth-based medical care for long periods during future exploration missions. Thus, it will be necessary for the astronauts to perform various medical tasks to monitor and maintain their health in the microgravity environment of space. Performance of these tasks will be constrained due to the limited volume available to perform the task, the absence of gravity, and the limited resources and capabilities available in the medical work area. It is therefore necessary to evaluate exploration medical workstation designs to determine how well the designs will support crew performance of medical tasks.

The Cross-cutting Computational Modeling Project (CCMP) team used biomechanical modeling and analysis tools to provide insight into the following questions:

(1) What is the unrestricted operational volume needed to perform the medical procedures?
(2) Is a smaller volume than the estimated unrestricted operational volume sufficient to perform the task? How much smaller?
(3) How does the operational volume change when assistance is provided by another crew member during the medical procedure?
(4) How much time is required to perform the medical procedures and the subtasks within the procedures?
(5) How does the caregiver's foot placement and ground reaction force change throughout the procedure?
(6) If the caregiver's feet are restricted in one or two locations, can the caregiver still perform the task?
(7) What are the critical workspace dimensions? Can a tall caregiver and a shorter caregiver both work effectively within the workspace?
(8) How many medical consumable resources does each medical procedure use?
(9) How does the field of view change throughout the procedure? How often does the caregiver look at various parts of the medical station?
(10) Which way does the caregiver's head face in relation to his or her body throughout the procedure?
(11) What is the caregiver's opinion on the medical station layout?

## Methods

### Experimental Protocol

Experimental testing occurred in the Exercise Countermeasures Laboratory (ECL) at NASA Glenn Research Center. Test subjects with professional medical training acted as caregivers and performed medical procedures on a medical manikin (Complete CRiSis™ Manikin, Nasco). Three subjects, one

male and two female, performed seven emergent medical procedures by themselves, and one procedure was performed by the male subject with one of the female subjects. The male subject (Subject 07), a pediatric surgeon, was in the 99th percentile for height. The first female subject (Subject 08), a physician assistant, was in the 26th percentile for height. The second female subject, a paramedic, was in the 94th percentile for height. The International Space Station (ISS) medical checklists were the source for these procedures, which are designed for spaceflight (Ref. 1).

The following modified procedures were used for this analysis. Procedures 1 to 5 were performed in 2018, and procedures 6 to 8 were performed in 2019. Subjects 07 and 08 performed all eight procedures, whereas Subject 09 only performed procedures 2 and 6 to 8. Additionally, Subject 09 performed procedure 2 with the patient vertical but without cardiopulmonary resuscitation (CPR) compressions.

(1) Automated external defibrillator- (AED-) assisted CPR with one caregiver, pulse returns and patient becomes responsive (APR)
(2) AED-assisted CPR with one caregiver with drug administration (ADA)
(3) Choking patient becomes unconscious (CPU)
(4) Abdominal ultrasound (AUL) examining a problem
(5) AED-assisted CPR and advanced life support with two crew members
(6) Intravenous fluid preparation and administration
(7) Visual acuity exam
(8) Optical coherence tomography (OCT) exam

Copies of the modified procedures from the ISS medical checklists may be requested from the authors. The caregivers used handheld props representing medical tools and equipment while performing the procedures on the medical manikin.

Four single-caregiver volume configurations and three dual-caregiver configurations were used, as illustrated in Figure 1. The test subjects performed the procedures without a volume restriction (unrestricted volume, URV) to obtain the task performance volume naturally used by the subject. The subjects repeated the procedures with restraints on the feet similar to those used on the ISS so that the subject's feet stayed in only one or two positions (Figure 1(a)). Subjects 07 and 08 repeated the trials within two restricted working volumes (Figure 1(b) and 1(c)). The value for the first restricted volume (restricted volume large, RVL) was obtained from NASA Johnson Space Center. The second restricted volume (restricted volume small, RVS) was 64 percent of the first restricted volume (80 percent reduction in each dimension). A tubular framework outlined the restricted volumes within which the caregivers stayed. The rectangular framework adjusted from 127 to 254 cm (50 to 100 in.) per side. The framework was 193 cm (76 in.) in height but did not include overhead restrictions. In these analyses, the x-axis is in the main direction that the caregiver is facing, the y-axis is up, and the z-axis is along the length of the manikin. For all procedures, the RVL was 229 by 183 cm (90 by 72 in.) (z × x) and the RVS was 163 by 145 cm (64 by 57 in.) (z × x). The medical manikin lay on a benchtop 152 by 51 cm (60 by 20 in.) (z × x) in area and 76 cm (30 in.) tall.

For the dual-caregiver scenario performed by Subjects 07 and 08, the operational volume was not restricted, but the starting position of the caregivers varied among three positions. The subjects started the procedure on the same long side of the table (LLS; long–long, same side) (Figure 1(d)), on opposite long sides of the table (LLO; long–long, opposite sides) (Figure 1(e)), or crosswise on a long and a short side of the table (LSX; long–short, crosswise sides) (Figure 1(f)).

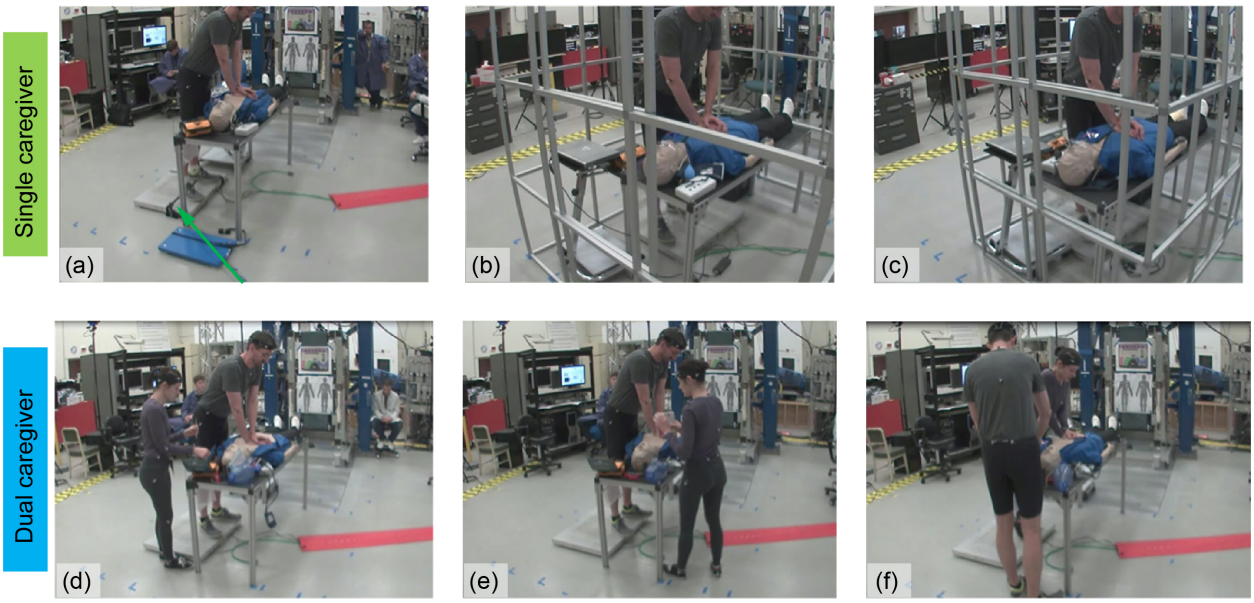


Figure 1.—Single-caregiver configurations ((a) to (c)) and dual-caregiver configurations ((d) to (f)). (a) Unrestricted volume with restricted feet. (b) Large restricted volume, 229 by 183 cm (90 by 72 in.). (c) Small restricted volume, 163 by 145 cm (64 by 57 in.). (d) Long–long, same side of table (LLS). (e) Long–long, opposite sides of table (LLO). (f) Long–short, crosswise sides of table (LSX).

The test matrices for the trials that occurred in 2018 and 2019 are given in Table I for the three subjects. The NASA Johnson Space Center Institutional Review Board (IRB) approved the experimental protocol. Subjects completed the IRB-approved informed consent form prior to any data collection. The Glenn Research Center Area 4 Safety Committee approved a safety permit for the activities.

## Data Collection and Experimental Measurements

The ECL's motion capture system (BTS Bioengineering Corp. 12-camera SMART DX 400) collected the motion data. Subjects 07 and 08 wore 33 reflective markers at key anatomical sites for use with the motion capture system; Subject 09 wore 27. For the two vision trials, the procedures were administered to a volunteer patient who wore 24 markers. The 33-marker system used appears in Figure 2. The marker names indicate their anatomical positions.

Digital photographs with a ruler in the camera view documented the marker positions. The motion capture system collected motion data (three-dimensional coordinates of the test subject versus time) while the test subjects performed the medical tasks. Additional markers on the work area extremes outlined the restricted volumes. Two live video cameras recorded the subjects performing the procedures: one side view and one head-mounted view using a camera attached to a headband worn by the subject.

The origin of the coordinate system was the posterior corner of the left force plate, relative to the subjects' starting position facing the table from the left side of the manikin. The x-axis pointed forward, the y-axis pointed up, and the z-axis pointed toward the manikin's head, as shown in Figure 3.

In addition to operational volume data for the medical procedures, the motion capture system collected data for each subject's maximum reach in all directions. The reported reach volume is the bounding box defined by the maximum extent of reach in all six directions (±X, ±Y, ±Z).

TABLE I.—TEST MATRICES FOR 2018 AND 2019 TRIALS

(a) Subject 07 (S07)—August 17, 2018

| Trial | Procedure | Identification (ID) | Configuration | ID |
|---|---|---|---|---|
| 4 | Choking patient becomes unconscious | CPU | Unrestricted volume | URV |
| 6 | Abdominal ultrasound | AUL | Unrestricted volume | URV |
| 7 | AED-assisted CPR, patient becomes responsive | APR | Restricted volume large | RVL |
| 8 | AED-assisted CPR with drug administration | ADA | Restricted volume large | RVL |
| 9 | Choking patient becomes unconscious | CPU | Restricted volume large | RVL |
| 10 | Abdominal ultrasound | AUL | Restricted volume large | RVL |
| 11 | Abdominal ultrasound | AUL | Restricted volume small | RVS |
| 12 | Choking patient becomes unconscious | CPU | Restricted volume small | RVS |
| 13 | Advanced lifesaving with drug administration | ADA | Restricted volume small | RVS |
| 14 | AED-assisted CPR, patient becomes responsive | APR | Restricted volume small | RVS |

(b) Subject 08 (S08)—August 23, 2018

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Abdominal ultrasound | AUL | Unrestricted volume | URV |
| 2 | Choking patient becomes unconscious | CPU | Unrestricted volume | URV |
| 3 | AED-assisted CPR, patient becomes responsive | APR | Unrestricted volume | URV |
| 4 | AED-assisted CPR with drug administration | ADA | Unrestricted volume | URV |
| 5 | AED-assisted CPR with drug administration | ADA | Restricted volume large | RVL |
| 7 | AED-assisted CPR, patient becomes responsive | APR | Restricted volume large | RVL |
| 8 | AED-assisted CPR, patient becomes responsive | APR | Restricted volume small | RVS |
| 9 | Abdominal ultrasound | AUL | Restricted volume large | RVL |
| 10 | Abdominal ultrasound | AUL | Restricted volume small | RVS |
| 11 | Choking patient becomes unconscious | CPU | Restricted volume large | RVL |
| 12 | Choking patient becomes unconscious | CPU | Restricted volume small | RVS |

(c) Subject 08 (S08)—September 7, 2018

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Abdominal ultrasound | AUL | Restricted feet | RFT |
| 2 | Choking patient becomes unconscious | CPU | Restricted feet | RFT |
| 3 | AED-assisted CPR, patient becomes responsive | APR | Restricted feet | RFT |
| 4 | AED-assisted CPR with drug administration | ADA | Restricted feet | RFT |

(d) Subject 07 (S07)—September 26, 2018

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Abdominal ultrasound | AUL | Restricted feet | RFT |
| 2 | Choking patient becomes unconscious | CPU | Restricted feet | RFT |
| 3 | AED-assisted CPR, patient becomes responsive | APR | Restricted feet | RFT |
| 4 | AED-assisted CPR with drug administration | ADA | Restricted feet | RFT |
| 1 | AED-assisted CPR, patient becomes responsive | APR | Unrestricted volume | URV |
| 2 | AED-assisted CPR with drug administration | ADA | Unrestricted volume | URV |

TABLE I.—Concluded.

(e) Subjects 07 and 08—October 19, 2018

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 6 | AED-assisted CPR with drug administration | ADA | Restricted volume small | RVS |
| 1 | AED-assisted CPR with two crew members | AC2 | Long–long same side | LLS |
| 2 | AED-assisted CPR with two crew members | AC2 | Long–long opposite side | LLO |
| 3 | AED-assisted CPR with two crew members | AC2 | Long–short side | LSX |

(f) Subject 07 (S07)—May 14, 2019

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Intravenous fluid preparation and administration | IVF | Unrestricted volume | URV |
| 2 | Intravenous fluid preparation and administration | IVF | Restricted feet | RFT |
| 3 | Visual acuity | VIS | Restricted feet | RFT |
| 4 | Optical coherence tomography | OCT | Unrestricted volume | URV |
| 5 | Optical coherence tomography | OCT | Restricted feet | RFT |

(g) Subject 08 (S08)—May 28, 2019

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Intravenous fluid preparation and administration | IVF | Unrestricted volume | URV |
| 2 | Intravenous fluid preparation and administration | IVF | Restricted feet | RFT |
| 3 | Visual acuity | VIS | Restricted feet | RFT |
| 4 | Optical coherence tomography | OCT | Unrestricted volume | URV |
| 5 | Optical coherence tomography | OCT | Restricted feet | RFT |

(h) Subject 09 (S09)—August 2, 2019

| Trial | Procedure | ID | Configuration | ID |
|---|---|---|---|---|
| 1 | Intravenous fluid preparation and administration | IVF | Unrestricted volume | URV |
| 2 | Intravenous fluid preparation and administration | IVF | Restricted feet | RFT |
| 3 | AED-assisted CPR with drug administration | ADA | Unrestricted volume | URV |
| 4 | AED-assisted CPR with drug administration | ADA | Restricted feet | RFT |
| 5 | AED-assisted CPR with drug administration | ADA | Patient vertical | VRT |
| 6 | Visual acuity | VIS | Restricted feet | RFT |
| 7 | Optical coherence tomography | OCT | Unrestricted volume | URV |
| 8 | Optical coherence tomography | OCT | Restricted feet | RFT |

Additional data collected included heart rate (Zephyr™ HxM, Medtronics, Subjects 07 and 08 only), the time to perform the procedures, and the quantity of resources used. The subjects provided subjective feedback, including completion of a NASA task load index (TLX) survey of workload, a System Usability Scale (SUS), and an open-ended assessment questionnaire.

Reference 2 describes the NASA TLX factors, and Reference 3 describes the SUS. The open-ended assessment questions appear in Appendix B. Figure 4 illustrates the process flow from data collection and analysis to results plot creation.

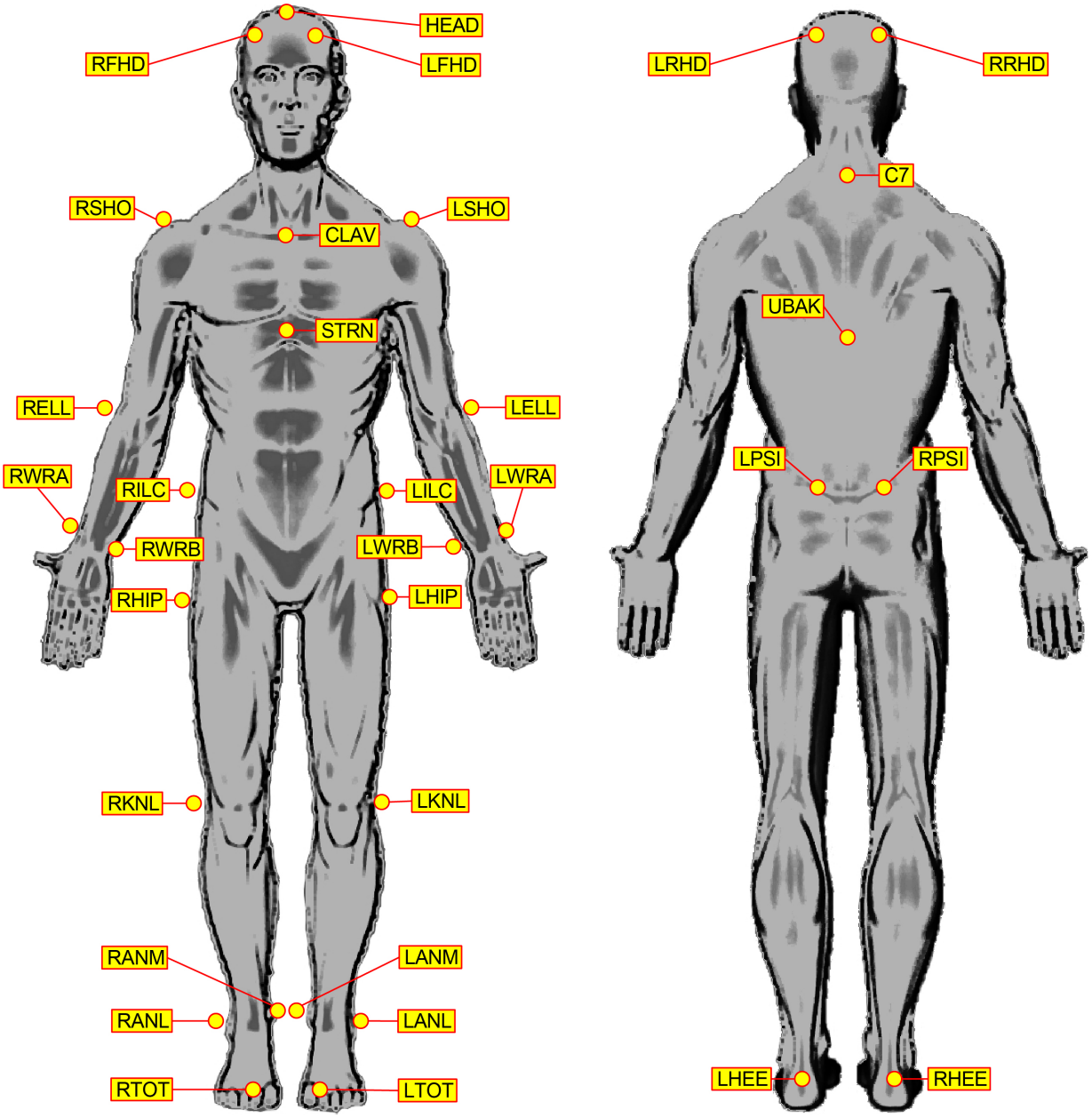


Figure 2.—Anatomical positions of 33 reflective markers used for motion capture by BTS Bioengineering system.

## Post-Testing Analysis Methods

### Maximum XYZ Bounding Box

For all of the procedures performed, the maximum and minimum body marker coordinate along each axis determined the maximum XYZ operational volume. Comparative analyses between volumes included unrestricted versus large and small restricted versus restricted feet; all volumes versus the NASA Johnson Space Center CTV database volume; and large male versus petite female.

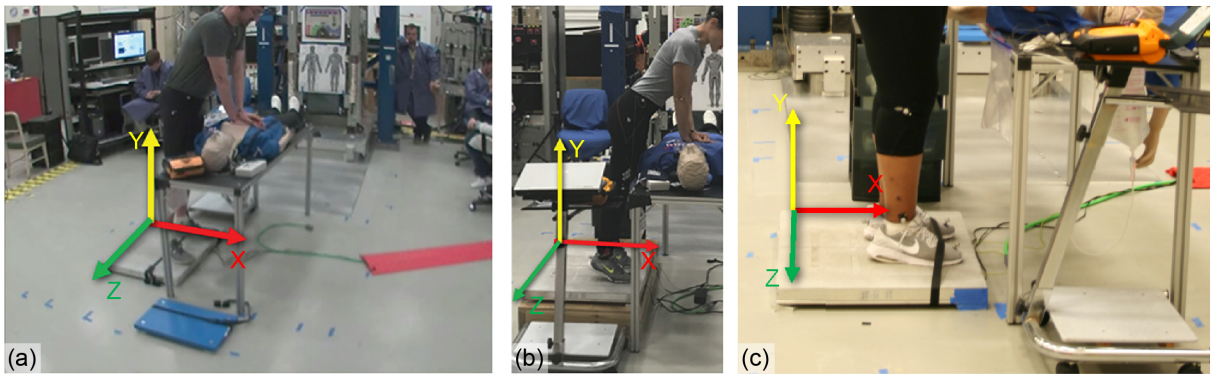


Figure 3.—Side view of test setup. Colored arrows depict origin and coordinate system for motion capture. (a) Setup for Subject 07, tall male. (b) Setup for Subject 08, petite female. Wooden box under female subject's feet positions her more advantageously for doing CPR compressions. (c) Setup for Subject 09, tall female.

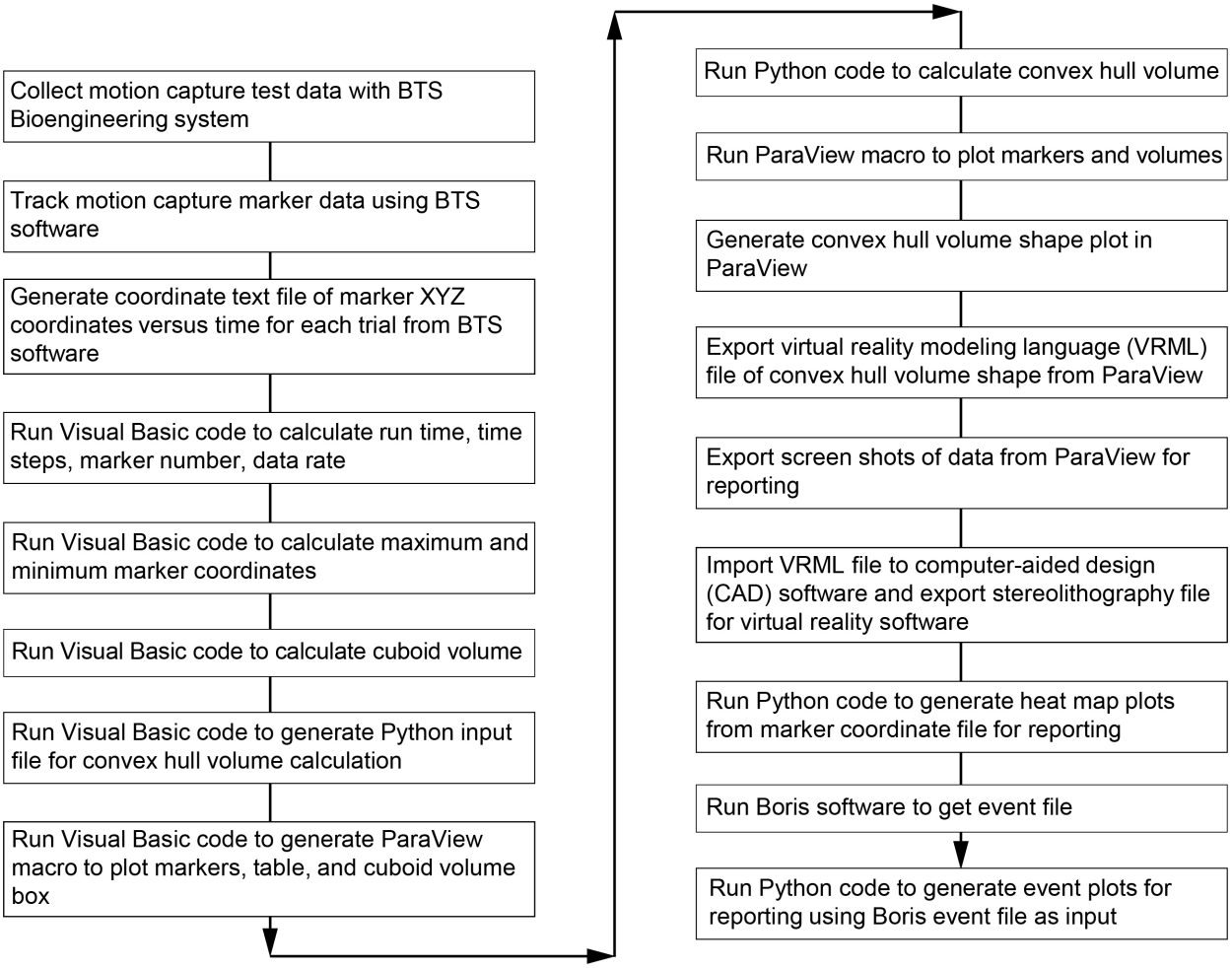


Figure 4.—Exploration medical station analysis process.

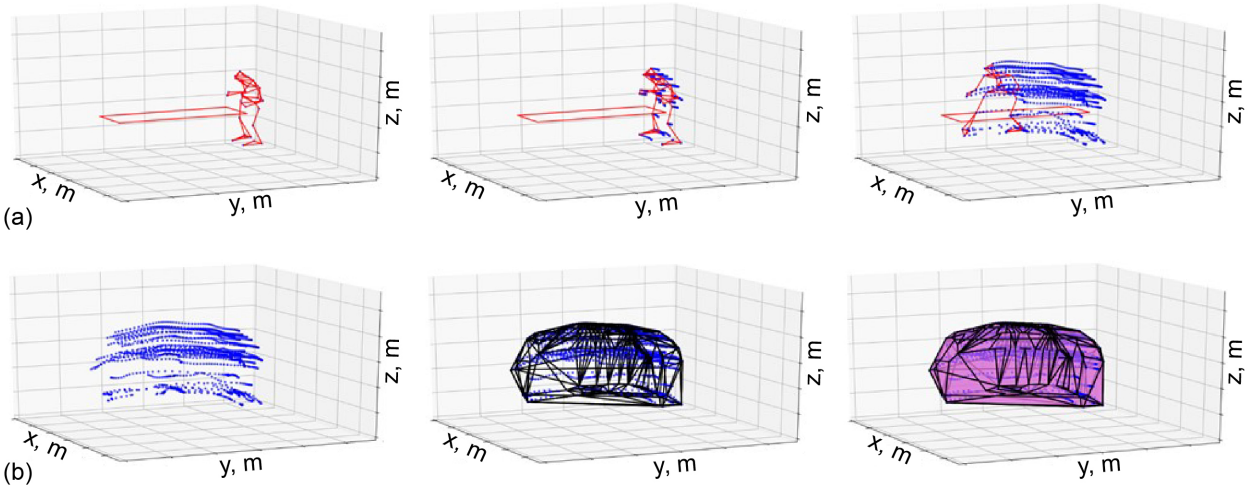


Figure 5.—Computation of convex volume using QuickHull method. (a) X, Y, and Z coordinates for each marker are obtained at every time step and accumulated over a period of time to form a point cloud. (b) QuickHull algorithm computes convex hull (i.e., outermost points of this point cloud). Surface is generated from these outermost points and volume within is calculated.

### Heat Map and Convex Volume

Custom Python code generated the heat maps that trace the XYZ position of every marker through space. The coordinates for each marker at every time step define and form a point cloud. Brighter colors in the resulting image indicate areas of greater marker density over time at a specific XYZ location in the volume. Three views (XY, XZ, and YZ) define the point cloud volume in all three dimensions. The outermost points of the cloud determine a surface. The convex volume is the volume within that surface. The software computes the convex volume of the resulting surface using the QuickHull method in Python, as depicted in Figure 5.

### Foot Placement Map

The foot placement map is a heat map of just the foot markers observed in the XZ plane for the duration of each procedure. The force plate positions appear on the foot placement map as adjacent rectangles.

### Activity-Dependent Volume

After manual segmentation of each procedure by activity, the Behavioral Observation Research Interactive Software (BORIS) (Ref. 4) generated a timeline plot of the subtasks of the procedures. Superimposed on this timeline are the cumulative operational volume, the intervals where reaching activities (i.e., not caregiving) occurred, and a plot of the subject's heart rate.

## Credibility Assessment and Reviews

The NASA Standard 7009A compliance analysis for this task appears in Appendix C.

# Results

## Operational Volumes

Subjects 07 and 08 were able to perform all of the procedures within the large and small restricted volumes without interferences, except for the intubation portion of the choking procedure while in the

smaller restricted volume. Interestingly, the volume used by the subjects was smaller for the restricted volumes than for the unrestricted, even though they did not experience interference with the restricting panels. Subject 08, the petite female, used relatively large volumes during some of the unrestricted volume trials, approximately twice the volume used by Subject 07, the tall male. When these volumes were not included, the operational volume used by the petite female was, on average, 83 percent of the volume used by the tall male. Subject 09 only performed procedures in the unrestricted volume. The volume used by Subject 09, the tall female, was typically less than that used by the tall male when the same procedures were performed by the three subjects. The operational volume used by the tall female was, on average, 91 percent of the volume used by the tall male.

