UMTRI-2021-4 OCTOBER 2021

Volunteer Evaluation of an Automated Wheelchair Tiedown and Occupant Restraint System

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Technical Report Documentation Page

1. Report No. UMTRI-2021-4	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Volunteer Evaluation of an Automated Wheelchair Tiedown and Occupant Restraint System		5. Report Date October 2021 6. Performing Organization Code
7. Author(s) Kathleen D. Klinich, Nichol R. Orton, Laura Malik, Ellison Zak, Miranda St. Amour, Miriam A. Manary		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Michigan Transportation Research Institute 2901 Baxter Rd. Ann Arbor MI 48109		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration		13. Type of Report and Period Covered Final, June 2020-September 2021 14. Sponsoring Agency Code

15. Supplementary Notes

We would also like to acknowledge the many valuable contributions of UMTRI staff members Brian Eby, Jen Bishop, Jacob Wettstein, Patrick Pek, and Joshua Fischer.

16. Abstract

This project evaluated an automated wheelchair tiedown and restraint system (AWTORS), developed as part of a study sponsored by the National Highway Traffic Safety Administration (NHTSA), that could be safely and independently used in an automated vehicle (AV) by someone using a wheelchair as vehicle seating. The NHTSA project used computational modeling to identify target geometry for belt anchors and placing wheelchair seating stations, which were then implemented in two test fixtures. The NHTSA project also designed and constructed an automated wheelchair securement system meeting specifications of the Universal Docking Interface Geometry (UDIG) that have been included in RESNA and ISO standards. Vehicle anchorages meeting the specifications were constructed, as were attachment designs for a commercial manual and power wheelchair. The occupant restraint portion of the AWTORS include an automatic seatbelt donning mechanism based on a past UMTRI prototype, but with geometric improvements. For the current project, volunteer testing was performed with 10 wheelchair users. Using the two study wheelchairs equipped with UDIG anchors, the study evaluated the usability of three wheelchair seating stations with different geometries, each with two different belt conditions, as well as conditions with the volunteer's own wheelchair. Data included videos of ingress and egress, scans of volunteer posture, and questionnaires to document the time spent docking the wheelchair and donning the seatbelt, belt fit, comfort, and potential usability issues. Average time for entry, docking, and donning just over 2 minutes in all conditions. To collect additional data on the range of wheelchair sizes and occupant size and posture, additional 3-D measurements of people seated in their wheelchairs were gathered outside a local medical facility, demonstrating feasibility of a field measurement method.

17. Key Word Wheelchair transportation, UDIG, occupant restraint, automated vehicles		18. Distribution Statement	
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages 137	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Introduction

Background

For people with disabilities who do not drive, automated vehicles (AVs) would provide a welcome opportunity for independent travel. The Americans with Disabilities Act (United States Department of Justice 2010) and its interpretation as the ADA Accessibility Guidelines (Architectural and Transportation Barriers Compliance Board 2016) through the US Access Board provides detailed transportation requirements that are translated into regulations by the US Department of Transportation. These establish necessary minimum levels of accessibility and accommodations that are required in compliant public transportation, including requirements for assistance by a driver or other operator. However, these requirements do not consider the scenario where an individual with a disability travels in a public vehicle without a driver, caregiver, or other source of assistance.

Some people who use wheelchairs cannot transfer to conventional vehicle seating and must remain seated in their wheelchair for motor vehicle travel. In these situations, it is necessary to secure the wheelchair to the vehicle and provide occupant protection with a Wheelchair Tiedown and Occupant Restraint System (WTORS). For this population to fully realize the promise of independent AV transportation, a WTORS must be crashworthy for use in smaller vehicles, able to be used without third-party assistance, and able to accommodate a wide range of wheelchair types.

NHTSA AWTORS Project Overview

UMTRI researchers recently completed a project to develop an automated WTORS (AWTORS) that could be safely and independently used in an AV by people who remain seated in their wheelchairs for travel (Klinich et al. 2021). This project was sponsored by the National Highway Traffic Safety Administration. The project began with a literature review related to wheelchair transportation safety, with a focus on topics that are relevant for providing the opportunity for safe, independent use of automated vehicles to people who use wheelchairs.

Design and Prototype Development

The automatic wheelchair tiedown portion of the AWTORS was designed to meet the specifications of the Universal Docking Interface Geometry (UDIG). The specifications for the geometry have been included in an annex of WC18 and WC19 (voluntary wheelchair transportation safety standards) since 2009 (RESNA 2017). Any wheelchair with attachment hardware meeting the specification should be able to connect with any vehicle securement hardware meeting the specification. The two wheelchairs selected for use in the NHTSA study (one manual, one power) met the voluntary WC19 standards for crashworthiness in frontal impacts.

Figure 1 shows the UDIG attachments developed for the manual wheelchair. The attachments are constructed of aluminum tubing components, connected via aluminum plates to the wheelchair structure near the crash-tested rear tiedown hooks. The attachments for the power wheelchair are shown in Figure 2. These attachments were also mainly constructed of aluminum tubing components and bolted to the wheelchair near the crash-tested rear tiedown securement points. The attachments were also secured to a third point between the rear caster wheels for increased stability because of a conveniently located structure on the wheelchair.

Figure 1. UDIG attachments for manual wheelchair.