Table II to Table IV list the rectangular cuboid volume and convex volume calculated for the subjects for each procedure. Figure 6 to Figure 10 illustrate this table for each subject in bar graph form. Illustrations of the estimated convex hull volumes appear in Figure 11 to Figure 17 for Subject 07 and in Figure 18 to Figure 24 for Subject 08, and in Figure 25 for the dual-caregiver trial. Convex hull volume illustrations for the 2019 testing appear in Figure 26 to Figure 30 for Subject 07, Figure 31 to Figure 35 for Subject 08 and Figure 36 to Figure 43 for Subject 09. The convex hull volume defines an envelope that fully encloses all of the subject's markers during the entire procedure. The convex hull volume represents the outline of the volume occupied by the person performing the task and is less than the conservative bounding rectangular cuboid volume. The maximum cuboid volume appears as a red box.

The AED procedure with drug administration (ADA) was performed by Subjects 07 and 08 together. They performed three trials, the difference being the starting location of the caregivers in relation to the manikin. During all three procedures, the caregivers moved to and ended in locations based on the care they needed to provide. For all three procedures, the ending position was with one subject on a long side and the other on the short side of the table where the manikin's head was located. The operational volume used during the dual-caregiver procedure was approximately twice the volume when a single caregiver performed the procedure, based on the trial where the starting and ending location of the caregivers was the same. The convex hull volume for the dual-caregiver trial appears in Figure 25.

Figure 44 depicts a perspective view of the marker-trace point cloud for Subject 07 at one instant of time during the ADA procedure. The markers appear connected to facilitate visualization. Note that the densest areas of point concentration occur in the position where the caregiver is performing chest compressions during CPR.

TABLE II.—SUBJECT 07 VOLUME SUMMARY—2018 TESTING

| Volume, $m^3$ | | AED[a] drug administration | AED pulse returns | Abdominal ultrasound | Choking patient becomes unconscious | Reach |
|---|---|---|---|---|---|---|
| Rectangular | Unrestricted | 4.1 | 2.7 | 3.4 | 7.5 | --- |
| | Large | 4.2 | 4.1 | 3.3 | 4.8 | --- |
| | Small | 3.2 | 3.1 | 2.4 | 3.2 | --- |
| | Restricted feet | 3.0 | 2.7 | 2.5 | 6.4 | 6.3 |
| Convex | Unrestricted | 2.1 | 1.4 | 1.7 | 6.3 | --- |
| | Large | 2.1 | 2.0 | 1.7 | 2.5 | --- |
| | Small | 1.7 | 1.6 | 1.3 | 1.6 | --- |
| | Restricted feet | 1.3 | 1.2 | 1.0 | 2.7 | --- |
| Crew Task Volume Database | | 10.5 | 10.5 | 9.8 | 8.7 | --- |

[a]Automated external defibrillator.

TABLE III.—SUBJECT 08 VOLUME SUMMARY—2018 TESTING

| Volume, $m^3$ | | AED[a] drug administration | AED pulse returns | Abdominal ultrasound | Choking patient becomes unconscious | Reach |
|---|---|---|---|---|---|---|
| Rectangular | Unrestricted | 10.6 | 5.5 | 2.9 | 10.9 | --- |
| | Large | 3.1 | 2.9 | 2.6 | 3.8 | --- |
| | Small | 3.1 | 2.8 | 1.9 | 2.7 | --- |
| | Restricted feet | 2.9 | 2.8 | 2.3 | 4.3 | 3.4 |
| Convex | Unrestricted | 5.7 | 2.6 | 1.2 | 5.9 | --- |
| | Large | 1.5 | 1.4 | 1.1 | 1.9 | --- |
| | Small | 2.0 | 1.4 | 1.0 | 1.2 | --- |
| | Restricted feet | 1.3 | 1.1 | 0.7 | 1.8 | --- |
| Crew Task Volume Database | | 10.5 | 10.5 | 9.8 | 8.7 | --- |

[a]Automated external defibrillator

TABLE IV.—SUBJECT 07 VOLUME SUMMARY—2019 TESTING

| Volume, $m^3$ | | | Intravenous fluid preparation and administration | Visual acuity exam | Optical coherence tomography (OCT) exam |
|---|---|---|---|---|---|
| Caregiver and patient | Rectangular | Unrestricted | --- | --- | 4.8 |
| | | Restricted feet | --- | 3.4 | 2.5 |
| | Convex | Unrestricted | --- | --- | 2.5 |
| | | Restricted feet | --- | 1.3 | 1.2 |
| Caregiver | Rectangular | Unrestricted | 3.9 | --- | 3.7 |
| | | Restricted feet | 2.3 | 1.5 | 1.6 |
| | Convex | Unrestricted | 2.3 | --- | 2.0 |
| | | Restricted feet | 1.1 | 0.6 | 0.8 |
| Patient | Rectangular | Unrestricted | --- | --- | 0.4 |
| | | Restricted feet | --- | 0.6 | 0.3 |
| | Convex | Unrestricted | --- | --- | 0.2 |
| | | Restricted feet | --- | 0.2 | 0.2 |

TABLE V.—SUBJECT 08 VOLUME SUMMARY—2019 TESTING

| Volume, $m^3$ | | | Intravenous fluid preparation and administration | Visual acuity exam | Optical coherence tomography (OCT) exam |
|---|---|---|---|---|---|
| Caregiver and patient | Rectangular | Unrestricted | --- | --- | 1.7 |
| | | Restricted feet | --- | 2.3 | 1.6 |
| | Convex | Unrestricted | --- | --- | 0.9 |
| | | Restricted feet | --- | 0.9 | 0.9 |
| Caregiver | Rectangular | Unrestricted | 3.9 | --- | 1.0 |
| | | Restricted feet | 2.8 | 1.3 | 0.9 |
| | Convex | Unrestricted | 1.6 | --- | 0.5 |
| | | Restricted feet | 1.0 | 0.5 | 0.4 |
| Patient | Rectangular | Unrestricted | --- | --- | 0.4 |
| | | Restricted feet | --- | 0.7 | 0.4 |
| | Convex | Unrestricted | --- | --- | 0.2 |
| | | Restricted feet | --- | 0.3 | 0.2 |

TABLE VI.—SUBJECT 09 VOLUME SUMMARY—2019 TESTING

| Volume, $m^3$ | | | Intravenous fluid preparation and administration | Visual acuity exam | Optical coherence tomography (OCT) exam | AED[a] drug administration |
|---|---|---|---|---|---|---|
| Caregiver and patient | Rectangular | Unrestricted | --- | --- | 3.7 | --- |
| | | Restricted feet | --- | 2.7 | 2.5 | --- |
| | Convex | Unrestricted | --- | --- | 2.1 | --- |
| | | Restricted feet | --- | 1.2 | 1.2 | --- |
| Caregiver | Rectangular | Unrestricted | 2.0 | --- | 2.8 | 3.9 |
| | | Restricted feet | 2.1 | 1.9 | 1.5 | 2.6 |
| | | Vertical | --- | --- | --- | 3.1 |
| | Convex | Unrestricted | 0.8 | --- | 1.4 | 1.6 |
| | | Restricted feet | 0.8 | 0.7 | 0.6 | 1.2 |
| | | Vertical | --- | --- | --- | 1.8 |
| Patient | Rectangular | Unrestricted | --- | --- | 0.6 | --- |
| | | Restricted feet | --- | 0.8 | 0.4 | --- |
| | Convex | Unrestricted | --- | --- | 0.3 | --- |
| | | Restricted feet | --- | 0.3 | 0.2 | --- |

[a]Automated external defibrillator

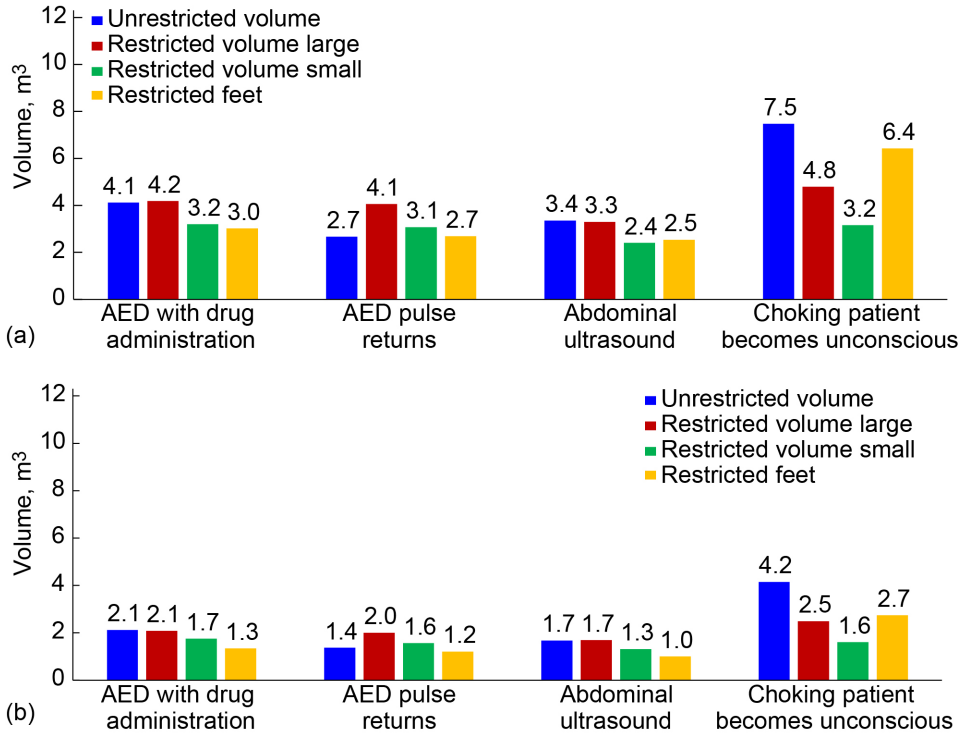


Figure 6.—Summary of volumes for all procedures performed by Subject 07 in 2018 testing. Automated external defibrillator, AED. (a) Rectangular volume. (b) Convex volume.

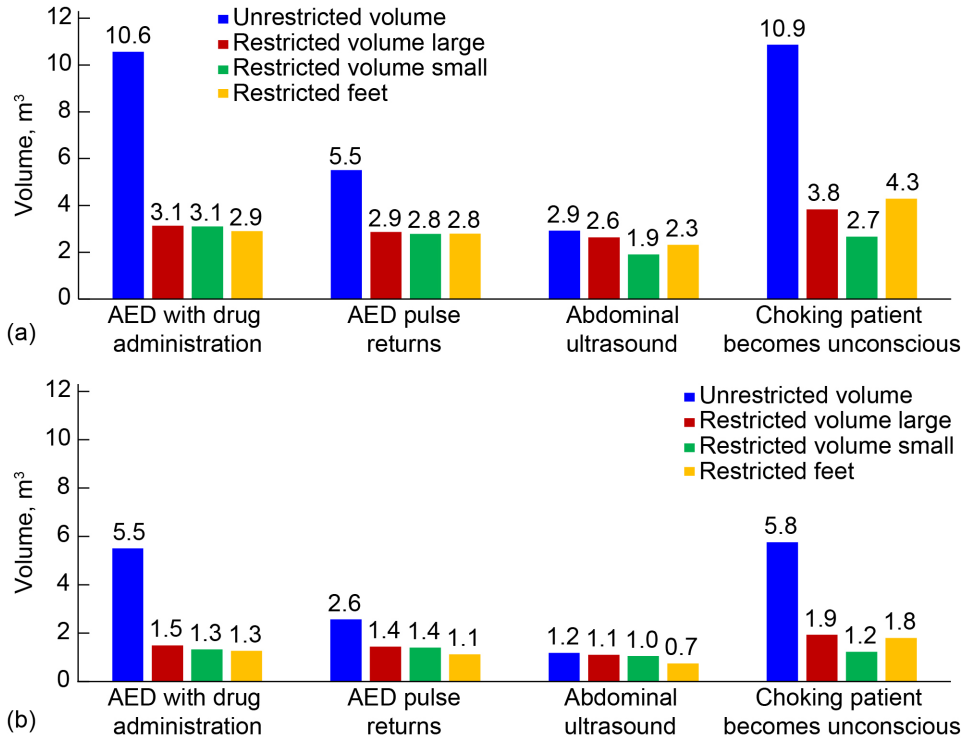


Figure 7.—Summary of volumes for all procedures performed by Subject 08 in 2018 testing. Automated external defibrillator, AED. (a) Rectangular volume. (b) Convex volume.

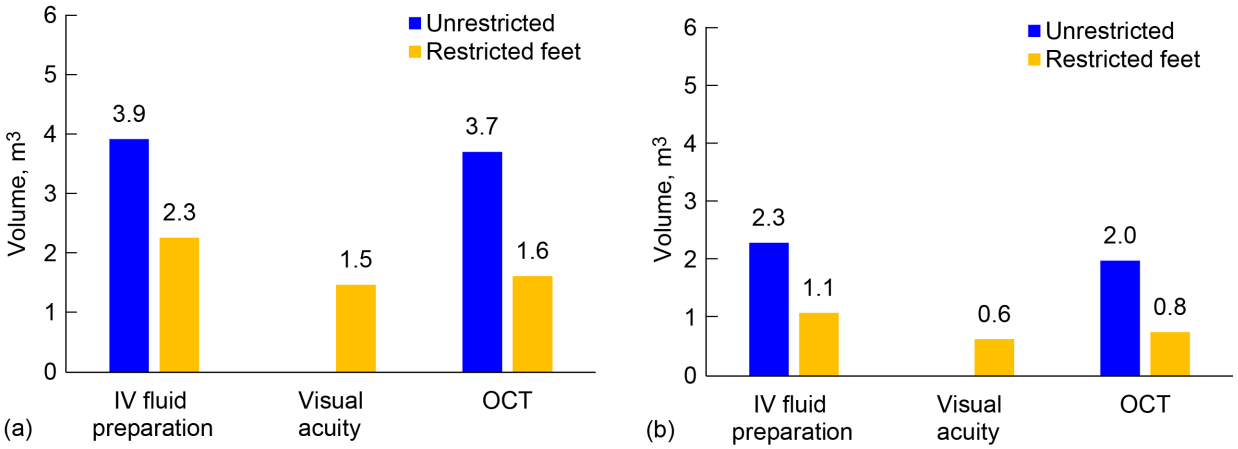


Figure 8.—Summary of volumes for all procedures performed by Subject 07 in 2019 testing. Intravenous, IV. Optical coherence tomography, OCT. (a) Rectangular volume. (b) Convex volume.

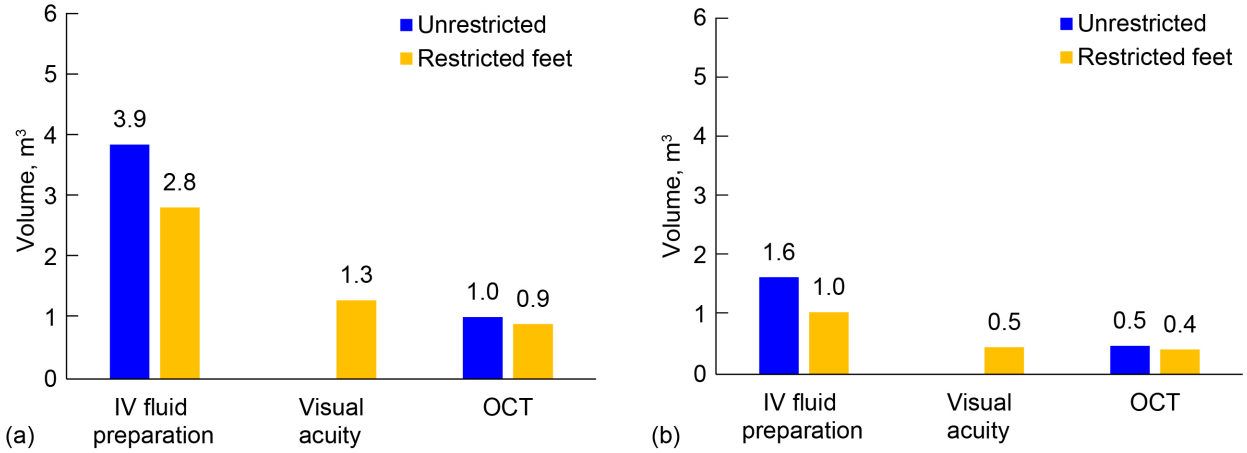


Figure 9.—Summary of volumes for all procedures performed by Subject 08 in 2019 testing. Intravenous, IV. Optical coherence tomography, OCT. (a) Rectangular volume. (b) Convex volume.

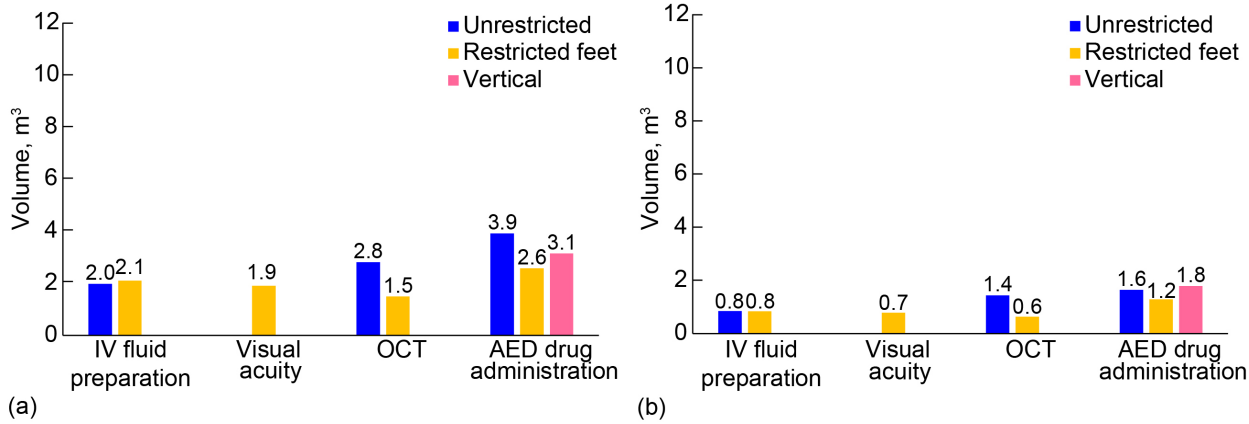


Figure 10.—Summary of volumes for all procedures performed by Subject 09 in 2019 testing. Intravenous, IV. Optical coherence tomography, OCT. Automated external defibrillator, AED. (a) Rectangular volume. (b) Convex volume.

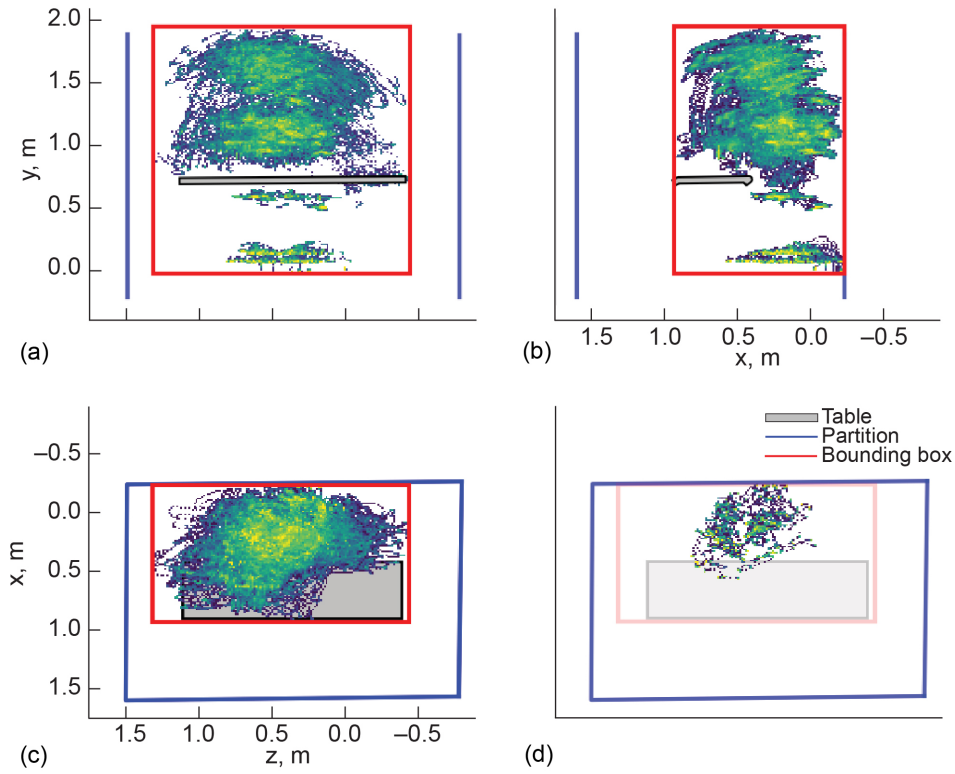


Figure 11.—Subject 07, large restricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

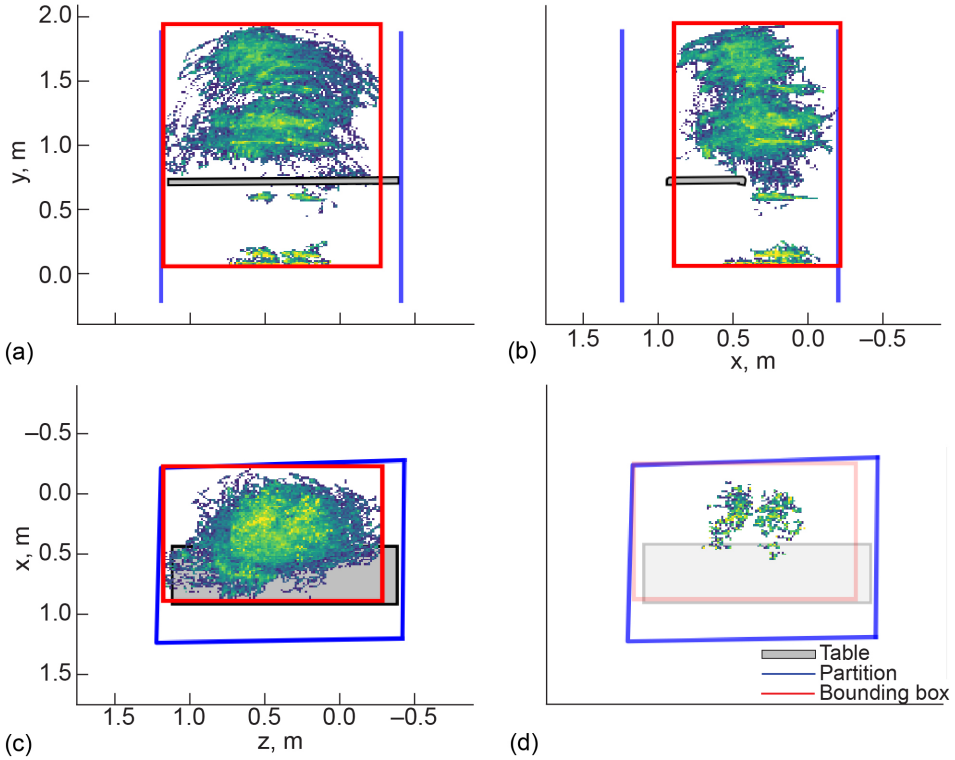


Figure 12.—Subject 07, small restricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

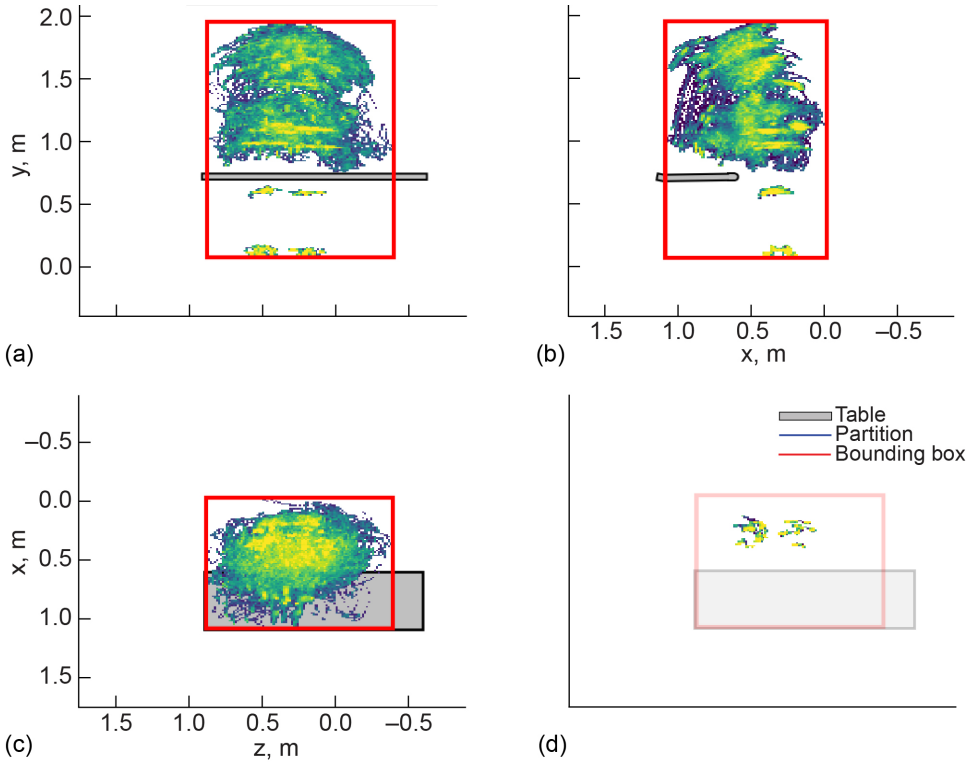


Figure 13.—Subject 07, restricted feet, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

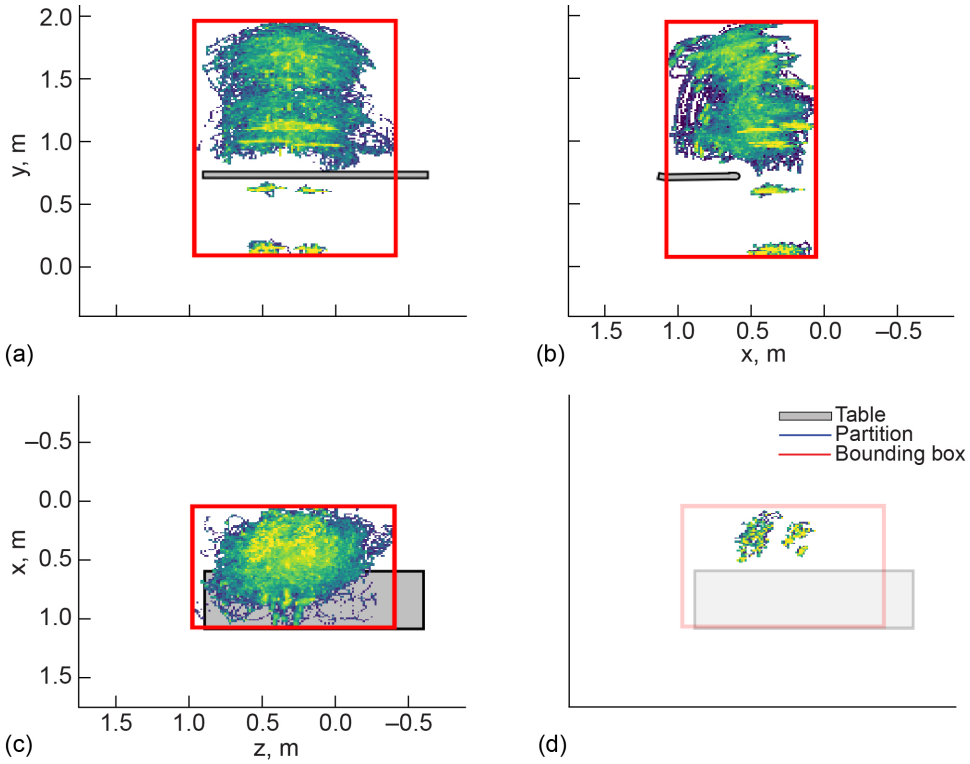


Figure 14.—Subject 07, unrestricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

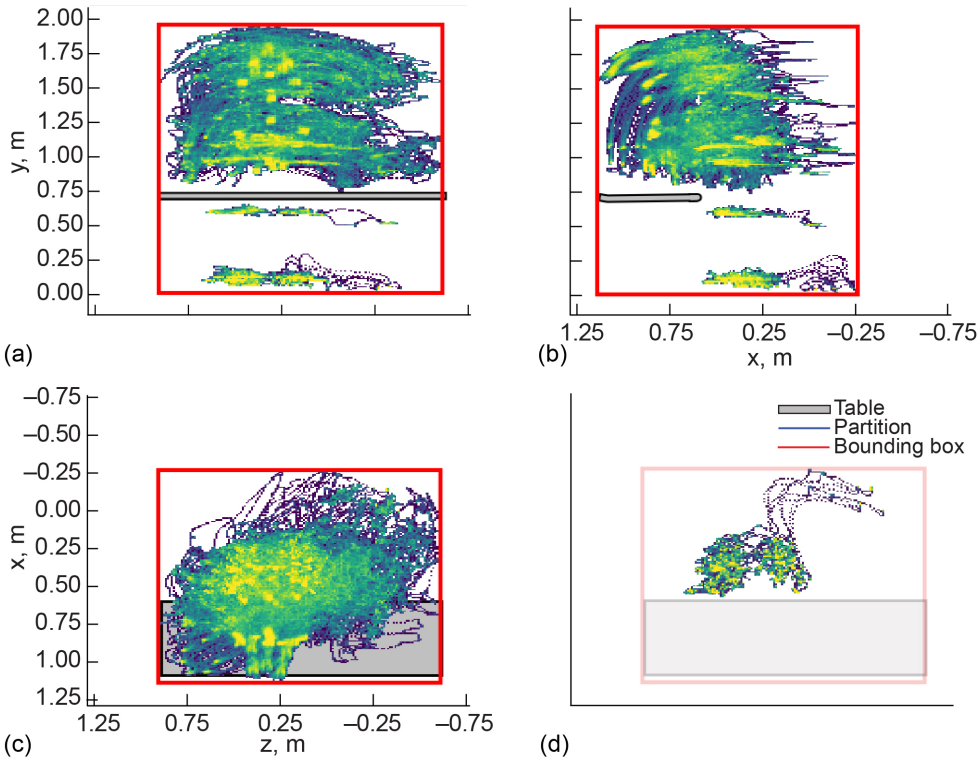


Figure 15.—Subject 07, unrestricted volume, automated external defibrillator (AED) with drug administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

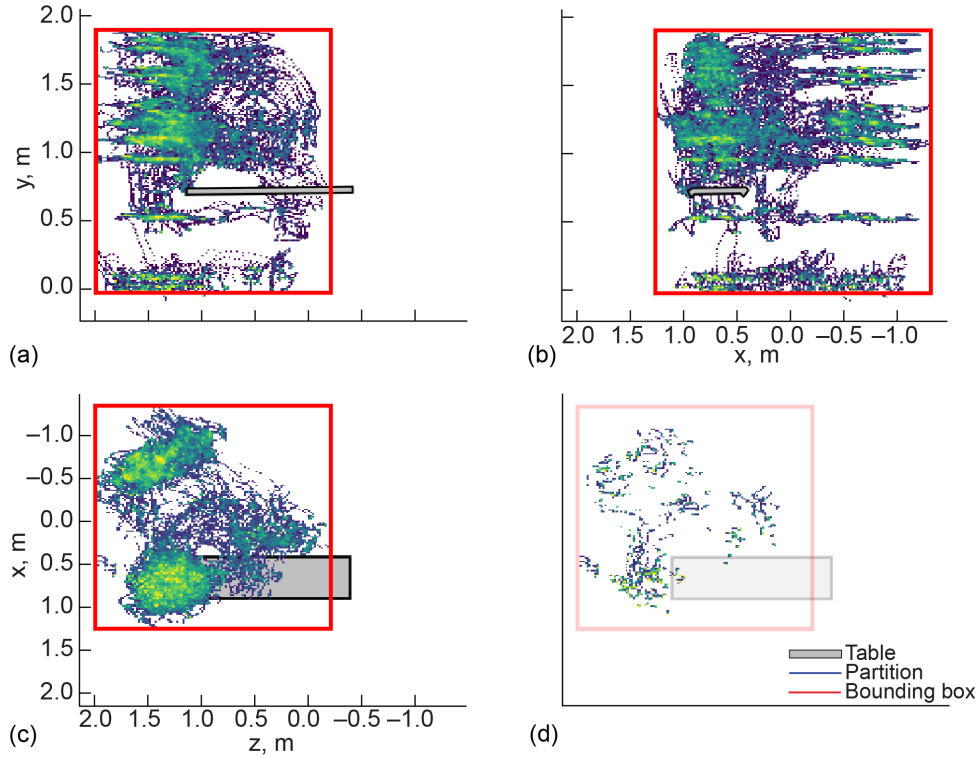


Figure 16.—Subject 07, unrestricted volume, choking patient becomes unconscious procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

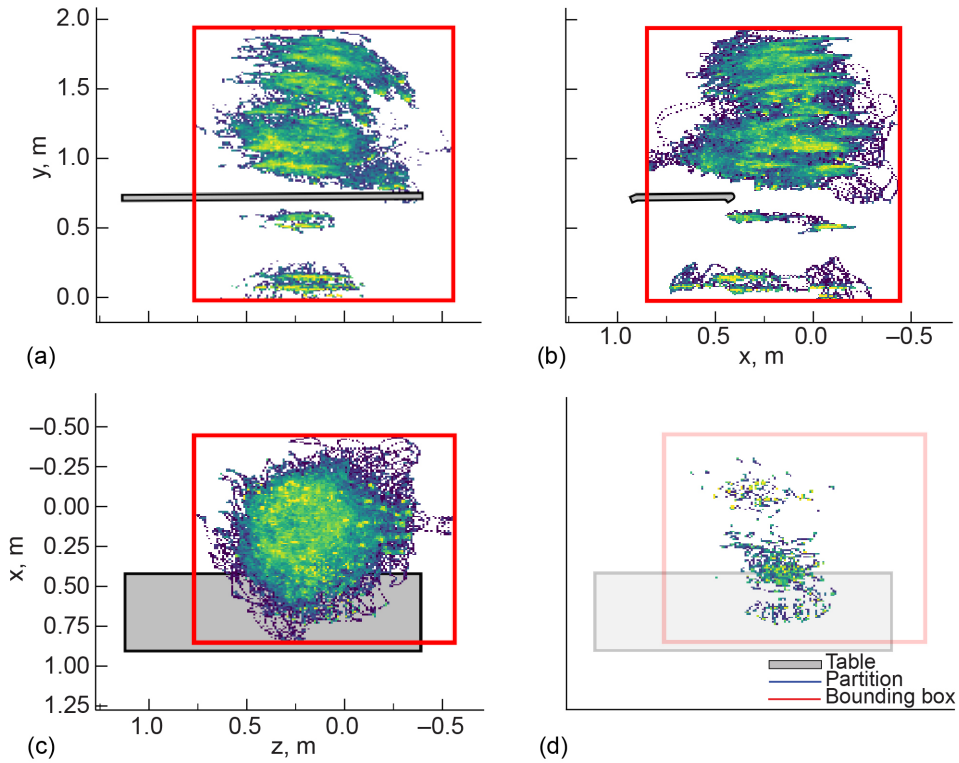


Figure 17.—Subject 07, unrestricted volume, abdominal ultrasound procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

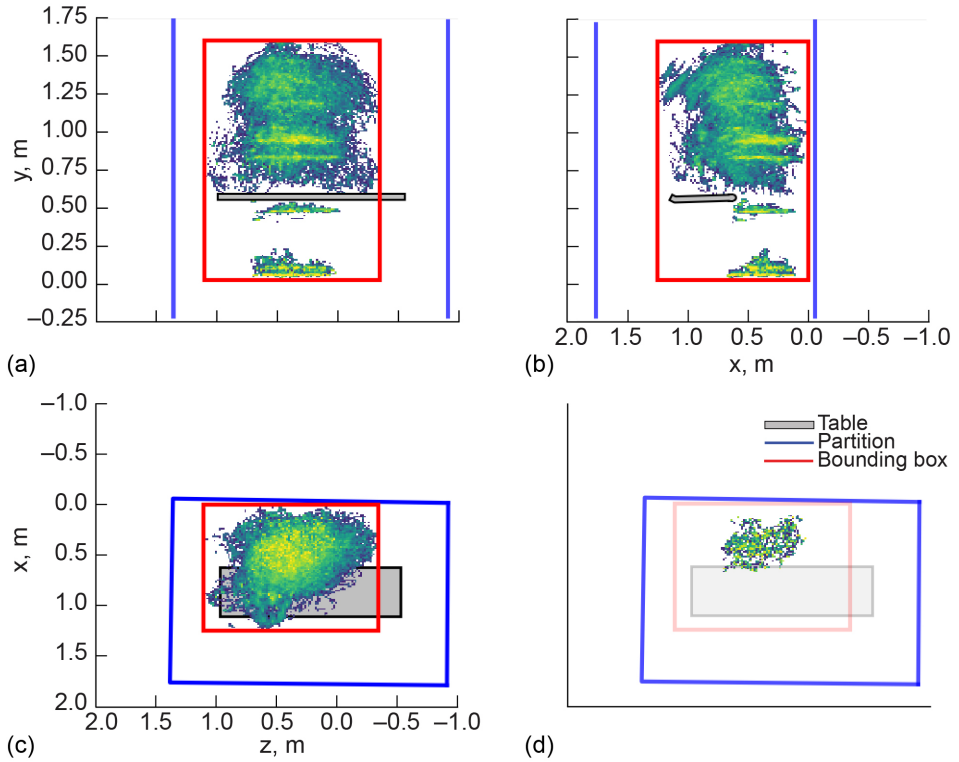


Figure 18.—Subject 08, large restricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

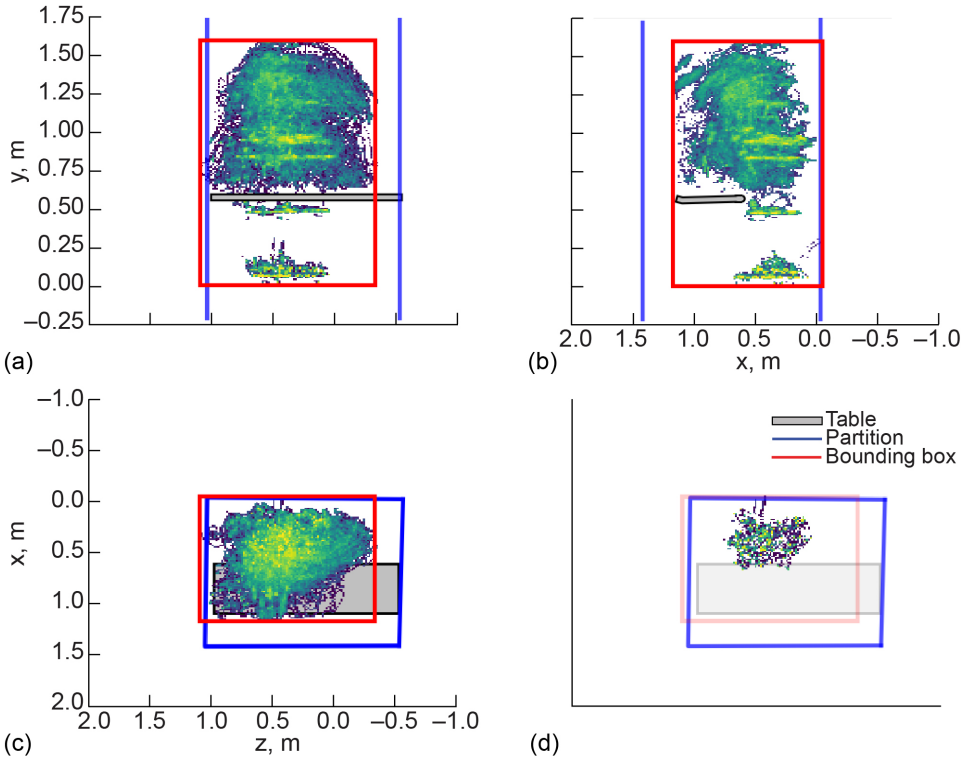


Figure 19.—Subject 08, small restricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

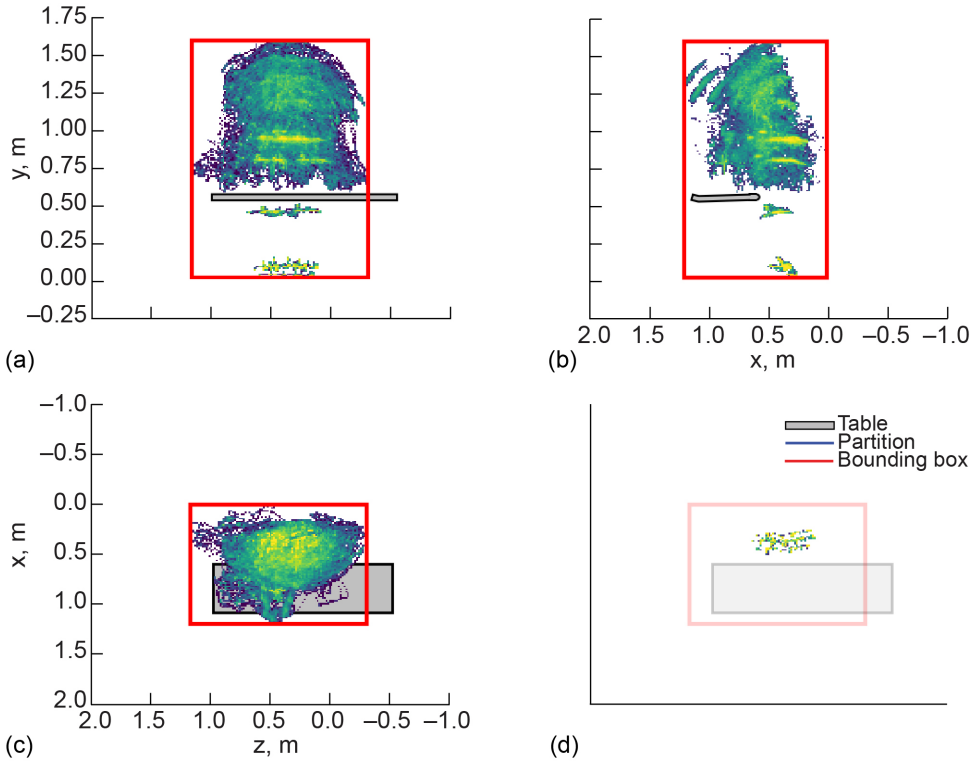


Figure 20.—Subject 08, restricted feet, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

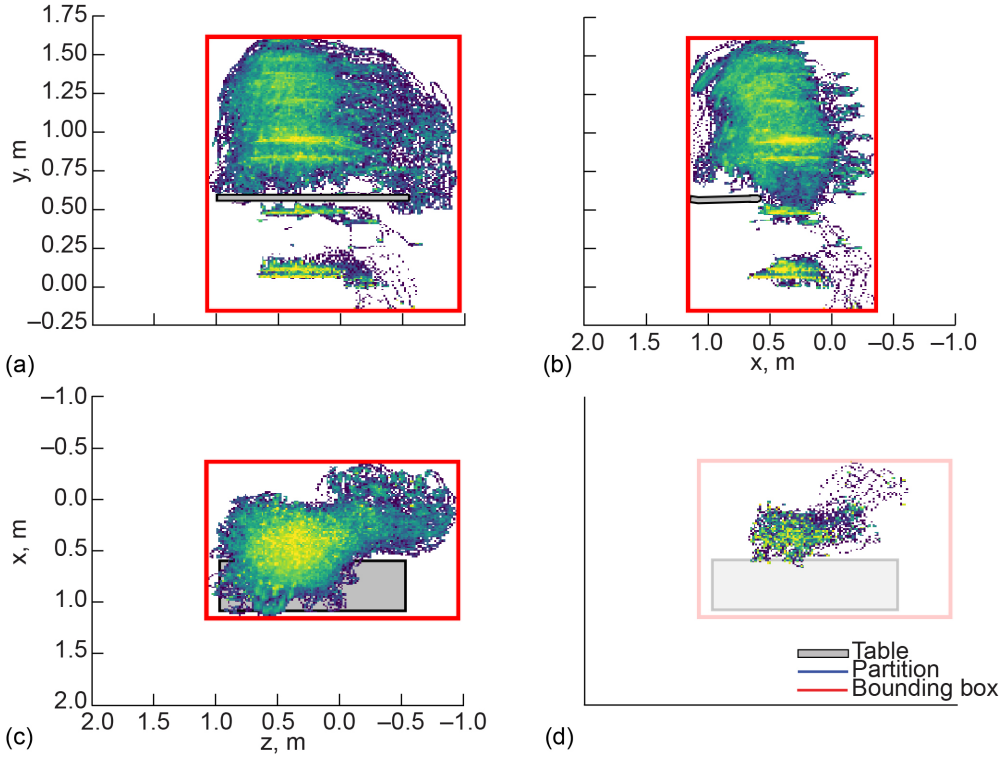


Figure 21.—Subject 08, unrestricted volume, automated external defibrillator (AED) pulse returns procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

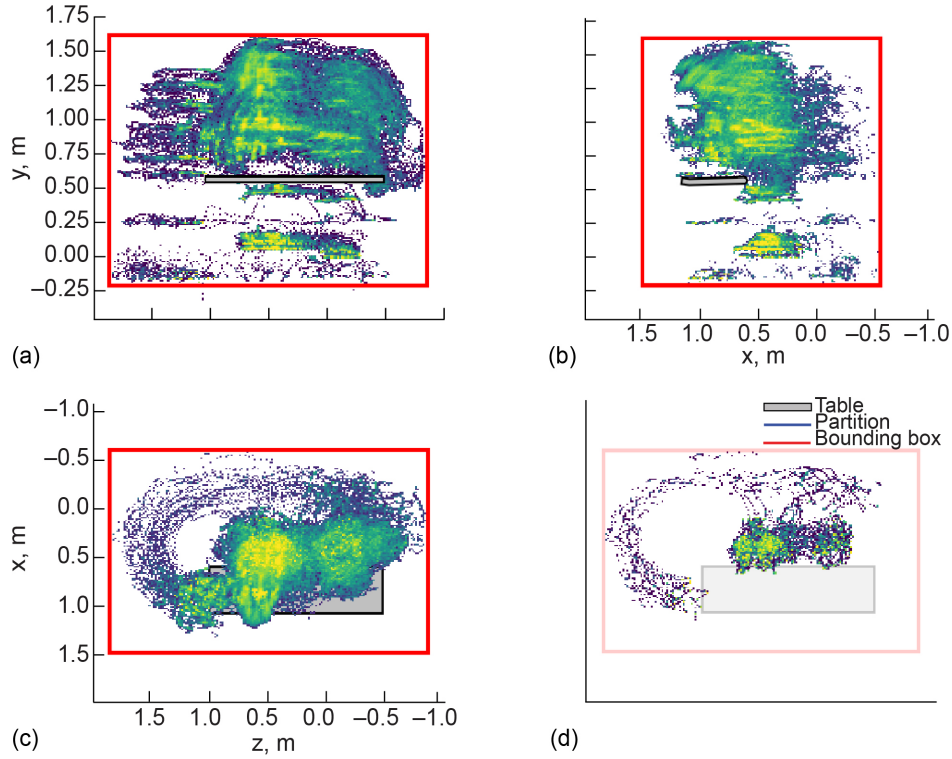


Figure 22.—Subject 08, unrestricted volume, automated external defibrillator (AED) with drug administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

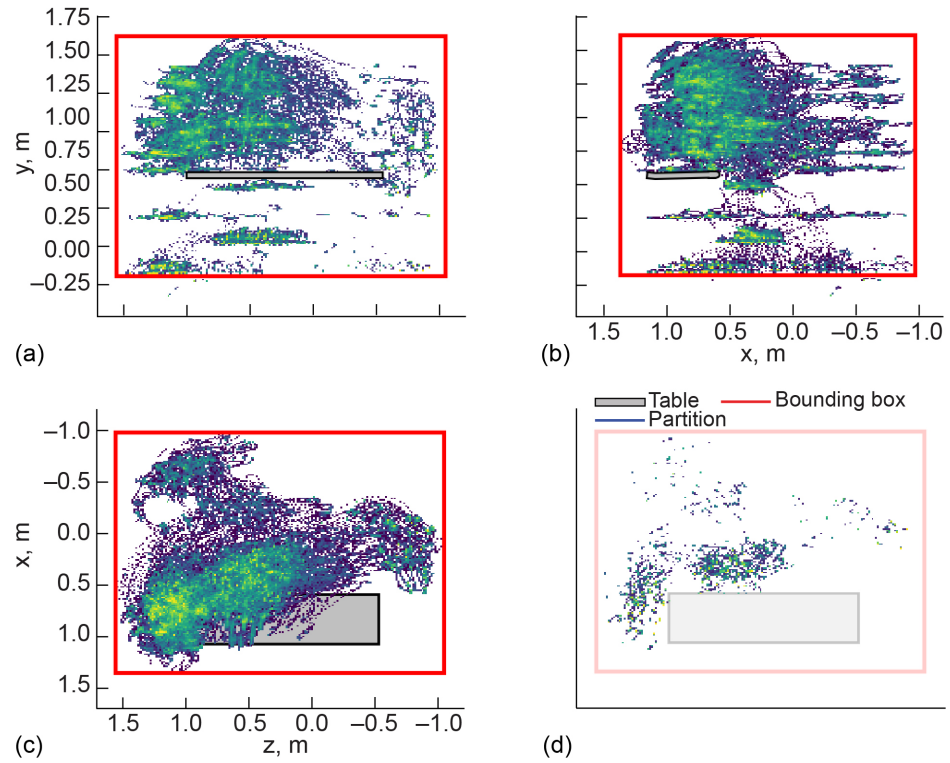


Figure 23.—Subject 08, unrestricted volume, choking patient becomes unconscious procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

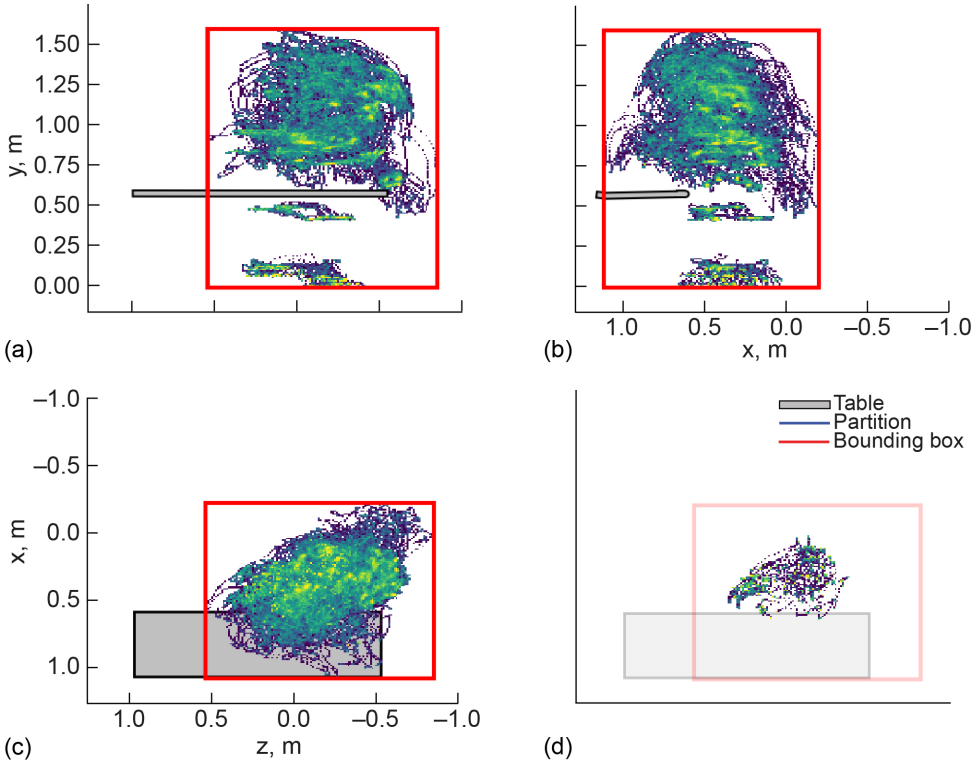


Figure 24.—Subject 08, unrestricted volume, abdominal ultrasound procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only

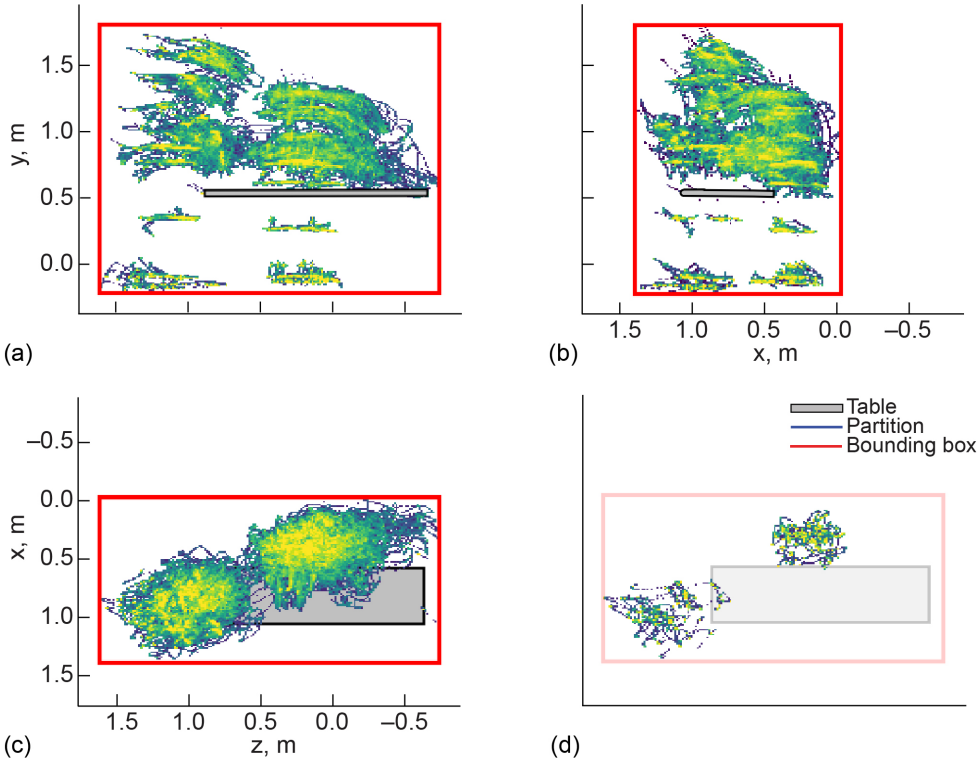


Figure 25.—Dual caregiver, unrestricted volume, automated external defibrillator (AED) with drug administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

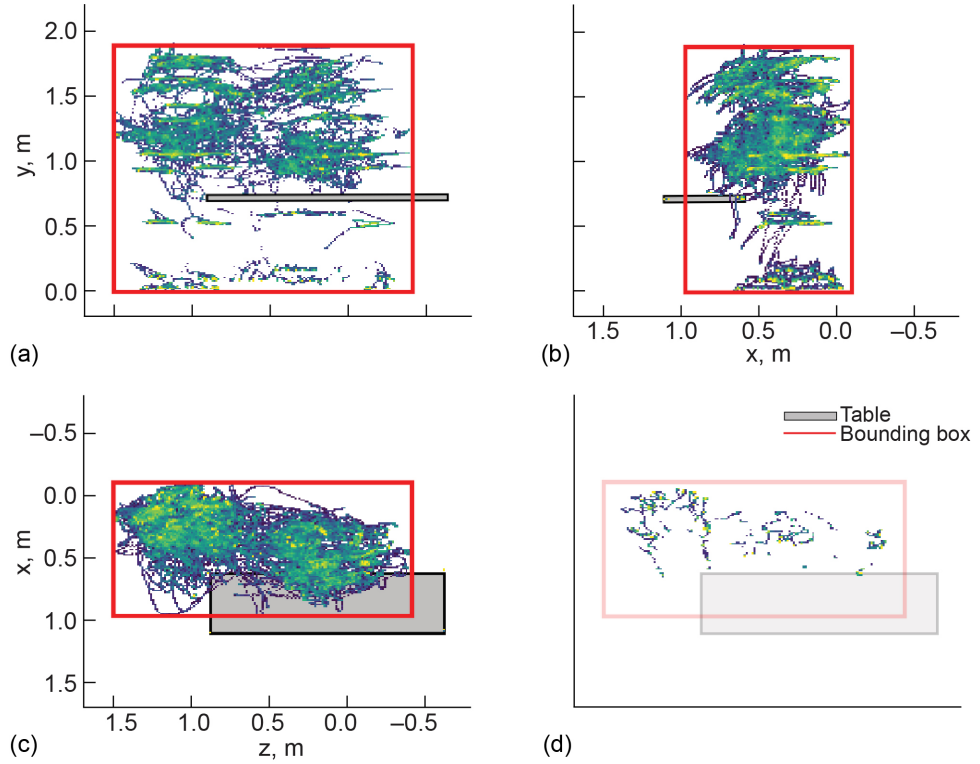


Figure 26.—Subject 07, unrestricted volume, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

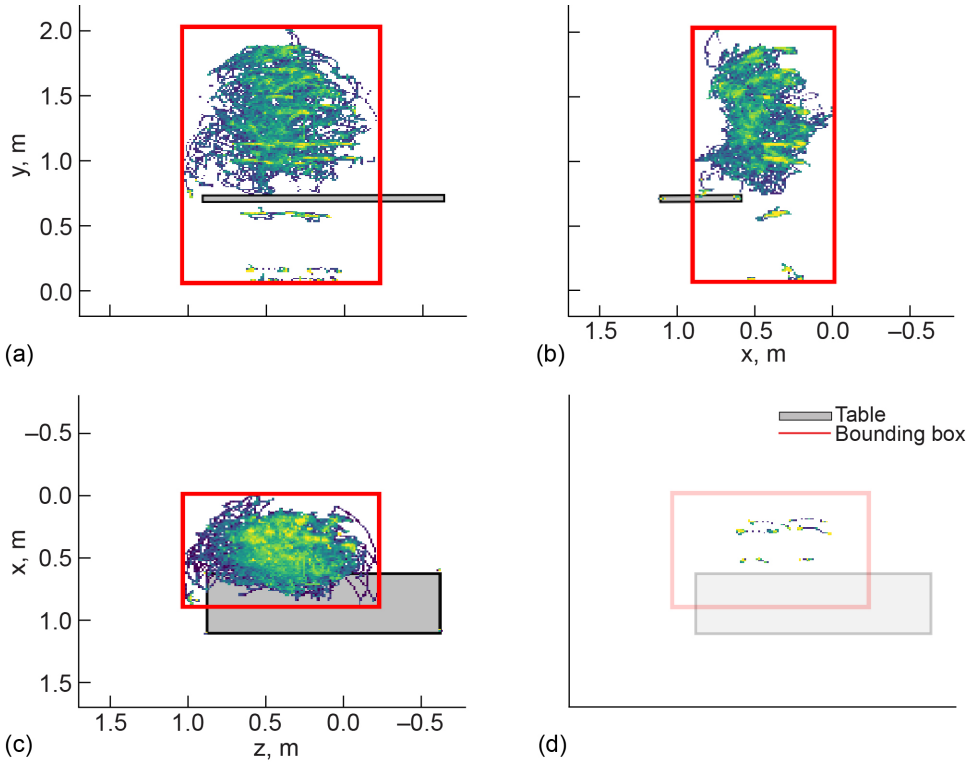


Figure 27.—Subject 07, restricted feet, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

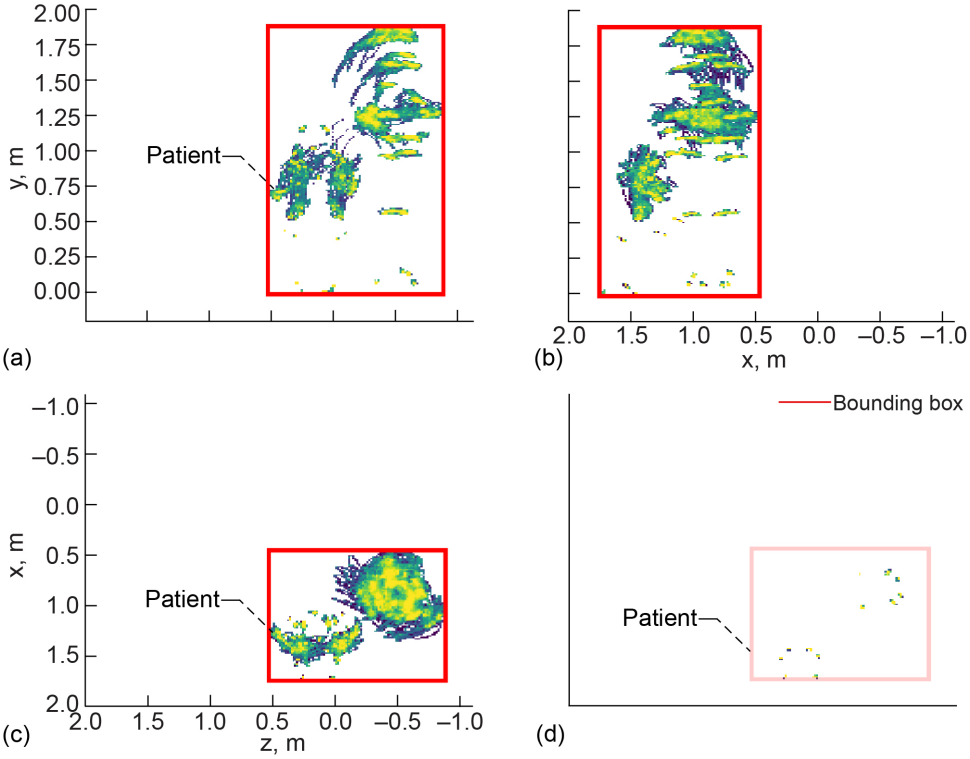


Figure 28.—Subject 07, restricted feet, visual acuity procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

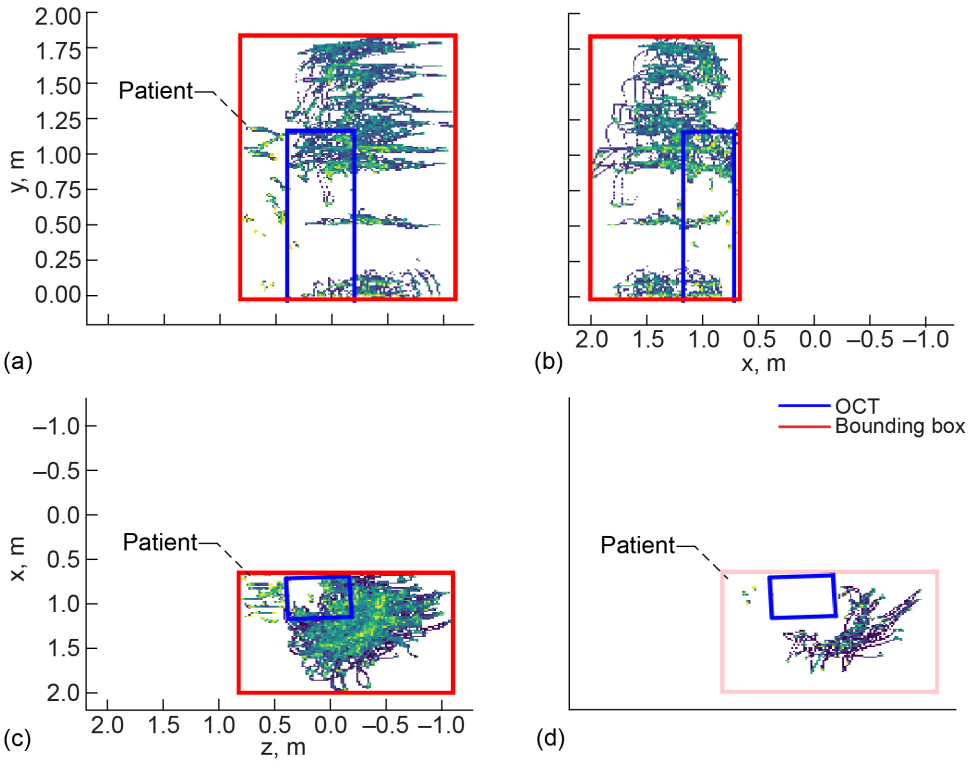


Figure 29.—Subject 07, unrestricted volume, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

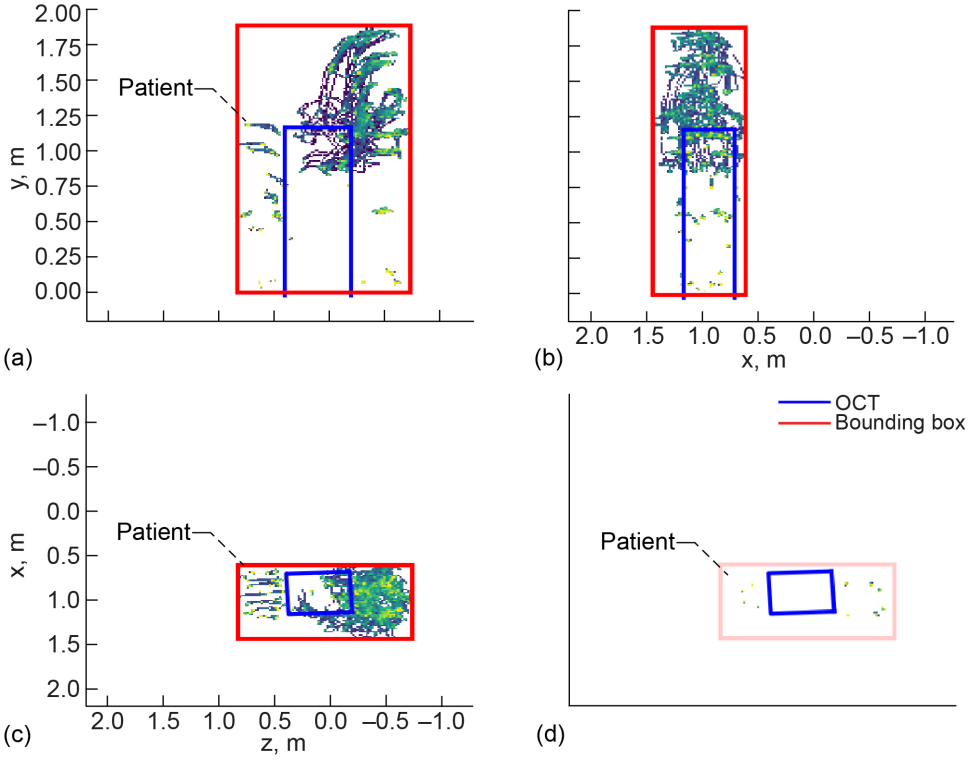


Figure 30.—Subject 07, restricted feet, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

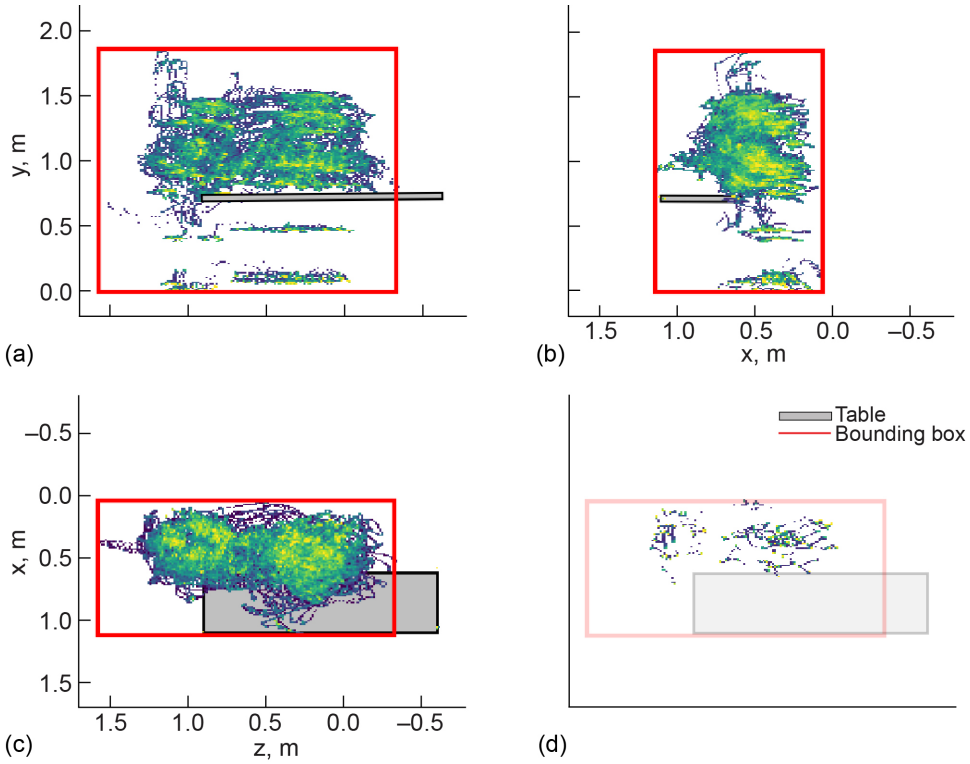


Figure 31.—Subject 08, unrestricted volume, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

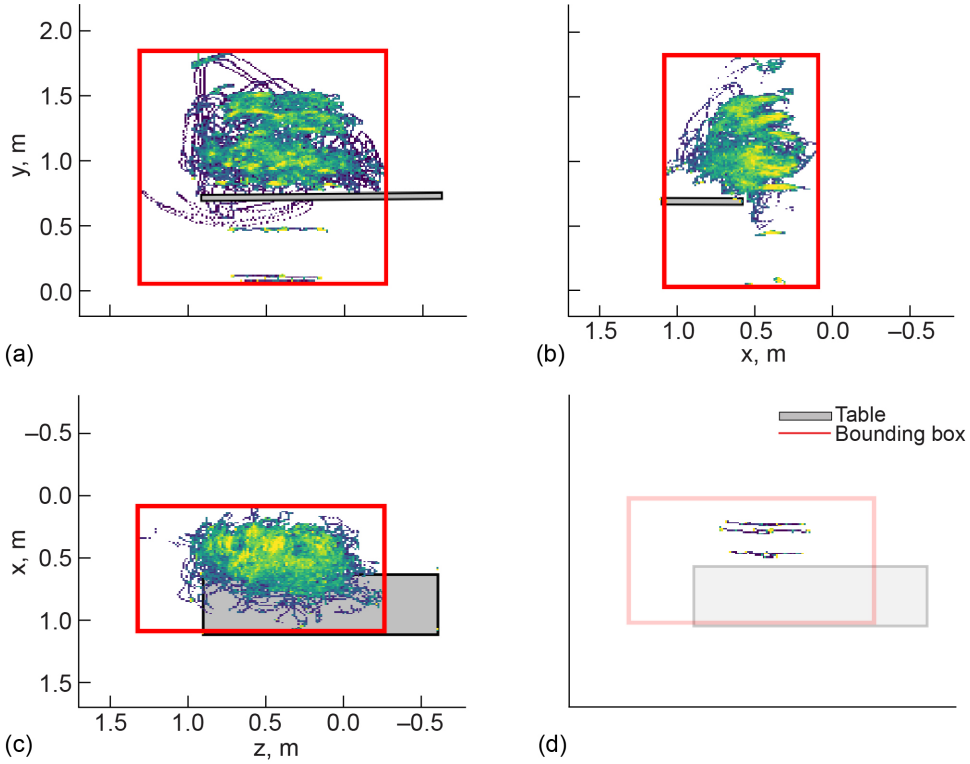


Figure 32.—Subject 08, restricted feet, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

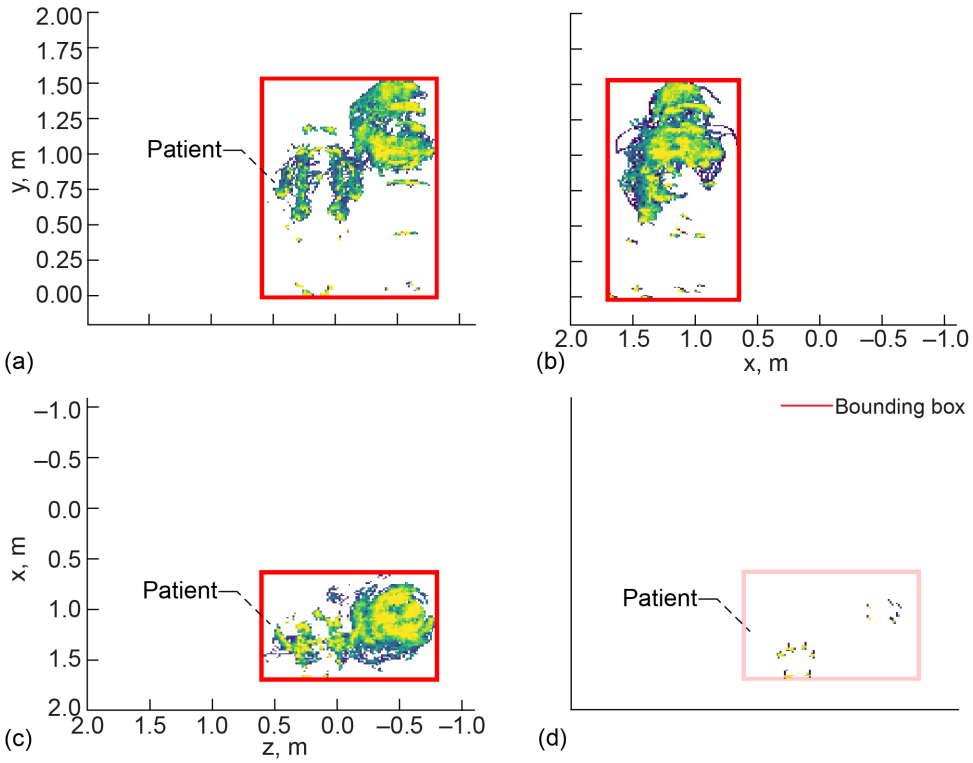


Figure 33.—Subject 08, restricted feet, visual acuity procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

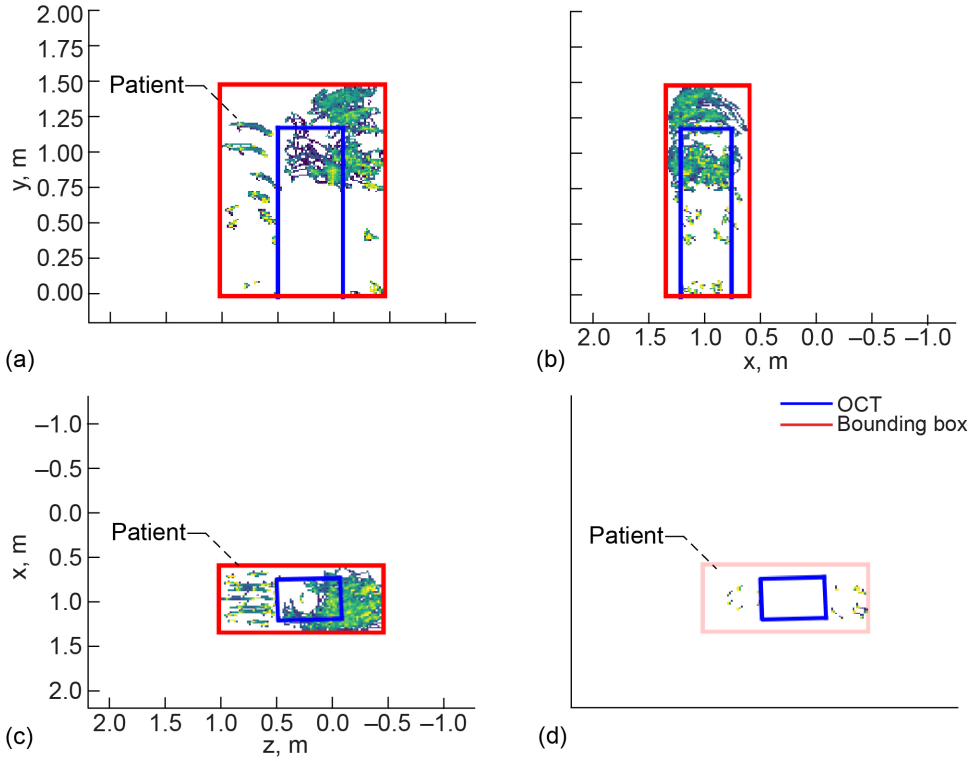


Figure 34.—Subject 08, unrestricted volume, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

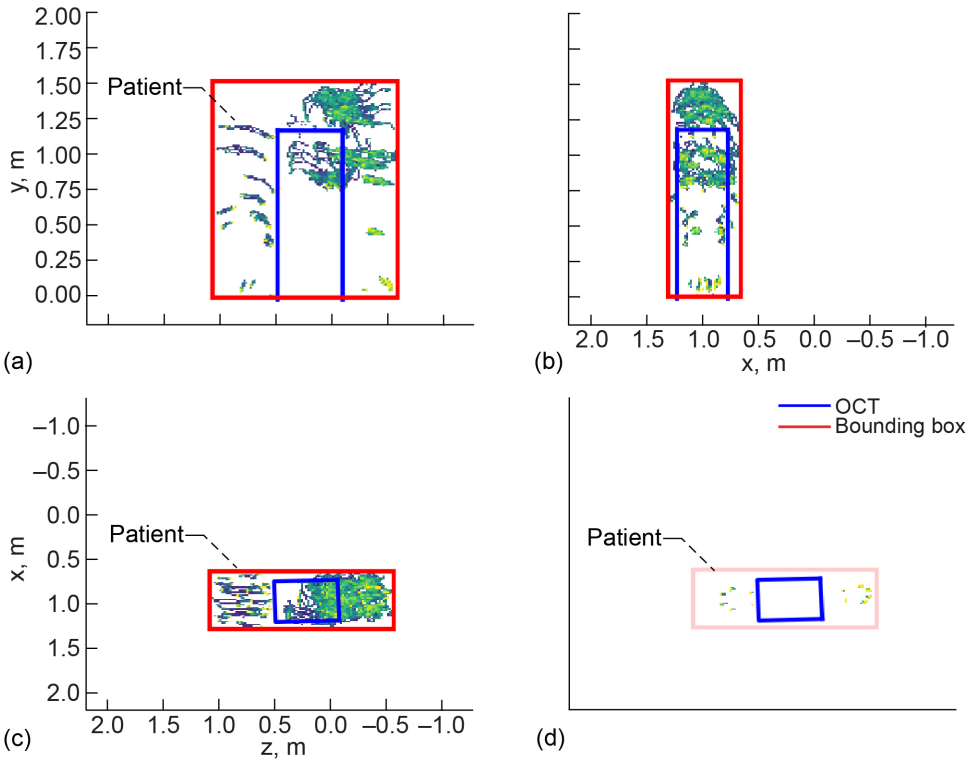


Figure 35.—Subject 08, restricted feet, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

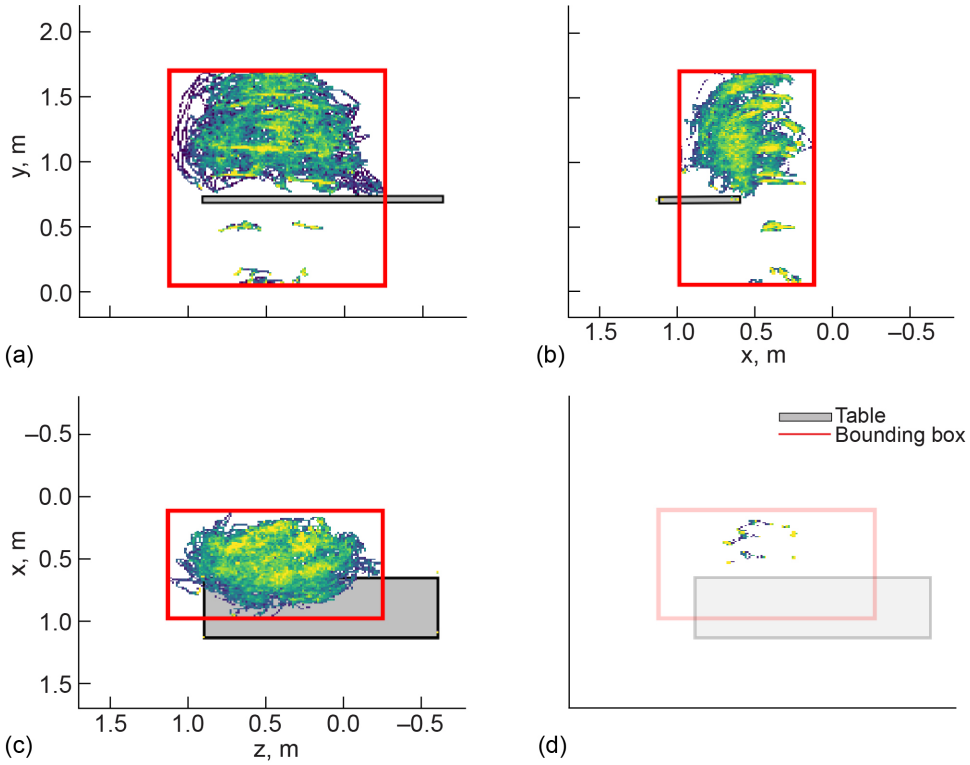


Figure 36.—Subject 09, unrestricted volume, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

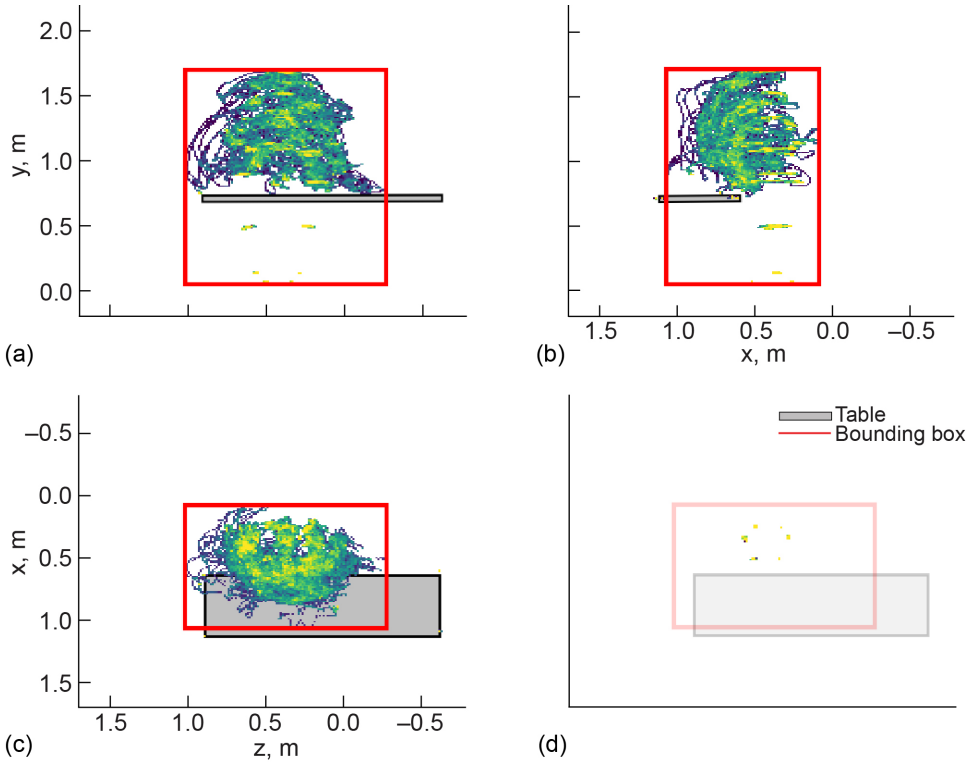


Figure 37.—Subject 09, restricted feet, intravenous fluid preparation and administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

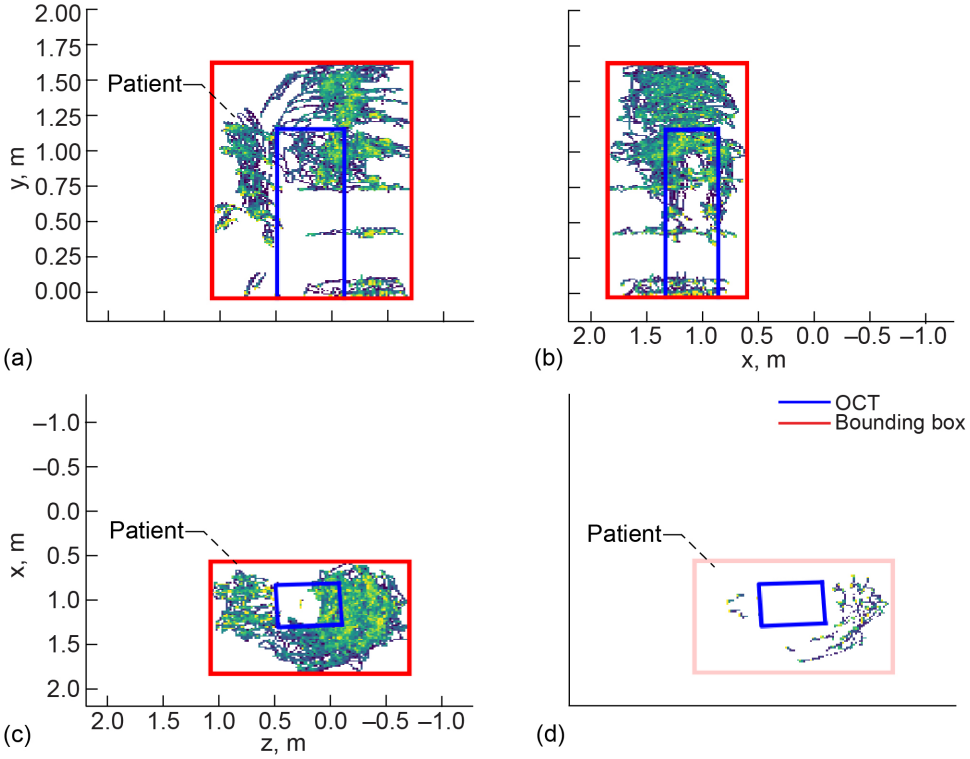


Figure 38.—Subject 09, restricted feet, visual acuity procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

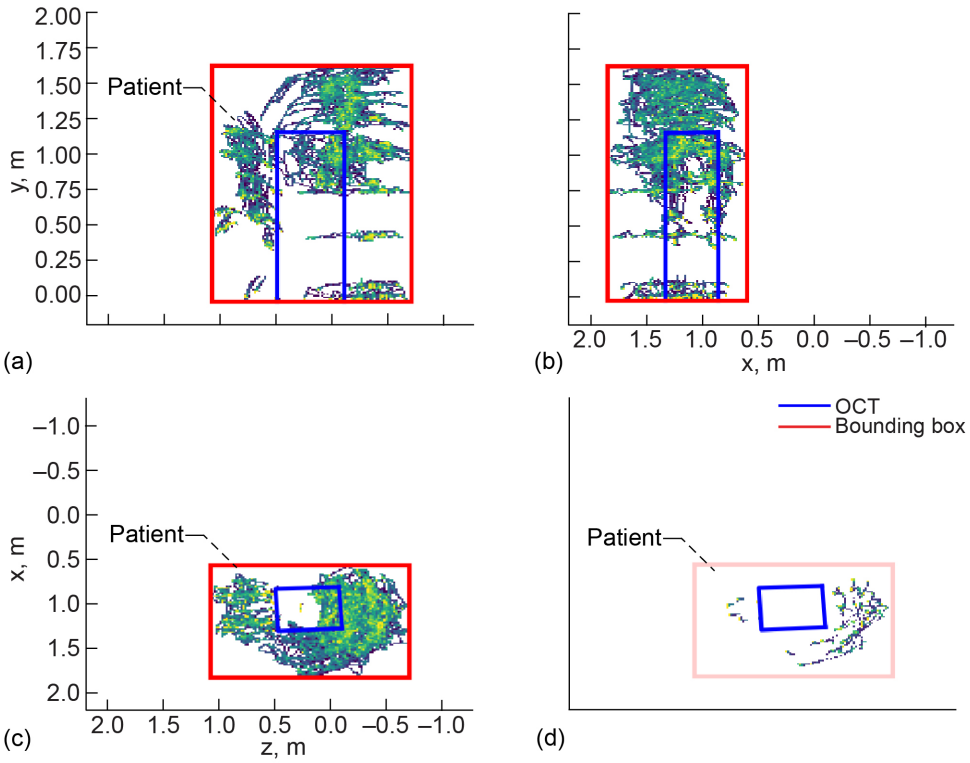


Figure 39.—Subject 09, unrestricted volume, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

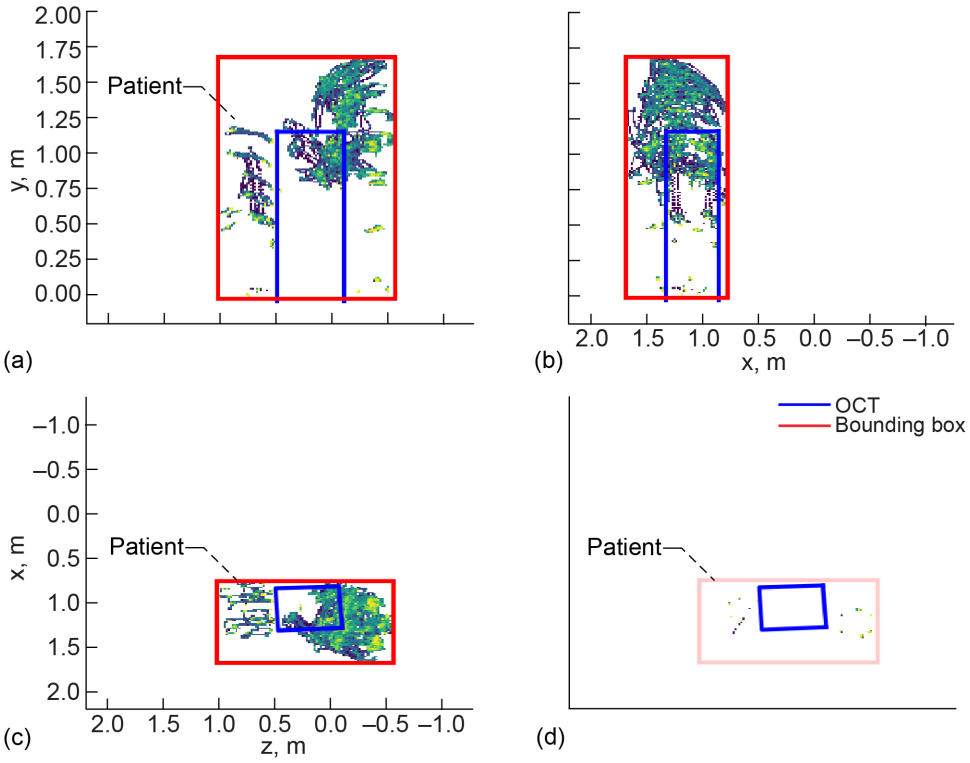


Figure 40.—Subject 09, restricted feet, optical coherence tomography (OCT) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

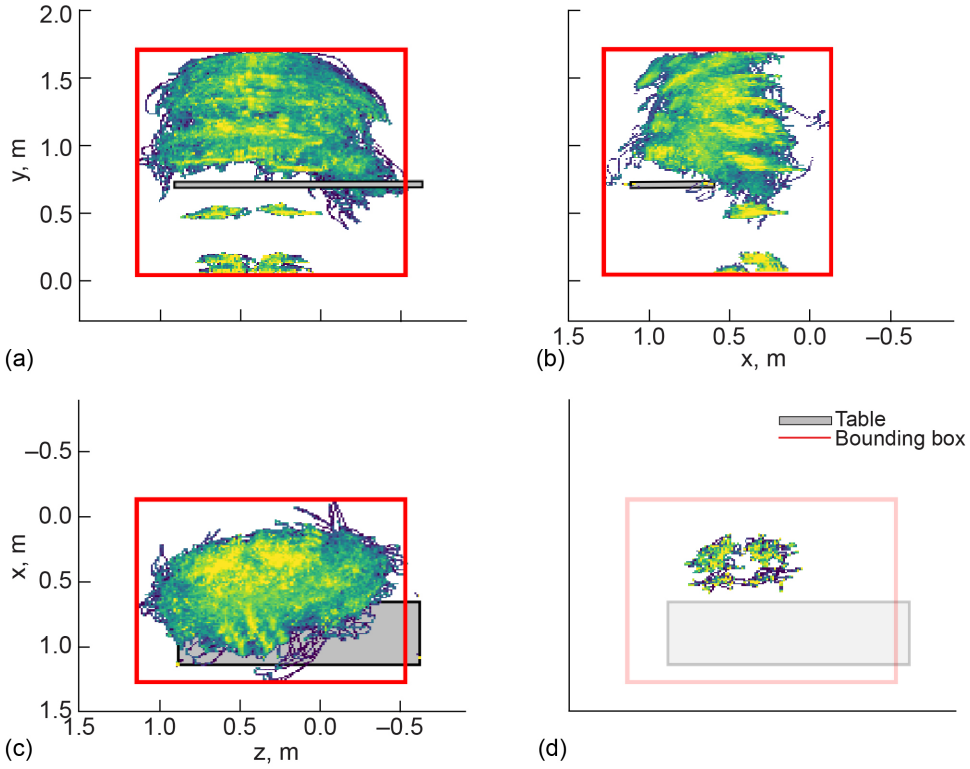


Figure 41.—Subject 09, unrestricted volume, automated external defibrillator (AED) with drug administration (ADA) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

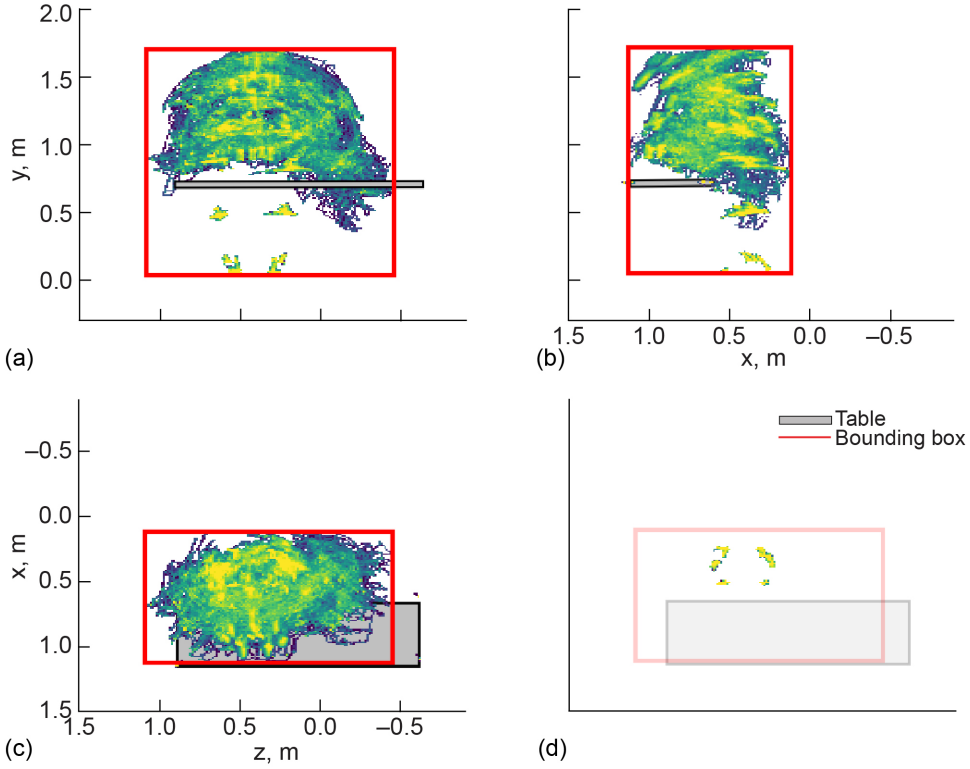


Figure 42.—Subject 09, restricted feet, automated external defibrillator (AED) with drug administration (ADA) procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

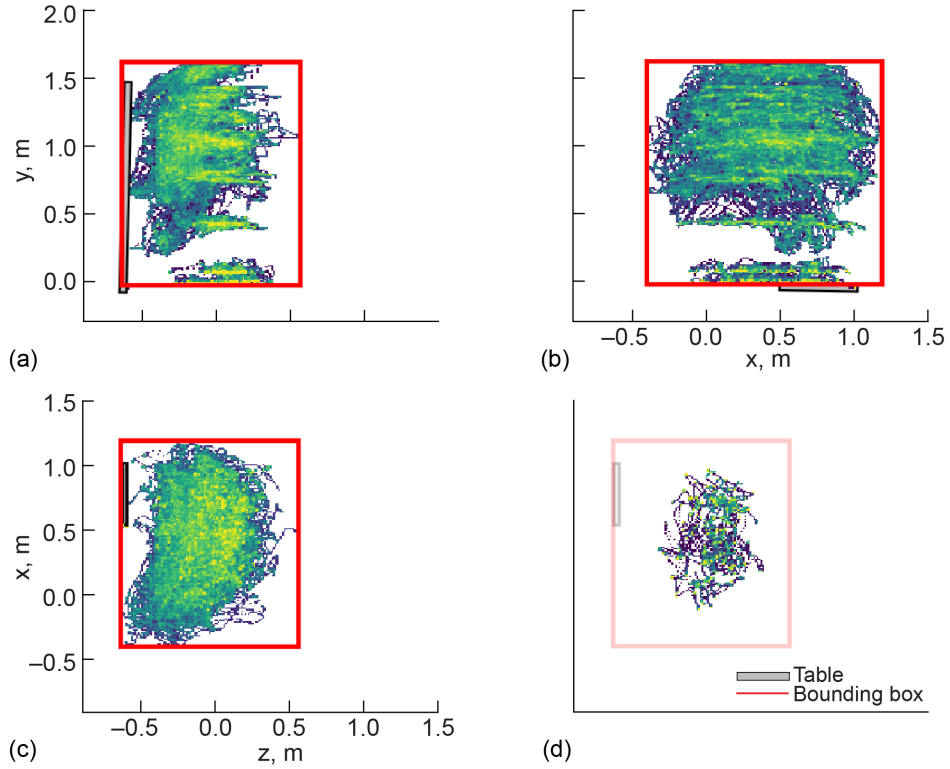


Figure 43.—Subject 09, patient vertical, automated external defibrillator (AED) with drug administration procedure. (a) Front. (b) Side. (c) Top. (d) Top, feet only.

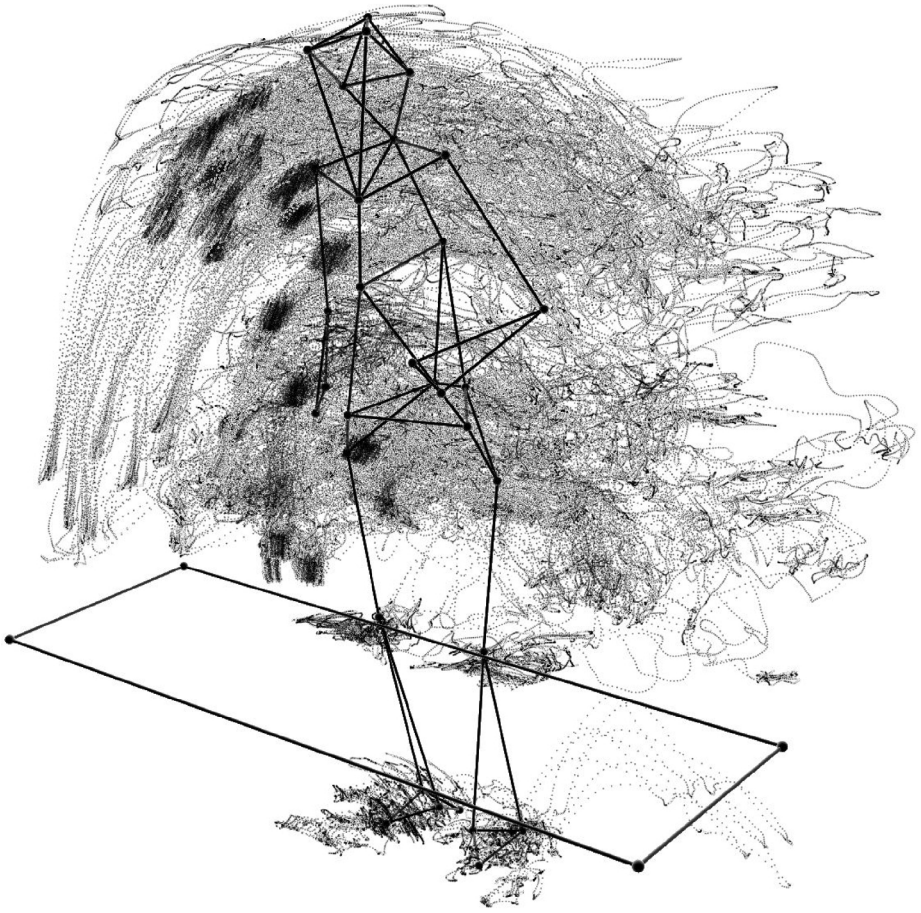

Figure 44.—Marker trace for Subject 07, unrestricted volume, automated external defibrillator (AED) with drug administration procedure.

## Foot Placement

The subjects successfully performed all procedures with their feet restricted. The limiting factor with the feet in the foot restraints was the extent to which caregivers had to reach for equipment and supplies, which were all within reach for these procedures. If the subjects had to reach for equipment in cabinets or drawers located in and around the workstation, they would potentially have to leave the foot restraints to retrieve the items. The maximum extent of the reach volume was 6.3 $m^3$ (221 $ft^3$) for Subject 07 and 3.4 $m^3$ (120 $ft^3$) for Subject 08. Figure 45 compares the reach volume with the restricted foot rectangular cuboid volume for the four procedures.

## Time Required to Perform Procedures and Resources Used

BORIS event plots of the various procedures appear in Figure 46 to Figure 52 for the 2018 testing and Figure 53 to Figure 70 for the 2019 testing. The plots denote when subprocedures occurred and when subjects provided care versus when subjects reached for items. The event plots also include the heart rate data plotted for the trial for Subjects 07 and 08 for 2018 testing only. Subject 07 had a relatively steady heart rate throughout the procedures, with an overall average of 67 bpm and standard deviation between 2.2 and 4.5, depending on the trial. Subject 08 had an overall average of 95 bpm with standard deviation between 2.2 and 9.6. Subject 08 had a higher heart rate for the AED procedures, with the heart rate

peaking while performing CPR, whereas Subject 07 typically had a steady heart rate over the entire procedure. Heart rate data for the dual-caregiver procedures was available for Subject 08 only. The average heart rate was 87 bpm for the three trials, with a standard deviation range from 2.2 to 5.8. Table VII includes the heart rate summary for all trials. The overall time required to perform each procedure appears in Table VIII. The resources and equipment used in each procedure appear in Table IX. As the caregivers became more experienced at performing the procedures, their elapsed time decreased. Additionally, the procedures streamlined as the test operators also became more experienced.

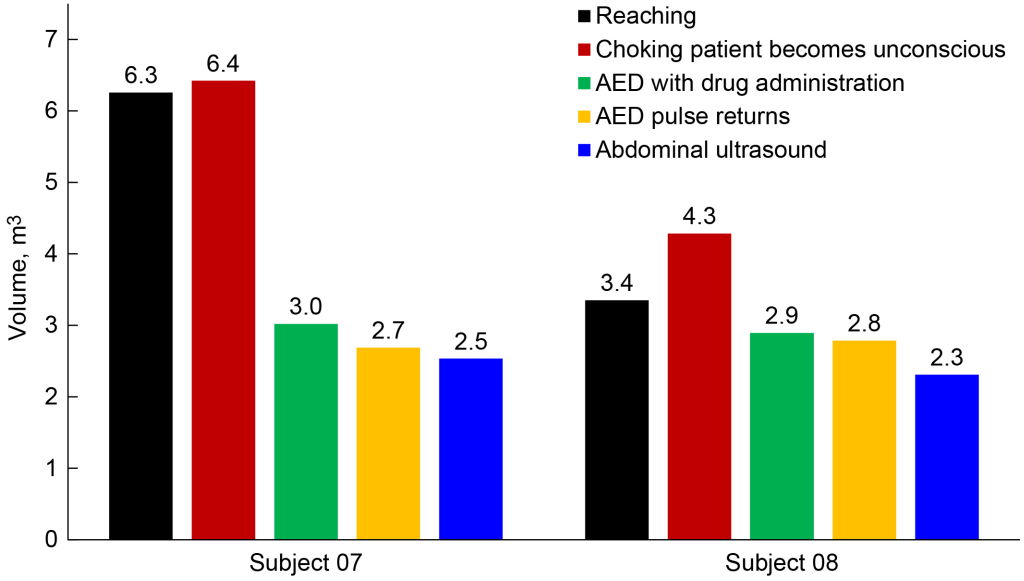


Figure 45.—Rectangular volume comparison, reach with caregiver stationary versus restricted feet trials. Automated external defibrillator, AED.

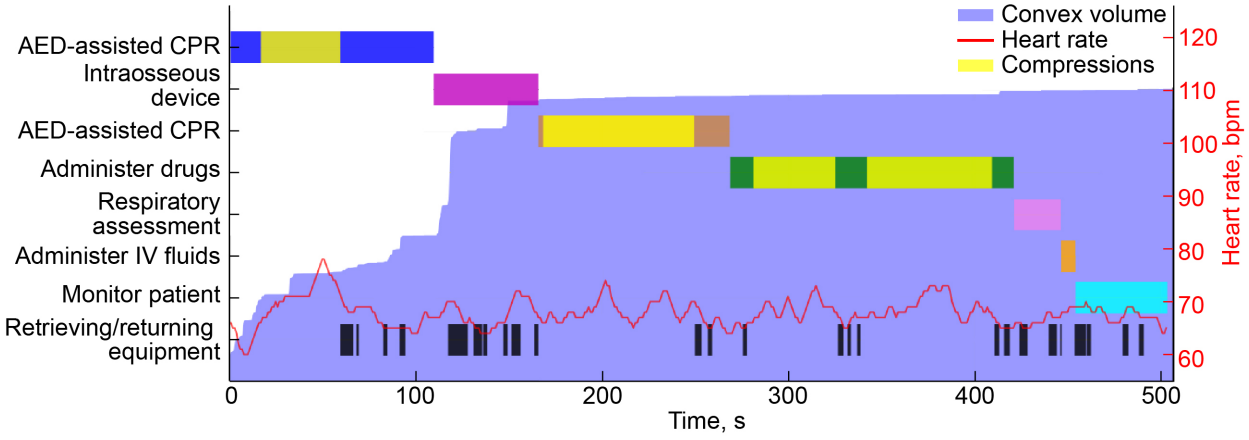


Figure 46.—Subject 07, unrestricted volume, automated external defibrillator (AED) with drug administration (ADA) procedure. Cardiopulmonary resuscitation, CPR; intravenous, IV.

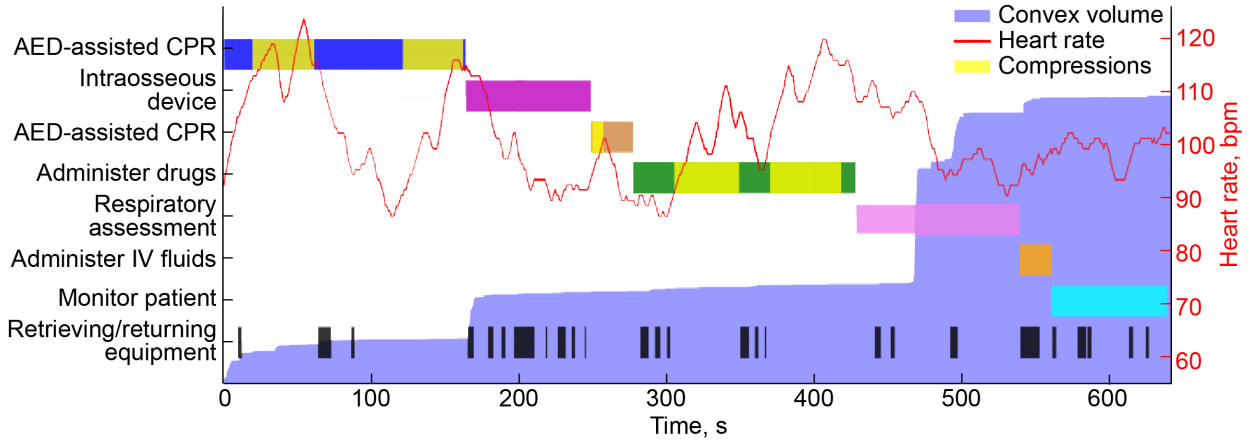


Figure 47.—Subject 08, unrestricted volume, automated external defibrillator (AED) with drug administration (ADA) procedure. Cardiopulmonary resuscitation, CPR.

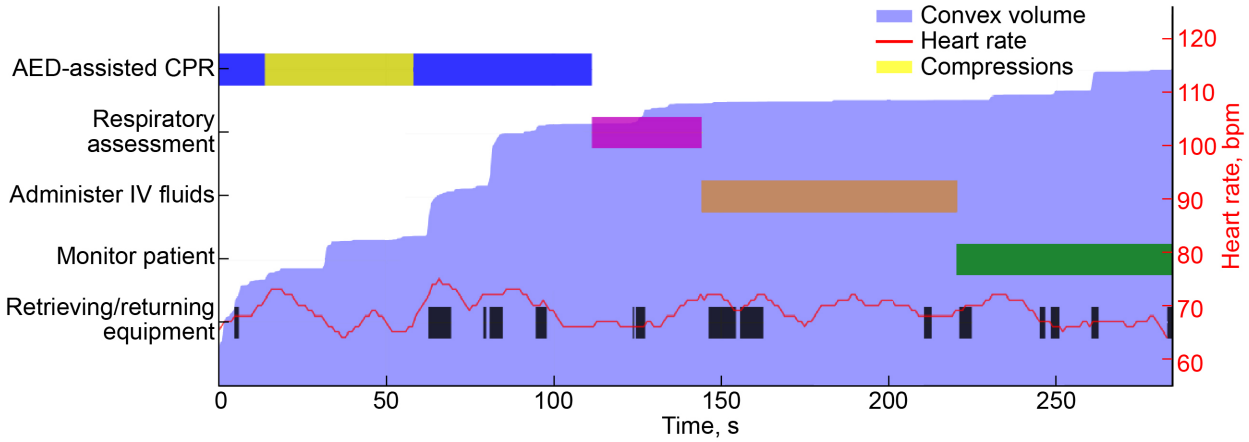


Figure 48.—Subject 07, small restricted volume, automated external defibrillator (AED) pulse returns (APR) procedure. Cardiopulmonary resuscitation, CPR. Intravenous, IV.

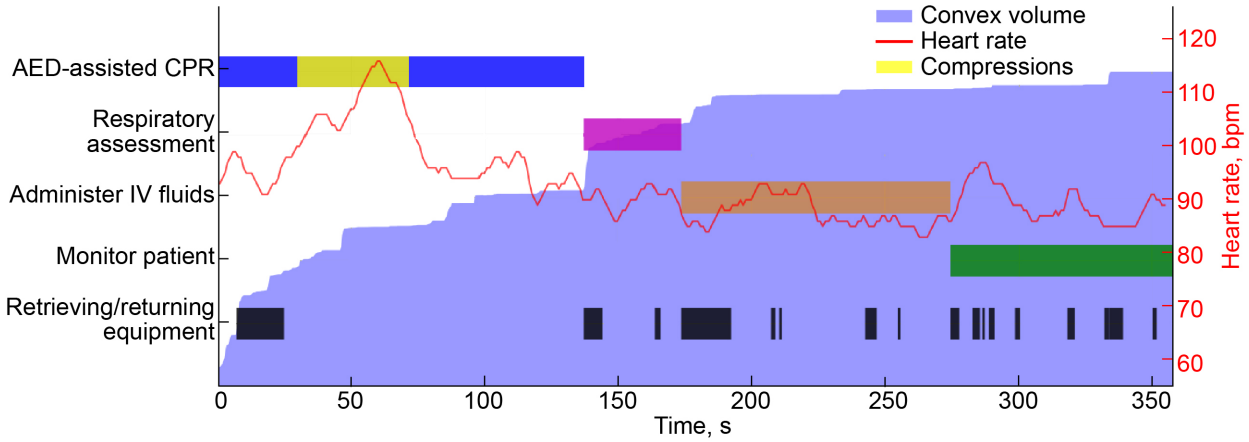


Figure 49.—Subject 08, large restricted volume, automated external defibrillator (AED) pulse returns (APR) procedure. Cardiopulmonary resuscitation, CPR. Intravenous, IV.

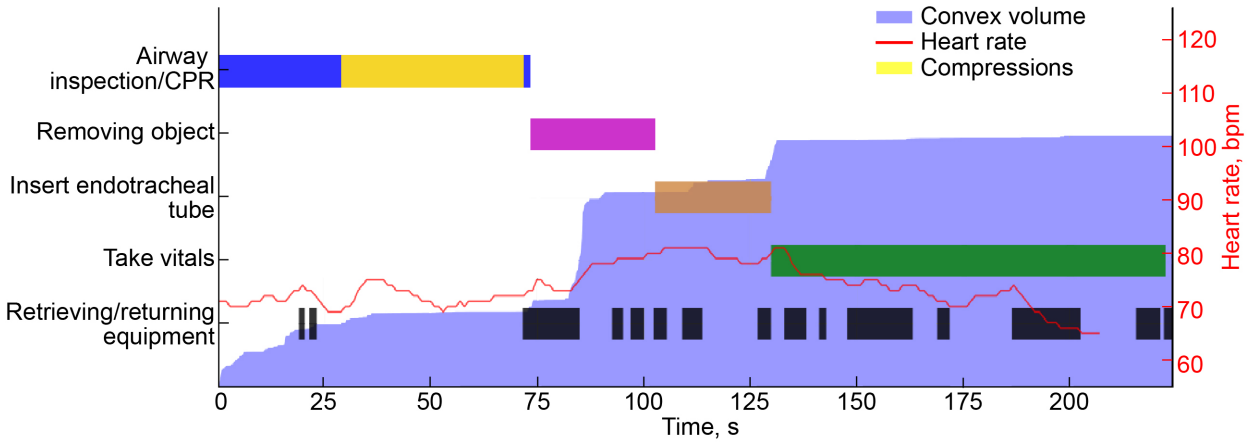


Figure 50.—Subject 07, restricted feet, choking patient becomes unconscious (CPU) procedure. Cardiopulmonary resuscitation, CPR.

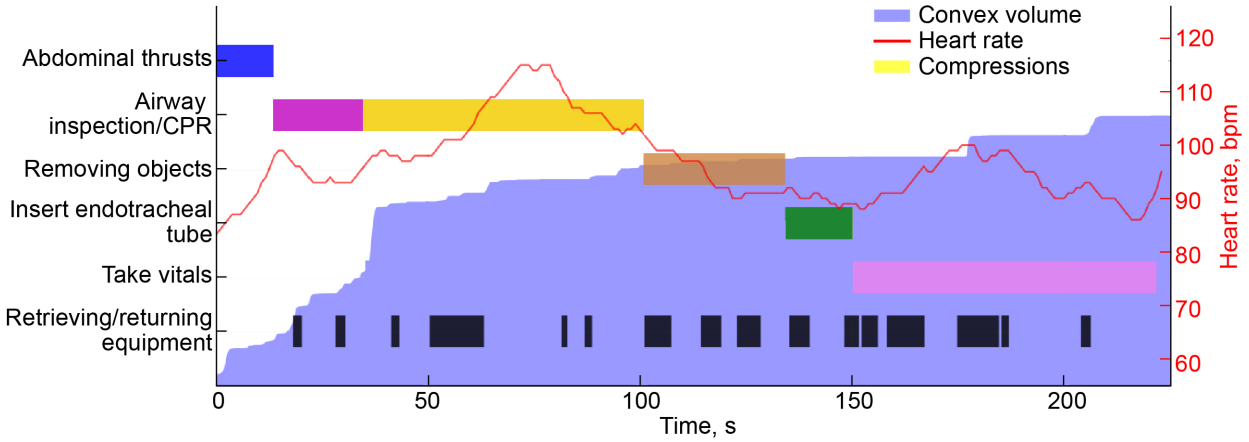


Figure 51.—Subject 08, large restricted volume, choking patient becomes unconscious (CPU) procedure. Cardiopulmonary resuscitation, CPR.

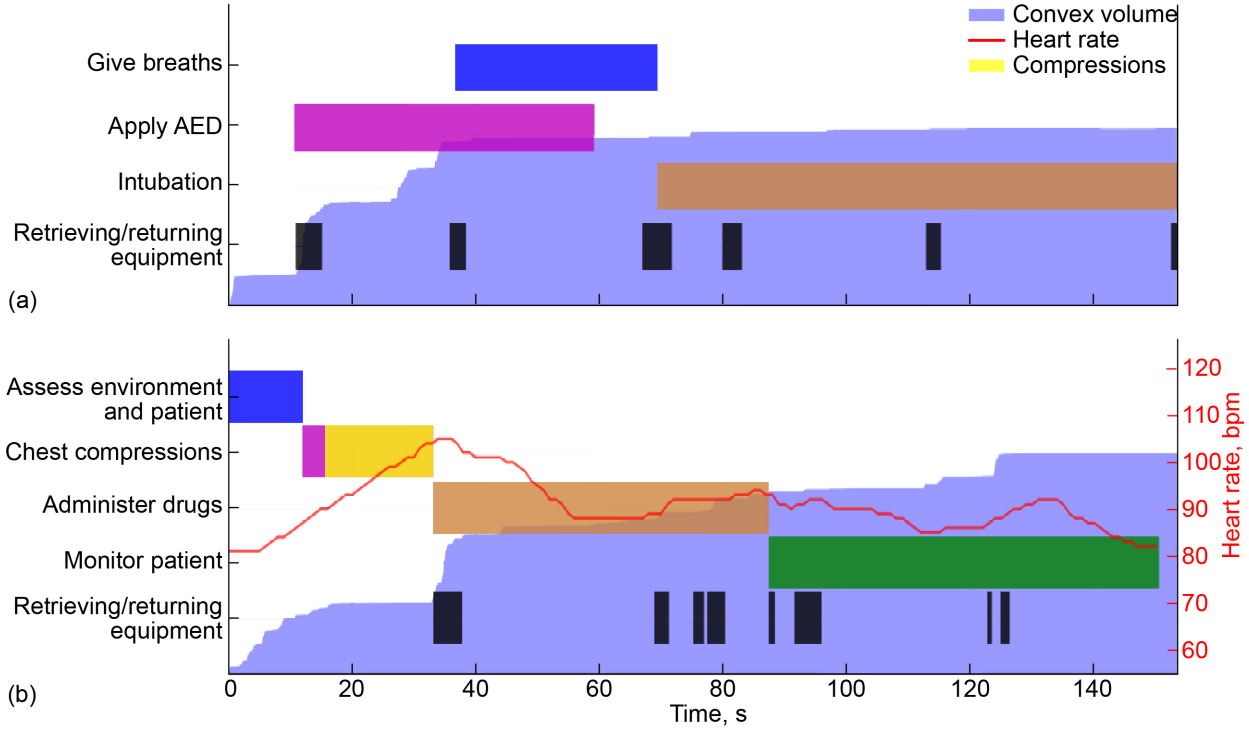


Figure 52.—Dual caregiver, automated external defibrillator (AED) with drug administration (ADA) procedure. (a) Subject 07. (b) Subject 08.

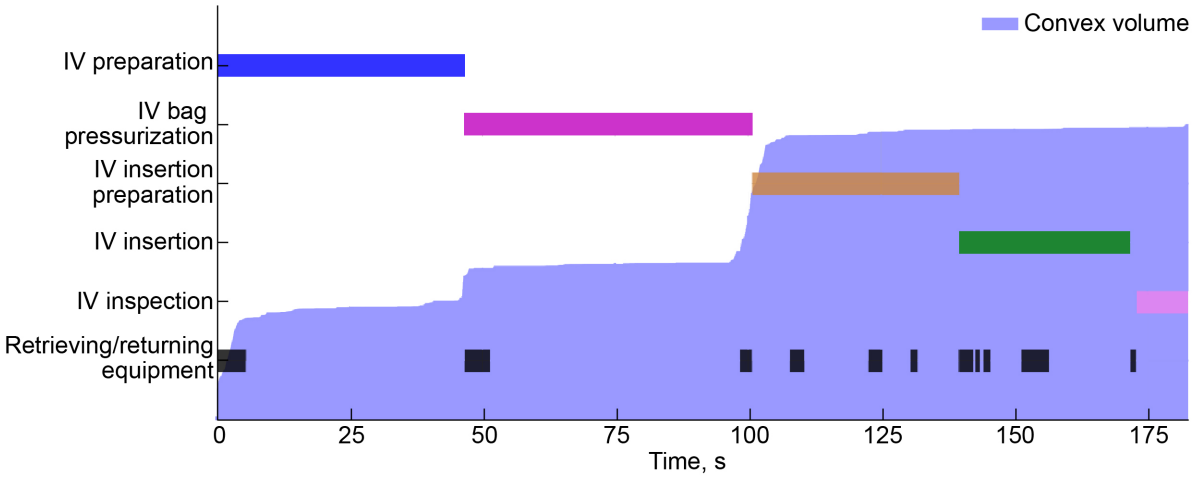


Figure 53.—Subject 07, unrestricted volume, intravenous (IV) fluid preparation and administration procedure.

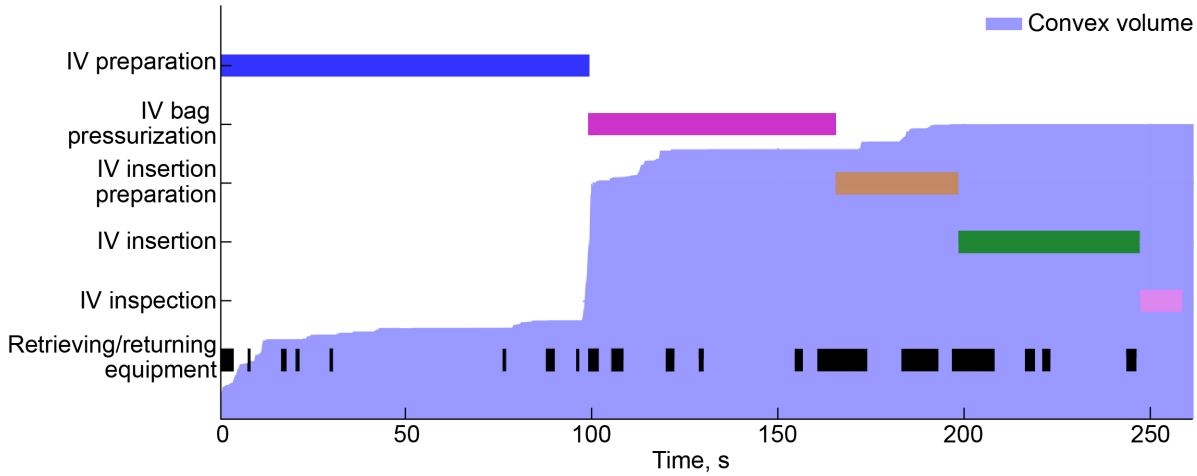


Figure 54.—Subject 08, unrestricted volume, intravenous (IV) fluid preparation and administration procedure.

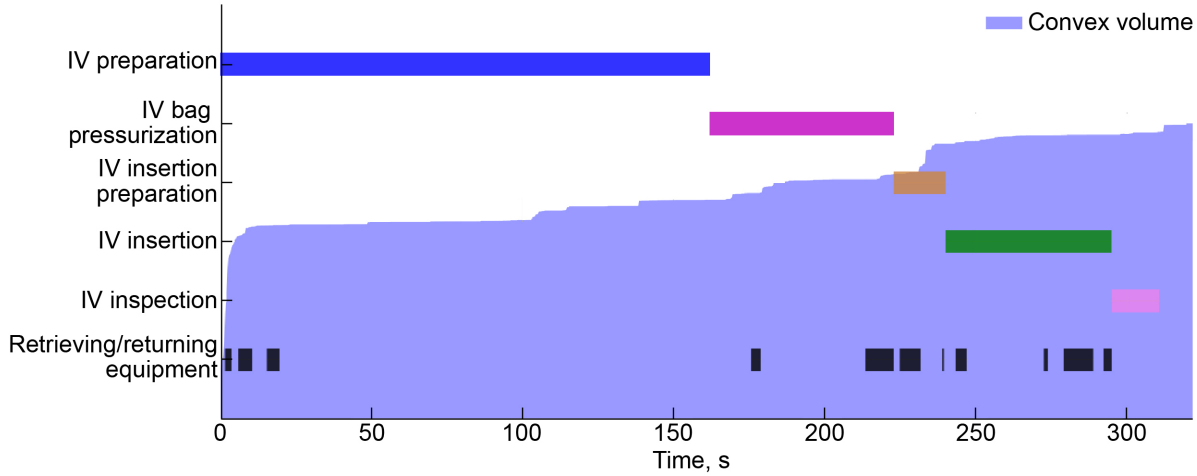


Figure 55.—Subject 09, unrestricted volume, intravenous (IV) fluid preparation and administration procedure.

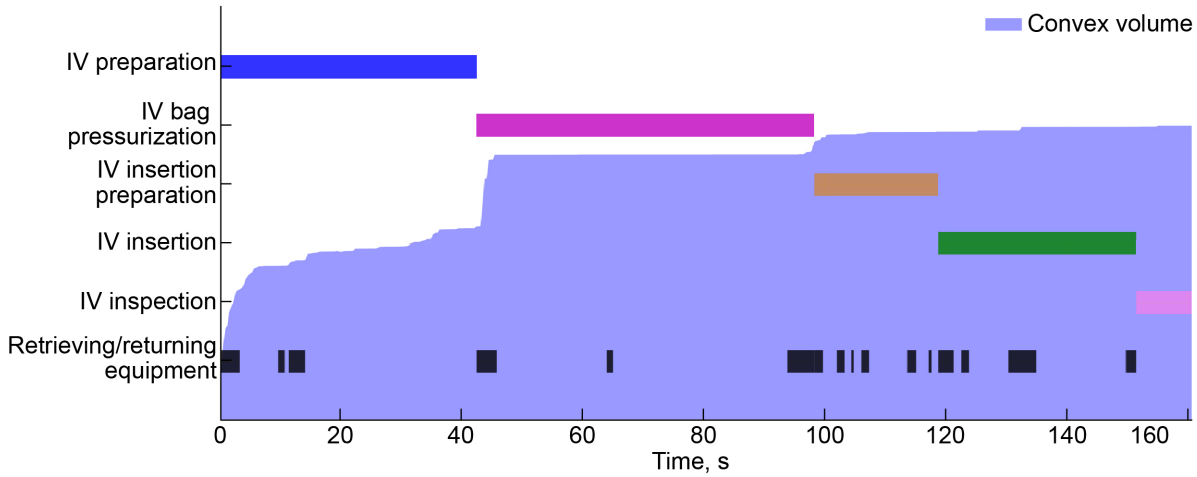


Figure 56.—Subject 07, restricted feet, intravenous (IV) fluid preparation and administration procedure.

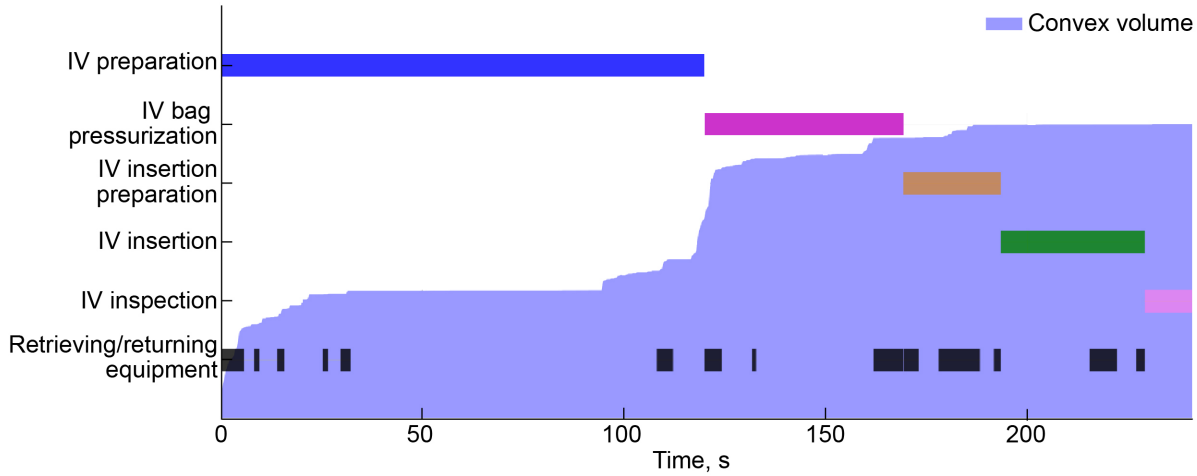


Figure 57.—Subject 08, restricted feet, intravenous (IV) fluid preparation and administration procedure.

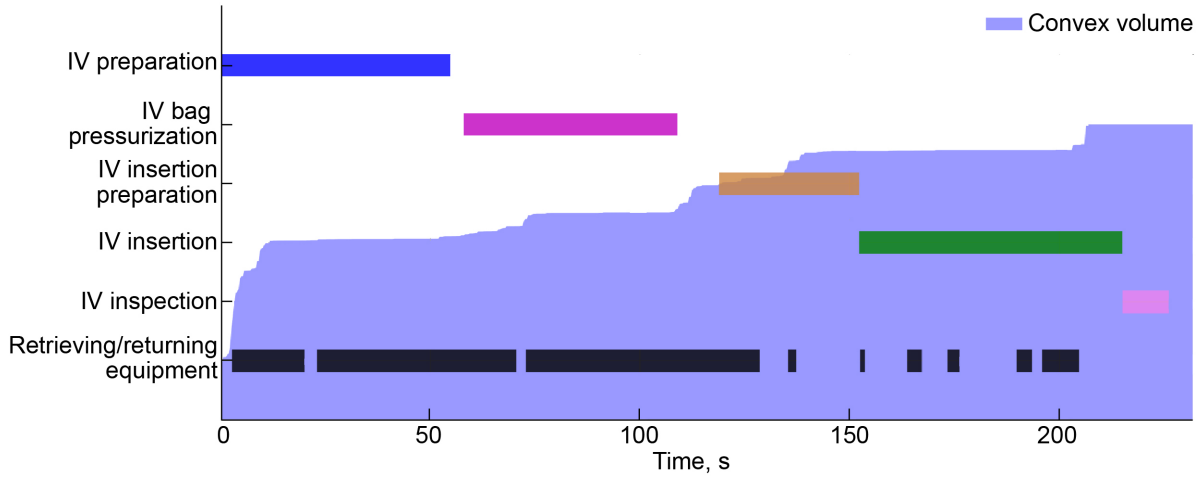


Figure 58.—Subject 09, restricted feet, intravenous (IV) fluid preparation and administration procedure.

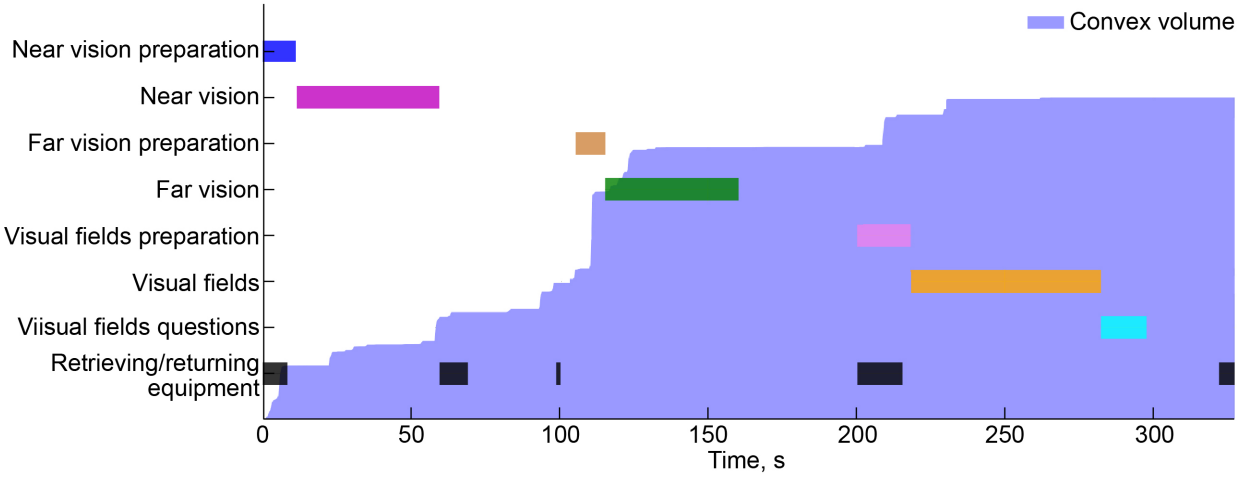


Figure 59.—Subject 07, restricted feet, visual acuity procedure.

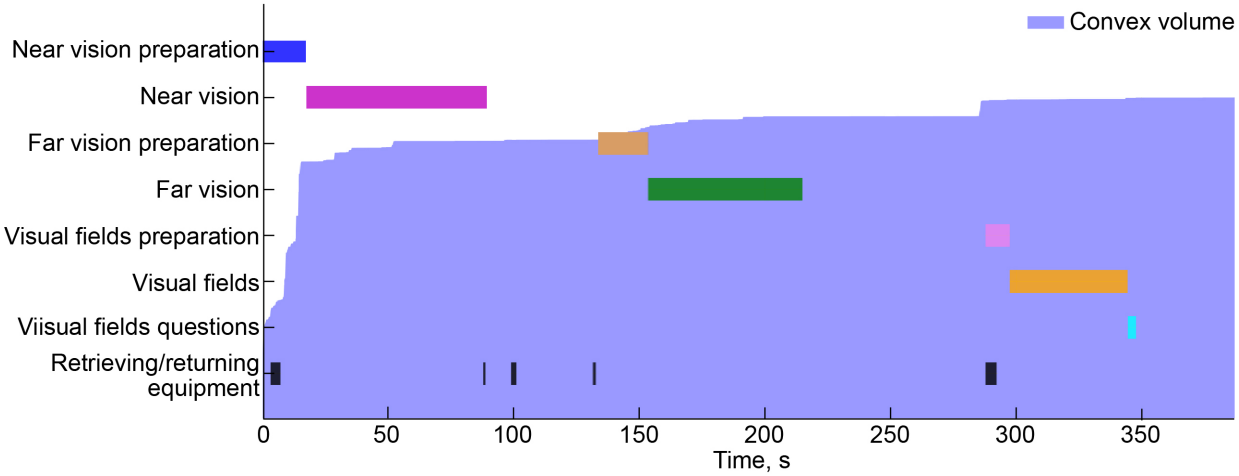


Figure 60.—Subject 08, restricted feet, visual acuity procedure.

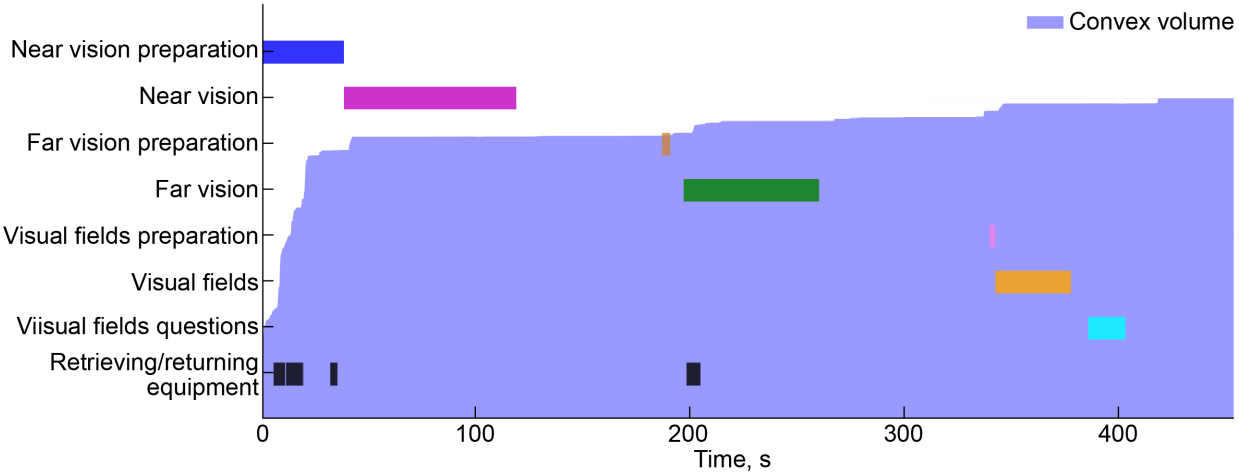


Figure 61.—Subject 09, restricted feet, visual acuity procedure.

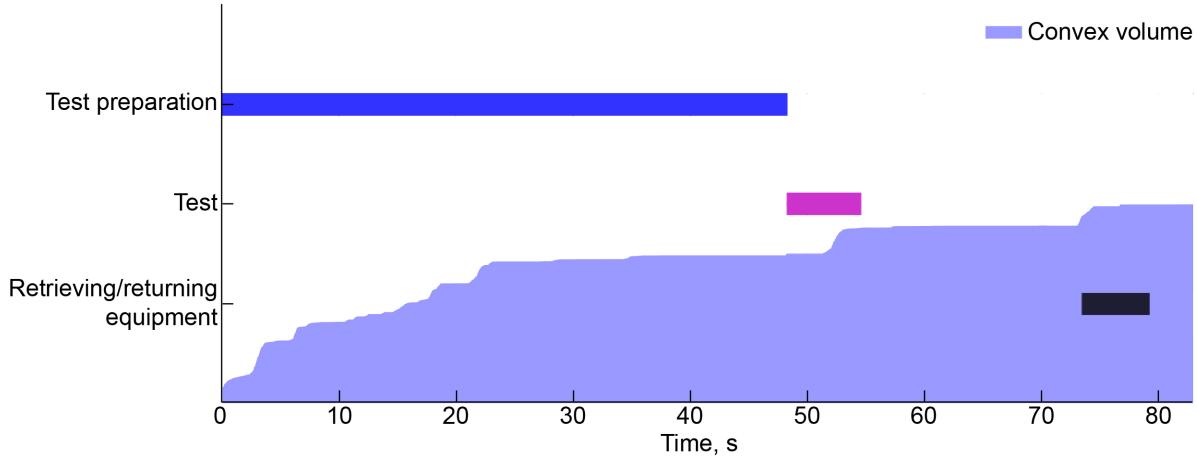


Figure 62.—Subject 07, unrestricted volume, optical coherence tomography (OCT) procedure.

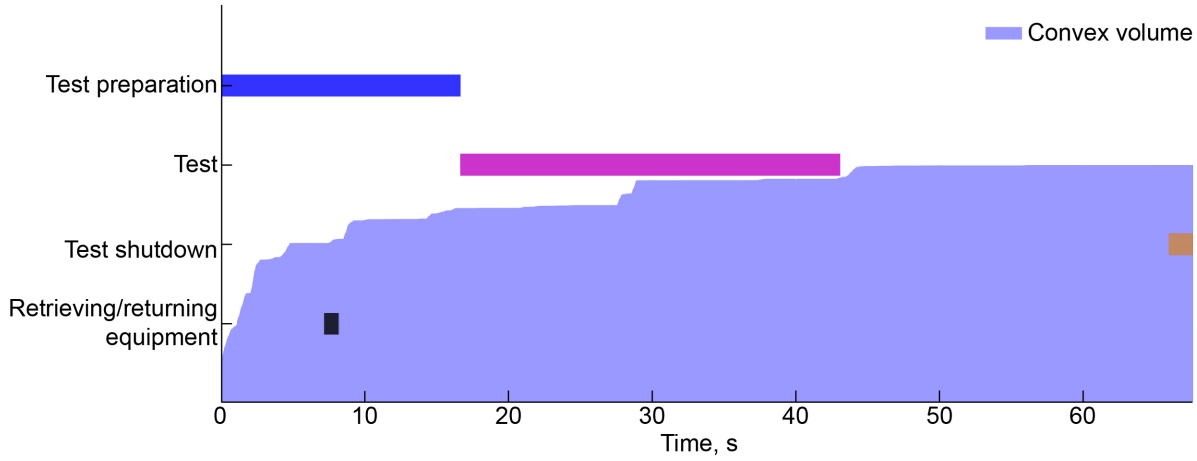


Figure 63.—Subject 08, unrestricted volume, optical coherence tomography (OCT) procedure.

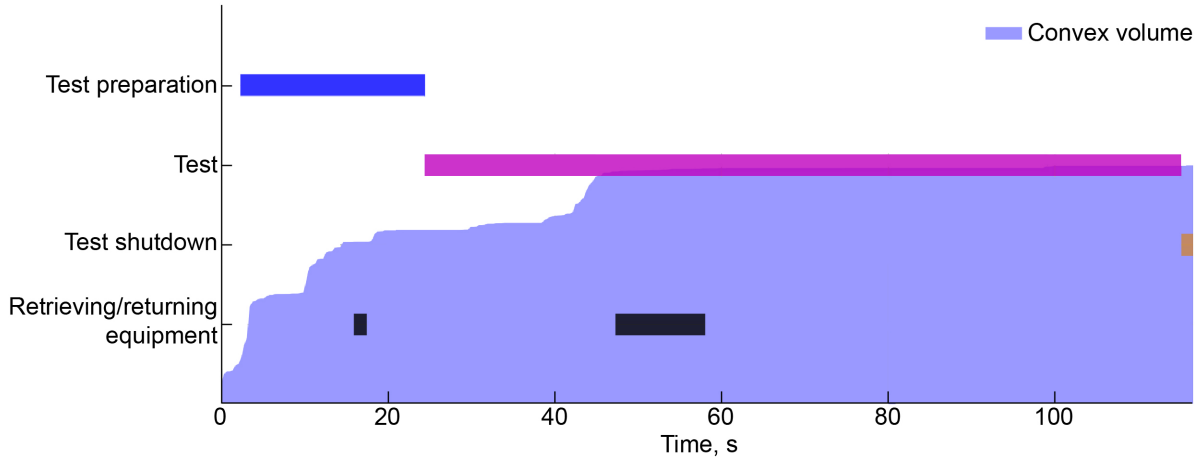


Figure 64.—Subject 09, unrestricted volume, optical coherence tomography (OCT) procedure.

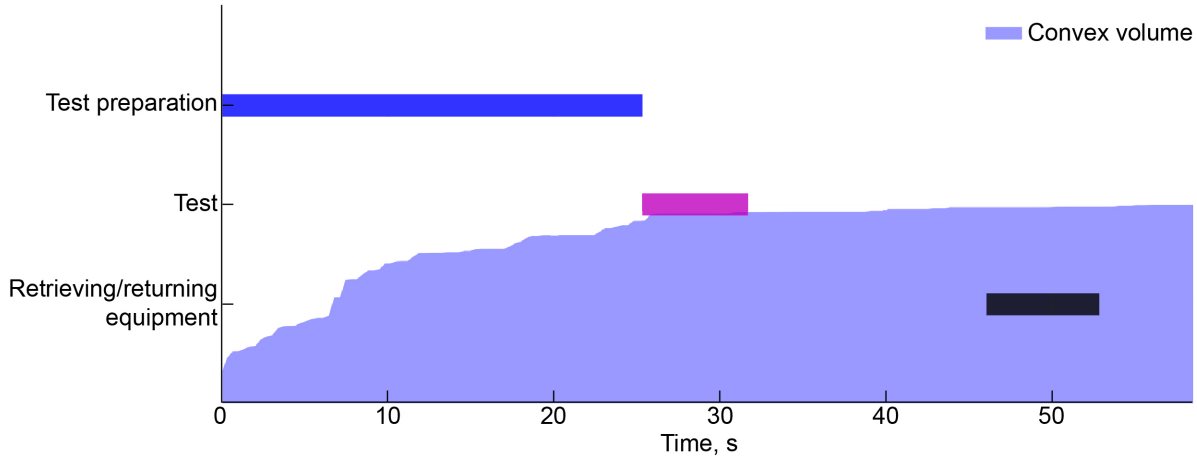


Figure 65.—Subject 07, restricted feet, optical coherence tomography (OCT) procedure.

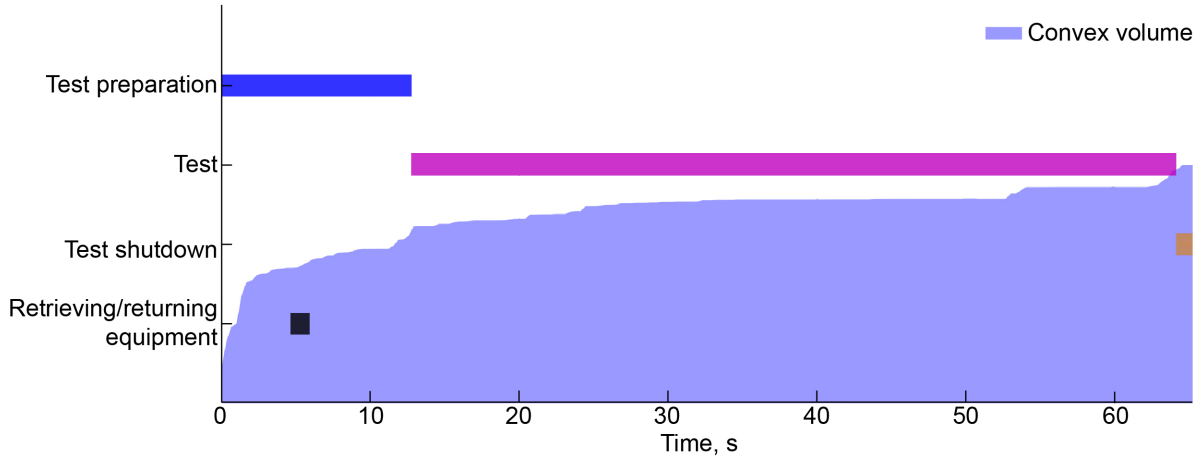


Figure 66.—Subject 08, restricted feet, optical coherence tomography (OCT) procedure.

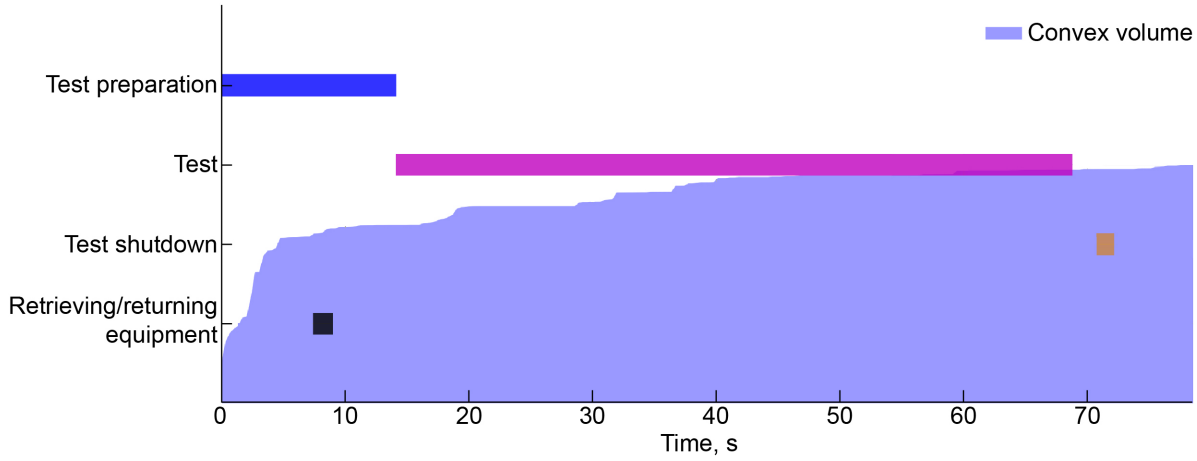


Figure 67.—Subject 09, restricted feet, optical coherence tomography (OCT) procedure.

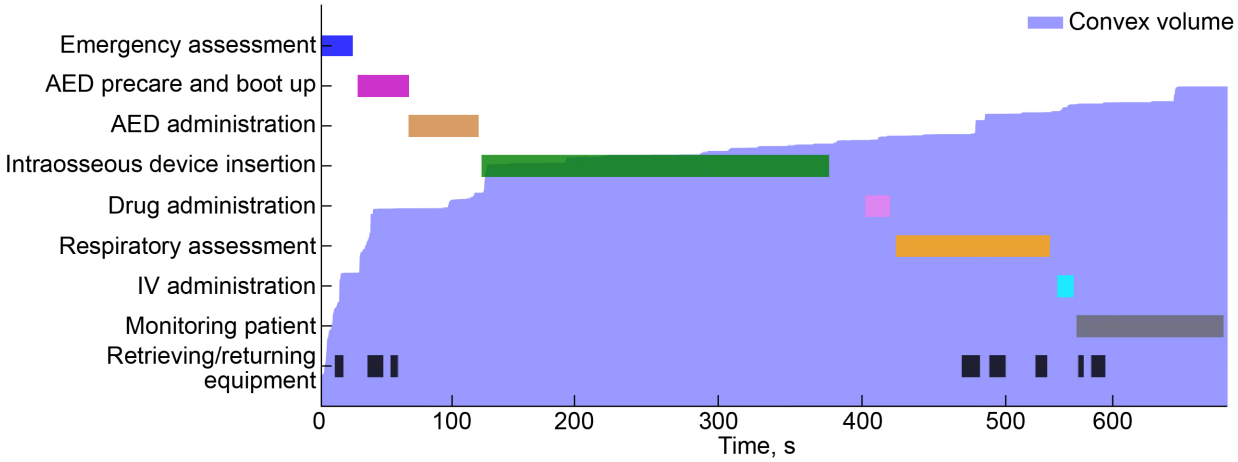


Figure 68.—Subject 09, unrestricted volume, automated external defibrillator (AED) with drug administration (ADA) procedure.

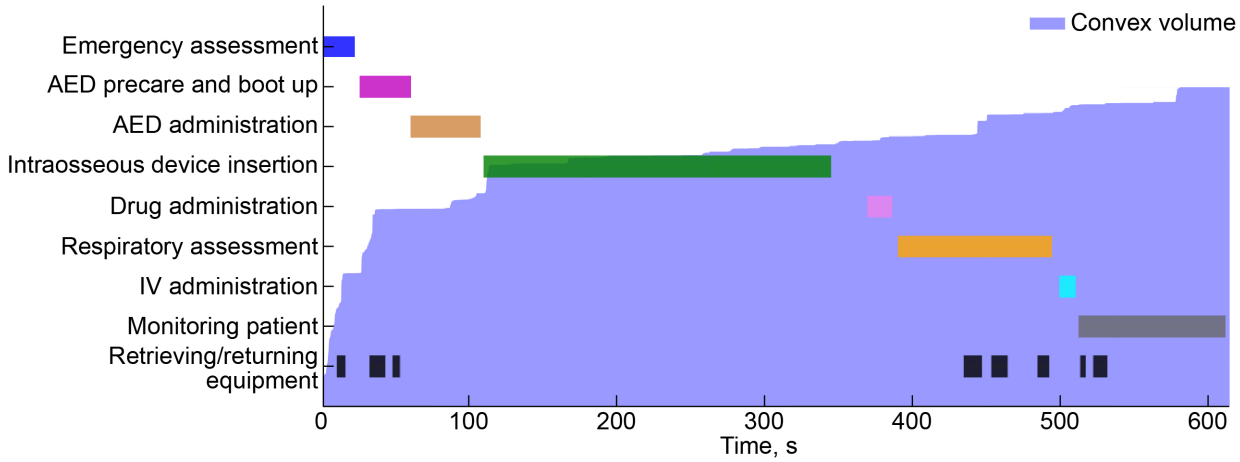


Figure 69.—Subject 09, restricted feet, automated external defibrillator (AED) with drug administration (ADA) procedure.

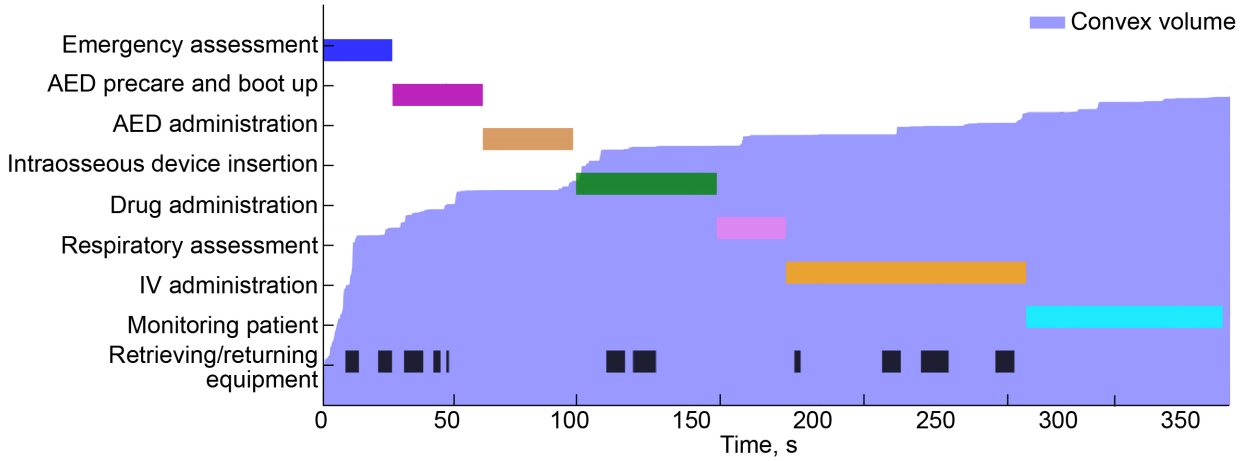


Figure 70.—Subject 09, patient vertical, automated external defibrillator (AED) with drug administration (ADA) procedure.

TABLE VII.—HEART RATE DATA

(a) Single caregiver.

| | | Average heart rate, bpm | | | |
|---|---|---|---|---|---|
| | | Volume | | | Restricted feet |
| | | Unrestricted | Large | Small | |
| Subject 07 | AED[a] with drug administration | 68±2.6 | 69±3.3 | 67±3.5 | 69±2.7 |
| | AED pulse returns | 69±2.7 | 66±2.5 | 69±2.4 | 70±3.0 |
| | Choking patient becomes unconscious | NA | 67±3.5 | 68±3.3 | 74±4.0 |
| | Abdominal ultrasound | 61±2.3 | 66±2.4 | 65±2.2 | 73±2.4 |
| Subject 08 | AED with drug administration | 102±8.7 | 104±9.6 | 97±6.0 | 97±8.7 |
| | AED pulse returns | 89±6.5 | 93±7.1 | 94±7.6 | 90±9.4 |
| | Choking patient becomes unconscious | 97±7.7 | 96±7.1 | 96±5.8 | 100±9.4 |
| | Abdominal ultrasound | 91±4.0 | 89±4.3 | 88±2.8 | 92±5.3 |

(b) Dual caregiver, AED with drug administration procedure, unrestricted volume.

| Table start position | Average heart rate, bpm |
|---|---|
| Long–long, same side | 86±4.6 |
| Long–long, opposite sides | 82±2.2 |
| Long–short, crosswise sides | 91±5.8 |

[a]Automated external defibrillator.

TABLE VIII.—PROCEDURE TIMES

(a) Single caregiver.

| | | Time to perform procedures, min | | | |
|---|---|---|---|---|---|
| | | Volume | | | Restricted feet |
| | | Unrestricted | Large | Small | |
| Subject 07 | AED[a] with drug administration | 8.4 | 11.0 | 9.9 | 9.2 |
| | AED pulse returns | 4.1 | 6.1 | 4.7 | 5.6 |
| | Choking patient becomes unconscious | 1.7 | 5.3 | 3.7 | 3.5 |
| | Abdominal ultrasound | 8.2 | 5.9 | 5.3 | 4.5 |
| Subject 08 | AED with drug administration | 10.7 | 9.8 | 5.2 | 9.7 |
| | AED pulse returns | 9.0 | 5.9 | 5.4 | 4.8 |
| | Choking patient becomes unconscious | 4.7 | 3.7 | 3.0 | 3.6 |
| | Abdominal ultrasound | 5.0 | 4.2 | 4.2 | 5.5 |

(b) Dual caregiver, AED with drug administration procedure, unrestricted volume.

| Table start position | Time, min |
|---|---|
| Long–long, same side | 3.6 |
| Long–long, opposite sides | 2.6 |
| Long–short, crosswise sides | 2.5 |

[a]Automated external defibrillator.

TABLE IX.—PROCEDURE EQUIPMENT LIST

| Choking patient becomes unconscious | Abdominal ultrasound | Both automated external defibrillator (AED) procedures | Additional equipment for AED with drug administration |
|---|---|---|---|
| Oral airway kit | Ultrasound | AED trainer | Intraosseous device |
| Blood pressure cuff | Ultrasound probe | AED electrodes | Epinephrine syringe |
| Stethoscope | Keyboard simulation | Cardiopulmonary resuscitation (CPR) mask | Atropine syringe |
| Blood oximeter | Benzalkonium (BZK) wipe | Medical tape | Lidocaine syringe |
| Laryngoscope | Thermometer | Stethoscope | |
| Forceps | Blood pressure monitor | Blood oximeter | |
| Endotracheal tube | Blood pressure cuff | AMBU bag | |
| Flashlight | Stethoscope | Non-rebreather mask | |
| Artificial manual breathing unit (AMBU) bag | Laptop | Electrocardiogram (ECG) device | |
| | | ECG lead set cable | |
| | | Electrode package | |
| | | Zip-lock bag | |
| | | Intravenous (IV) cap | |
| | | IV bag | |
| | | Tourniquet | |

## Subjective Feedback

### NASA Task Load Index Feedback

There was high intrasubject variability even when the subjects' open-ended feedback suggested that the volume changes made no difference.

*AED procedures*: A summary of the NASA TLX responses for these procedures for 2018 testing appears in Figure 71. For the male subject, temporal and mental demand are both consistently high factors. For the female subject, temporal demand is higher, and frustration is sometimes higher. Overall, reducing the volume seemed to lower the ratings rather than increase them. This was not expected, but it may be attributable to the subjects' learning the procedures as they repeated them.

*Non-AED procedures*: A summary of the NASA TLX responses for these procedures for 2018 testing appears in Figure 72. Subject 07 rated frustration very high. The subject mentioned the lack of fidelity in feedback as a major contributing factor to his frustration. Subject 08 rated all of the TLX factors high for the large-volume trials. An explanation for this was not obvious.

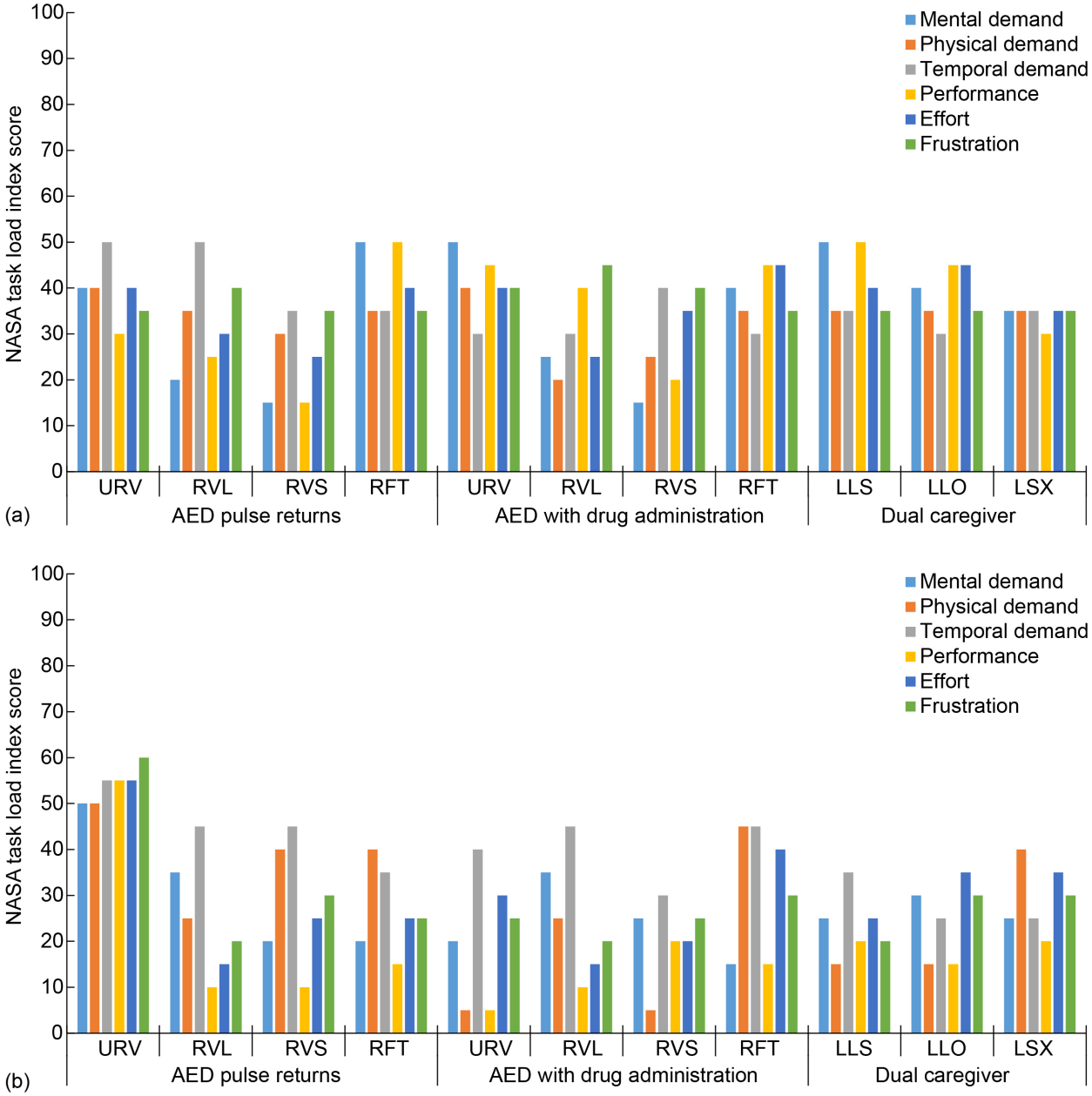


Figure 71.—NASA task load index score for automatic external defibrillator- (AED-) based procedures (AED pulse returns, AED with drug administration, and dual-caregiver AED); 2018 testing. Unrestricted volume, URV; restricted volume large, RVL; restricted volume small, RVS; restricted feet, RFT; long–long, same side of table, LLS; long–long, opposite sides of table, LLO; long–short, crosswise sides of table, LSX. (a) Subject 07, tall male. (b) Subject 08, petite female.

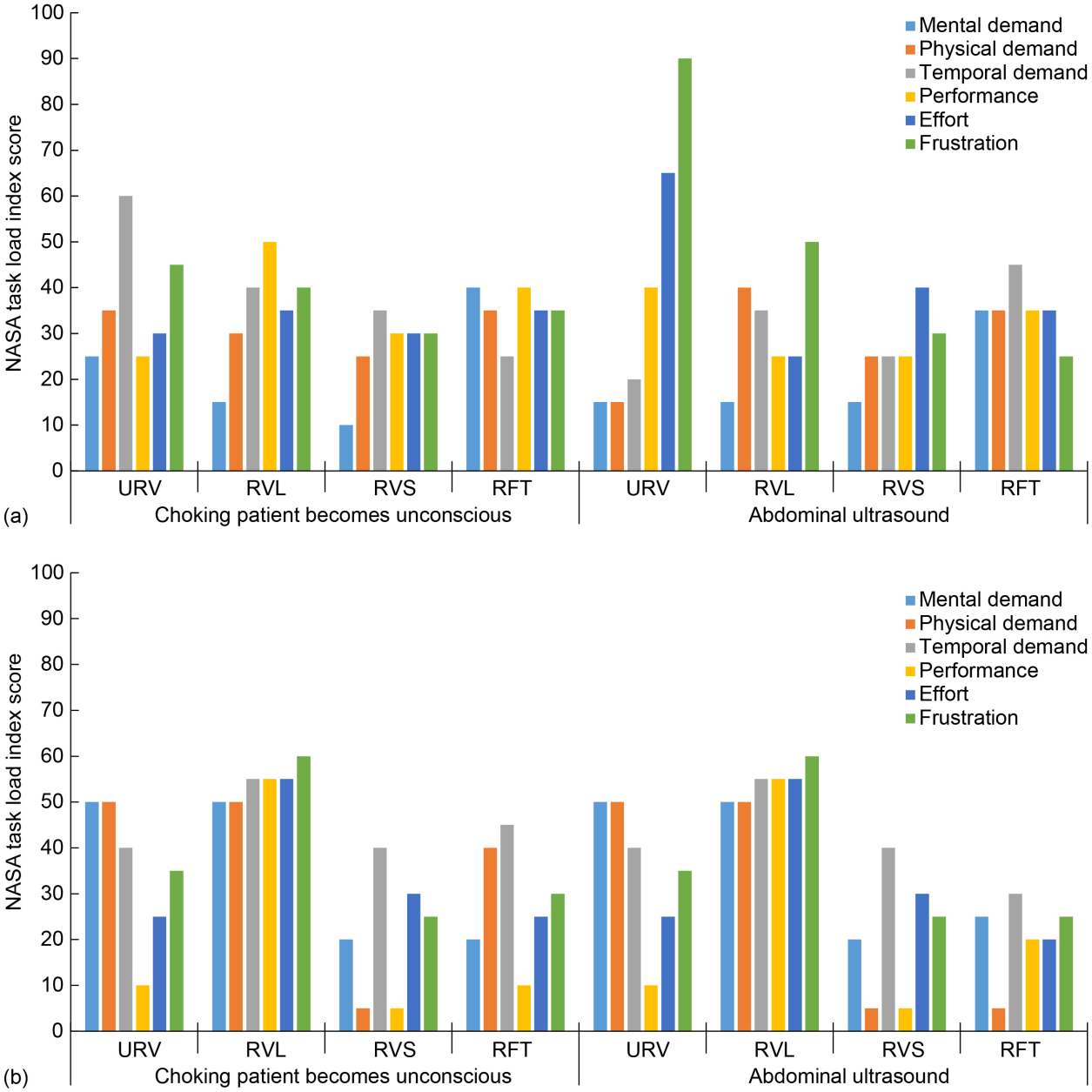


Figure 72.—NASA task load index scores for non-AED-based procedures; 2018 testing. Unrestricted volume, URV; restricted volume large, RVL; restricted volume small, RVS; restricted feet, RFT. (a) Subject 07, tall male. (b) Subject 08, petite female.

*Intravenous Fluid Preparation and Administration:* Figure 73 to Figure 75 summarize the NASA TLX responses for these procedures for Subject 07, Subject 08, and Subject 09. All three subjects rated the temporal demand highest even though this was not a timed procedure. Subject 09 rated the mental demand and frustration high for this trial in the unrestricted volume. Restricting the feet had no effect for Subject 07, whose ratings for restricted feet and unrestricted volume were approximately the same. Subject 08 preferred the unrestricted volume and Subject 09 preferred restricted feet.

*Visual Acuity Exam—Restricted Feet Only* (Figure 73 to Figure 75): Subject 07 appeared not to prefer the feet restricted for this trial. Mental demand was highest for Subject 08. Subject 09 rated time and effort highest.

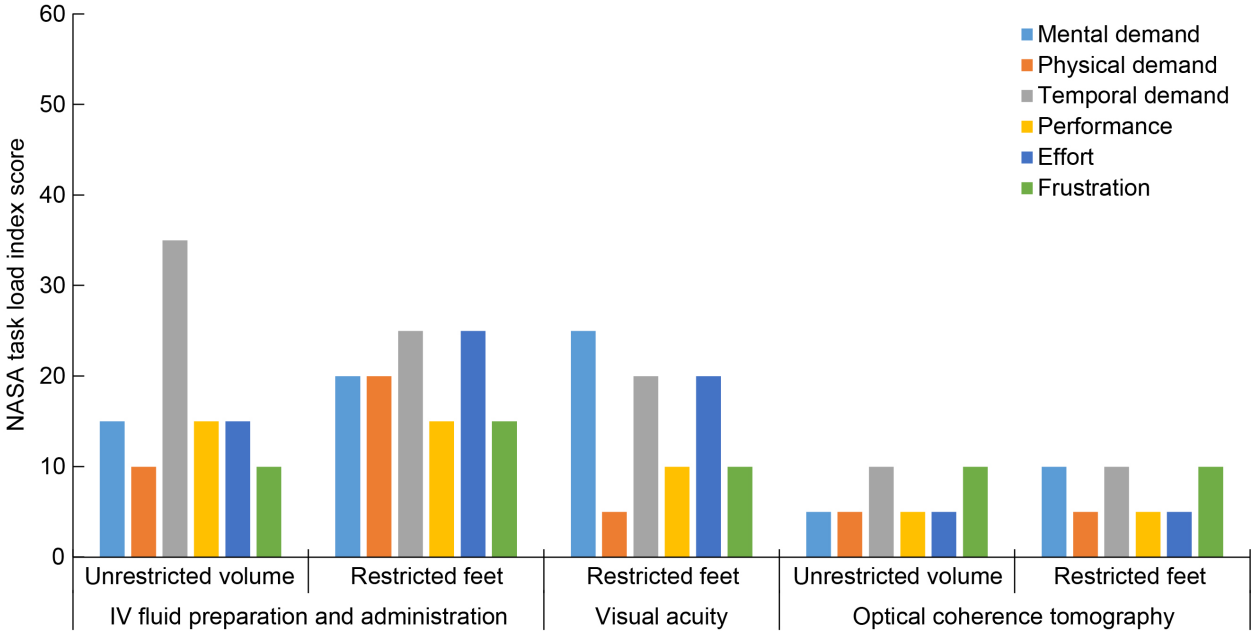


Figure 73.—NASA task load index score for Subject 07; 2019 testing.

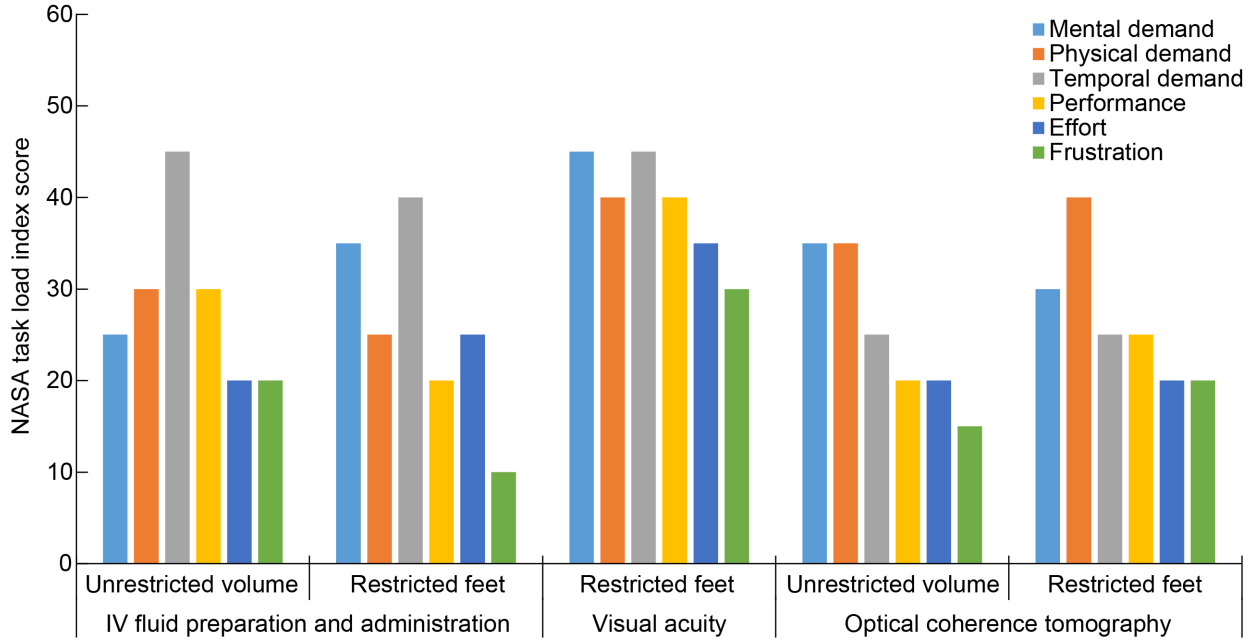


Figure 74.—NASA task load index score for Subject 08; 2019 testing. Intravenous, IV.

*Optical Coherence Tomography (OCT) Exam* (Figure 73 to Figure 75)*:* Subject 07 required higher physical and mental demand. Subject 08 appeared relaxed for both trials. Time was a factor for Subject 09 when unrestricted, and Subject 09 rated frustration high when the feet were restricted.

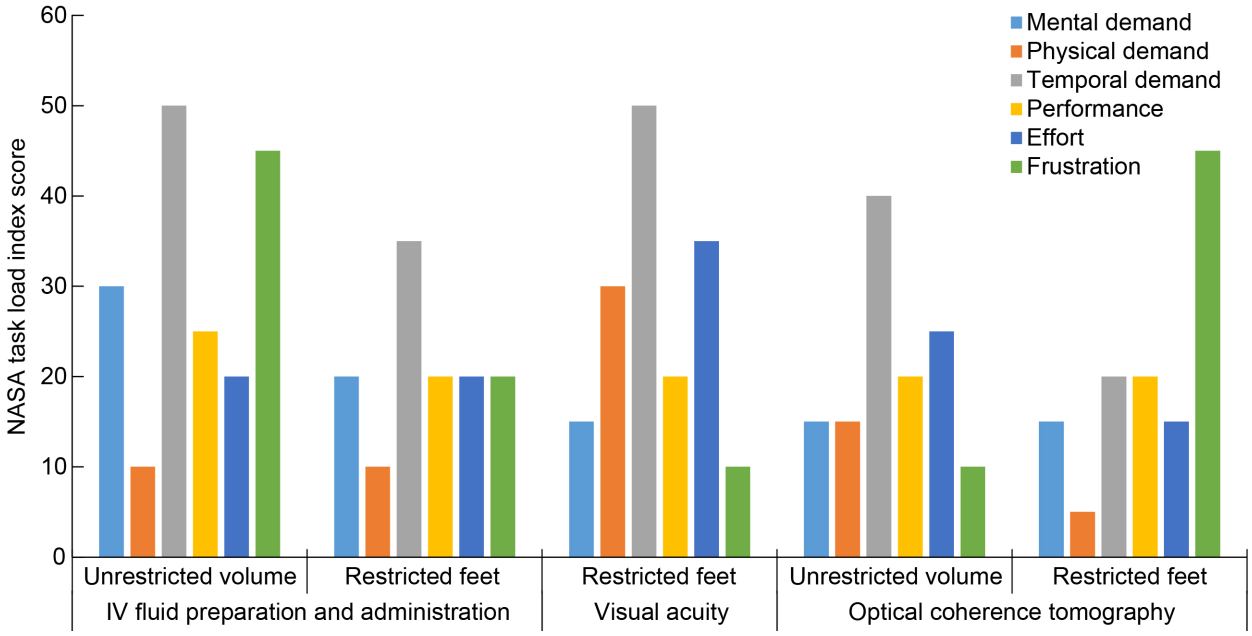


Figure 75.—NASA task load index score for Subject 09; 2019 testing. Intravenous, IV.

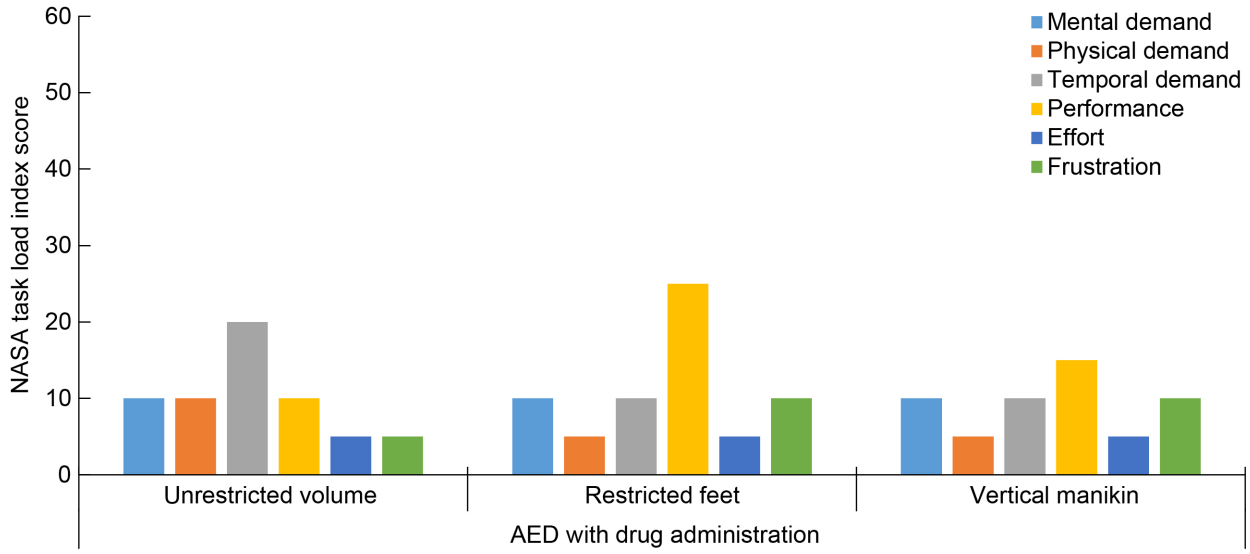


Figure 76.—NASA task load index score for Subject 09 for automated external defibrillator- (AED-) based procedures; 2019 testing.

*AED with Drug Administration—Subject 09 Only:* NASA TLX ratings for these procedures are summarized in Figure 76. Subject 09 was comfortable performing all three AED trials, probably due to a background as a paramedic.

### System Usability Scale Feedback

SUS responses for all procedures are summarized in Figure 77 to Figure 80. Based on research (Ref. 2), a SUS score above a 68 would be an above-average usability score and anything below 68 is

below average (Ref. 3). The petite female found the space more usable overall than the tall male did. Restricting the volume or the feet tended to reduce the SUS score slightly. The dual-caregiver scenario raised the SUS score for the male, but not for the female. Generally, all three subjects did not discern between the unrestricted volume and restricted feet. For the AED procedures, Subject 09 rated the restricted feet trial slightly higher than the unrestricted (83 versus 75) and gave the vertical manikin a low score (38) due to the abnormal vertical position. Subject 07 (physician) ratings were around average, whereas Subject 09 (paramedic) ratings were above average and Subject 08 (physician's assistant) ratings were high for the 2019 trials.

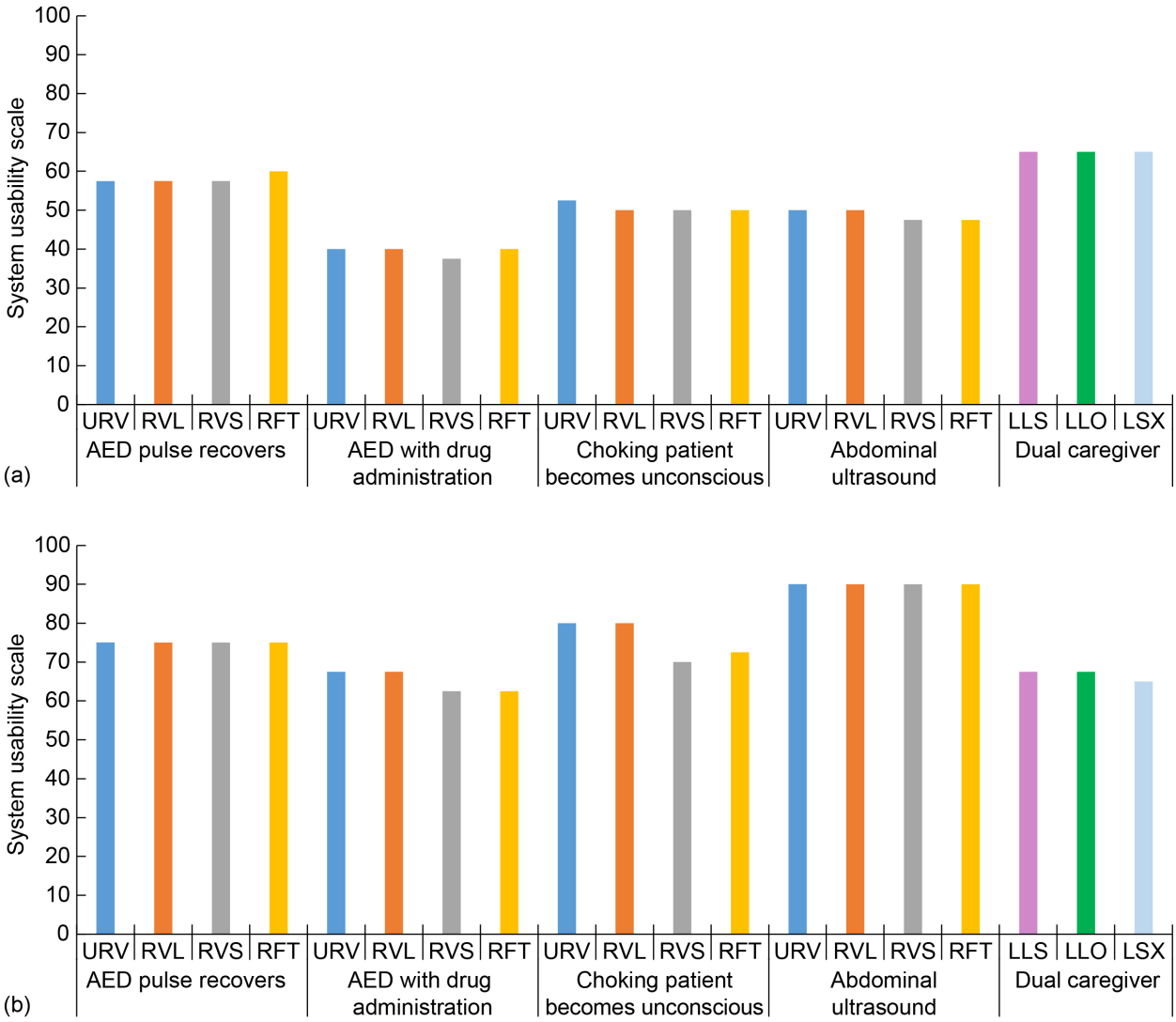


Figure 77.—System Usability Scale (SUS) data for all procedures; 2018 testing. Unrestricted volume, URV; restricted volume large, RVL; restricted volume small, RVS; restricted feet, RFT; automated external defibrillator, AED; long–long, same side of table, LLS; long–long, opposite sides of table, LLO; long–short, crosswise sides of table, LSX. (a) Subject 07, tall male. (b) Subject 08, petite female.

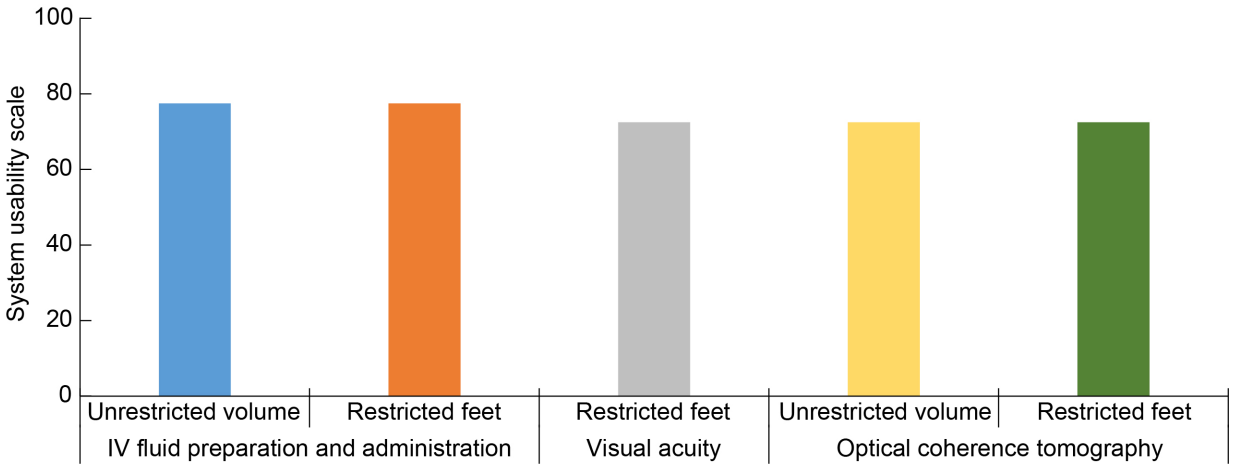


Figure 78.—System Usability Scale (SUS) data for Subject 07; 2019 testing. Intravenous, IV.

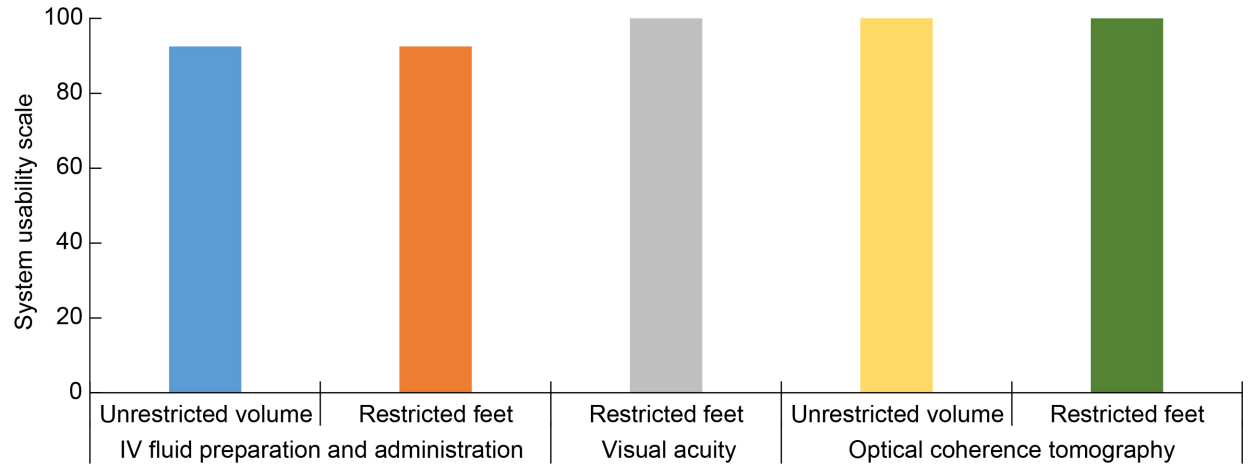


Figure 79.—System Usability Scale (SUS) data for Subject 08; 2019 testing. Intravenous, IV.

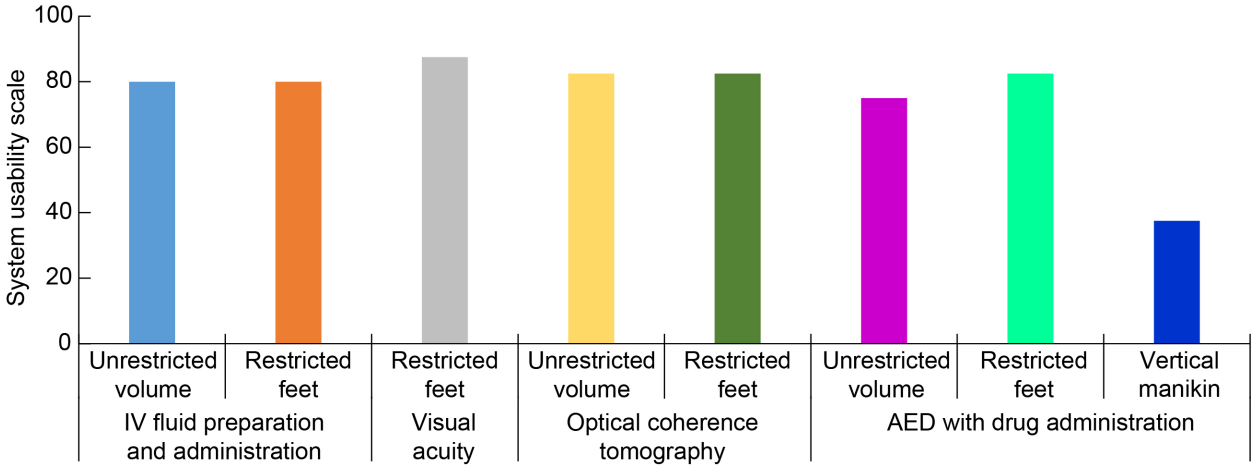


Figure 80.—System Usability Scale (SUS) data for Subject 09; 2019 testing. Intravenous, IV. Automated external defibrillator, AED.

### Open-Ended Feedback

The following is a summary of the significant responses to the open-ended questions:

- Low-fidelity simulation generally inhibited the ability to truly simulate emergent care.
- Suggested improvements included using more realistic intubation equipment and real ultrasound images.
- Access to the patient's head with sightline down the airway is critical for intubation and bag mask procedures. This is a very important factor to consider for design in small restricted volumes. How will this be achieved in a microgravity environment?
- A dual-caregiver approach was more effective for all procedures and tasks, especially when chest compressions must be performed.
- Ultrasound machine placement in relation to the patient must factor in the dominant hand of the caregiver. In particular, the ultrasound probe should be in the dominant hand and the patient should be on the side of the caregiver's dominant hand.
- It was difficult to remove air from the IV bag and prime the tubing with liquid while also holding the bag for the IV procedure. Securing the tubing and bag while priming would help.
- Additional equipment may be required to find the vein for IV placement if the patient is ill.
- Not enough height to perform CPR compressions with the patient horizontal on the table.
- It would be difficult to perform CPR compressions with the patient vertical. It was difficult to use the AMBU bag with the patient vertical. (CPR was not performed on the vertical patient.)
- With restricted feet
    - Supplies must be placed within the caregiver's reach space and near the part of the patient's body where used (e.g., intubation supplies near the head and intraosseous supplies near the legs).
    - An easy way to translate from the patient's side to the patient's head should be factored into the design.
- There should be ways to temporarily hold equipment in place to free up the caregiver's hands, especially for intubation.
- What do you do after the first 10 min of care? How do you provide ongoing care in the environment?
- Getting input from ER nurses and EMS/paramedics is highly recommended. They would be able to give better insight into space design and equipment layout and doing emergency procedures in limited-resource environments.

## Discussion and Key Findings

Restricting the volume with an external barrier did not necessarily affect completion of the task or the time required to perform it, with the exception of intubation procedures. Intubation requires visual access to the subject's airway, looking down the throat from behind the head. Restricting the volume to limit this access makes the procedure more difficult for the caregiver and likely more risky for the patient.

The operational volume tends to be mushroom-shaped (i.e., much more upper body movement), especially with restricted feet. The presence of restricted volume, or even the caregiver's perception of restricted volume, reduced the actual operational volume. Note that the subjects did not receive verbal prompting to be aware of their operational volume. Even when the unrestricted volume fits within the imposed volume, the resulting operational volume will diminish with restrictions in place.

The volume needed for performing caregiving operations is significantly smaller than the total volume with reaching for supplies or equipment factored in. The design of the workstation and the placement of supplies and equipment relative to where they are needed will drive the true operational volume. The smallest possible operational volume of any candidate medical station design will likely lie between the unrestricted operational volume and the volume occupied when performing caregiving only (i.e., with all reaching operations eliminated).

Subject 07 and Subject 08 occupied about the same volume for the IV procedure with the volume unrestricted, but Subject 09 occupied half the volume of the other subjects. Subject 09 used about 35 percent more average volume for the visual acuity with the feet restricted, which was probably due to greater reaching length. Subject 07 and 09 used about the same volume for the unrestricted volume AED procedure trial but half the volume used by Subject 08.

## Concluding Remarks

Future medical station analysis (MSA) efforts will seek to build upon the baseline established by this report. The statistical power of the findings will increase as more caregivers with broader experience perform emergent care on a regular basis. Incorporating virtual reality (VR) or augmented reality (AR) technology to increase the fidelity of the simulation would allow for the analysis of specific candidate designs for the medical station. VR technology would allow researchers to incorporate storage locations into the simulation and insert additional environmental factors into the analysis.

To date, the simulations have occurred in a 1g environment. Future work would benefit from incorporating simulations performed in a microgravity environment into the analyses. The reason for this is to overcome the 1g bias that might mask opportunities for a more convenient design that are independent of any gravity vector. Use of the enhanced Zero-gravity Locomotion Simulator (eZLS) in the Exercise Countermeasures Laboratory could help accomplish this objective.

# Appendix A.—Acronym List

| | |
|---|---|
| ADA | AED-assisted CPR, one caregiver, with drug administration |
| AED | automated external defibrillator |
| AMBU | artificial manual breathing unit |
| APR | AED-assisted CPR, one caregiver, pulse returns patient becomes responsive |
| AR | augmented reality |
| AUL | abdominal ultrasound |
| BORIS | Behavioral Observation Research Interactive Software |
| BZK | benzalkonium |
| CAD | computer-aided design |
| CCMP | Cross-cutting Computational Modeling Project |
| CPR | cardiopulmonary resuscitation |
| CPU | choking patient becomes unconscious |
| CTV | crew task volume |
| ECG | electrocardiogram |
| ECL | Exercise Countermeasures Laboratory |
| eZLS | enhanced Zero-gravity Locomotion Simulator |
| IRB | Institutional Review Board |
| ISS | International Space Station |
| IV | intravenous |
| LLO | long–long, opposite sides of table |
| LLS | long–long, same side of table |
| LSX | long–short, crosswise sides of table |
| MSA | medical station analysis |
| OCT | optical coherence tomography |
| RFT | restricted feet |
| RVL | restricted volume large |
| RVS | restricted volume small |
| SUS | system usability scale |
| TLX | task load index |
| URV | unrestricted volume |
| VR | virtual reality |
| VRML | virtual reality modeling language |

# Appendix B.—Post-Testing Feedback Questionnaires

## B.1 Subject Post-Session Feedback Questionnaire

Subjects were given the following questionnaire after completion of each trial:

Name/Title:
Organizational Affiliation:
Date of testing:
Experimenter:
Scenario:

POST-SESSION QUESTIONNAIRE

1. Were you able to conduct the procedure in this session to a satisfactory level of realism?

   Yes – my actions and times to complete them were representative of how I conduct this procedure in real life.
   No – the environment did not permit me to execute this procedure as I would in real life.
   If you answered No, please tell us what was missing or disruptive.

2. Describe the sufficiency of the spatial allocation to perform the procedures when a fixed volume was imposed.

   - Did you feel you were able to conduct the procedure without being hampered by the volume available?
   - Even if you felt your performance didn't suffer due to the volume available, did you feel uncomfortable performing the procedure in this space?
   - If you were uncomfortable, please tell us where the space needed to be larger (and by how much) for you this discomfort to be relieved.

3. Please comment on the degree to which your stature and physical characteristics were supported by the environment and layout in this scenario.
4. Describe the challenges you encountered when performing these procedures. What could be done to reduce these challenges?
5. If you were working with another caregiver, describe the way you divided your roles – and how you used the space in your role.
6. If you worked alone on this procedure, what (if anything) would you have asked a second caregiver to do if one were available?
7. We know this is difficult to think about, but if you consider doing this procedure in a microgravity environment, what do you think we'd need to change to support that? What would you recommend?
8. Please provide any further thoughts you wish to share.

## B.2 Subject Post-Study Feedback Questionnaire

Subjects were given the following questionnaire at the completion of all testing:

Name/Title:
Organizational Affiliation:
Date of testing:
Experimenter:

POST-STUDY QUESTIONNAIRE

1. Try to think about doing these in microgravity, and please comment on the conditions that you experienced where there was restricted volumes vs. unrestricted volumes for the same procedure.
2. Try to think about doing these in microgravity, and please comment on the conditions that you experienced, and how well your performance was supported by the environment, when you were free-ranging vs. when your feet were restricted to predetermined positions (restriction in general, but also the locations tested).
3. In your professional opinion, was the test setup sufficient to validly evaluate the exploration medical station design and determine the operation volume of performing the procedures? If not, why not?
4. Is there anything else you would like to tell us that would influence the design of a medical workstation?
5. Is there anything else you would like to tell us that would help us improve any part of the study (design, procedures, hardware, etc.)?

# Appendix C.—NASA–STD–7009A Compliance

Table C.1 lists the criteria for the scoring levels as described in NASA–STD–7009A (Ref. 5). Table C.2 lists the self-assessment scores and evidence of compliance from the Medical Station Analysis Project.

TABLE C.1.—KEY ASPECTS OF CREDIBILITY ASSESSMENT LEVELS (FROM REF. 5)

| | Models and simulations (M&S) development | | | M&S use (operations) | | | Supporting evidence | |
|---|---|---|---|---|---|---|---|---|
| Level | Data pedigree | Verification | Validation | Input pedigree | Uncertainty characterization | Results robustness | M&S history | M&S process/ product management |
| 4 | All data known and traceable to real-world system (RWS) with acceptable accuracy, precision, and uncertainty | Reliable practices applied to verify the end-to-end model; all model errors satisfy requirements. | All M&S outputs agree with data from the RWS over the full range of operation in its real operating environment. | All input data known and traceable to RWS with acceptable accuracy, precision, and uncertainty. | Statistical analysis of the output uncertainty after propagation of all known sources of uncertainty. | Sensitivities known for most parameters; most key sensitivities identified. | Nearly identical model *and* use. | Controlled processes are applied; measurements used for process improvement. |
| 3 | All data known and traced to sufficient referent. Significant data has acceptable accuracy, precision, and uncertainty. | Formal practices applied to verify the end-to-end model; all important errors satisfy requirements. | All key M&S outputs agree with data from the RWS operating in a representative environment. | All input data known and traced to sufficient referent. Significant input data has acceptable accuracy, precision, and uncertainty. | Uncertainty of results are provided quantitatively through propagation of all known uncertainty. | Sensitivities known for many parameters including many of the key sensitivities. | At most minor changes in model *and* at most minor differences in model use. | Controlled processes are applied; process compliance is measured. |
| 2 | Some data known and formally traceable with estimated uncertainties. | Documented practices applied to verify all model features; most important errors satisfy requirements. | Key M&S outputs agree with data from a sufficiently similar referent system. | Some input data known and formally traceable with estimated uncertainties. | Most sources of uncertainty identified, expressed quantitatively, and correctly classified. Propagation of the uncertainties is assessed. | Sensitivities known for a few parameters. Few or no key sensitivities identified. | At most moderate changes in model *and* at most moderate differences in model use. | Formal processes are applied. |
| 1 | Some data known and informally traceable. | Informal practices applied to verify some features of the model and assess errors. | Conceptual model addresses problem statement and agrees with available referents. | Some input data known and informally traceable. | Sources of uncertainty identified and qualitatively assessed. | Qualitative estimates only for sensitivities in M&S. | New model or major changes in model, *or* major differences in model use; but, model/changes/ uses documented. | Informal processes are applied. |
| 0 | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. | Insufficient evidence. |

TABLE C.2.—SELF-ASSESSMENT SCORES AND EVIDENCE OF COMPLIANCE

| Factor | Self assessment | Evidence of compliance |
|---|---|---|
| Data pedigree | NA | All of the data processing was performed with commercially available or open-source software. |
| Verification | 1 | Mathematical checks were used to determine the accuracy of the custom codes used to calculate the cuboid volumes and the convex hull volumes.<br>Motion capture data collection methods include quantification of the motion capture system calibration error. |
| Validation | 2 | Comparison of plots to video data. |
| Input pedigree | 3 | Documented data collection procedures based upon industry standards.<br>Test plan established prior to data collection.<br>Motion data collected from a human subject performing the medical procedures in 1g. |
| Results uncertainty | 1 | The sources of uncertainty have been identified (subject adaptability, anthropometric variability, variability in procedure performance due to experience level, training, etc., variability due to performing the tasks in 0g versus 1g). |
| Results robustness | NA | All of the data processing was performed with commercially available or open-source software. |
| Use history | 1 | Similar analysis methods were used to calculate the operational volume used when exercising on exploration exercise devices. An analysis was performed to determine if the exercise motions would remain contained within the volume allocated for exercise by the Multi-Purpose Crew Vehicle (MPCV) program. |
| Models and simulations (M&S) management | 2 | Roles and responsibilities are defined within the analysis plan.<br>The Cross-cutting Computational Modeling Project (CCMP) biomechanical modeling effort follows NPR 7150.2B and NASA–STD–7009A.<br>The codes used for the analysis are available on a NASA shared drive. |

# References


1. International Space Station Integrated Medical Group (IMG) Medical Checklist. JSC–48522–E4, 2001. https://www.nasa.gov/centers/johnson/pdf/163533main_ISS_Med_CL.pdf Accessed Aug. 6, 2019.
2. NASA Task Load Index. https://healthit.ahrq.gov/health-it-tools-and-resources/evaluation-resources/workflow-assessment-health-it-toolkit/all-workflow-tools/nasa-task-load-index Accessed Aug. 6, 2019.
3. System Usability Scale (SUS). https://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html Accessed Aug. 6, 2019.
4. Behavioral Observation Interactive Software (BORIS). http://www.boris.unito.it/ Accessed Aug. 6, 2019.
5. Standard for Models and Simulations. NASA–STD–7009A, 2016.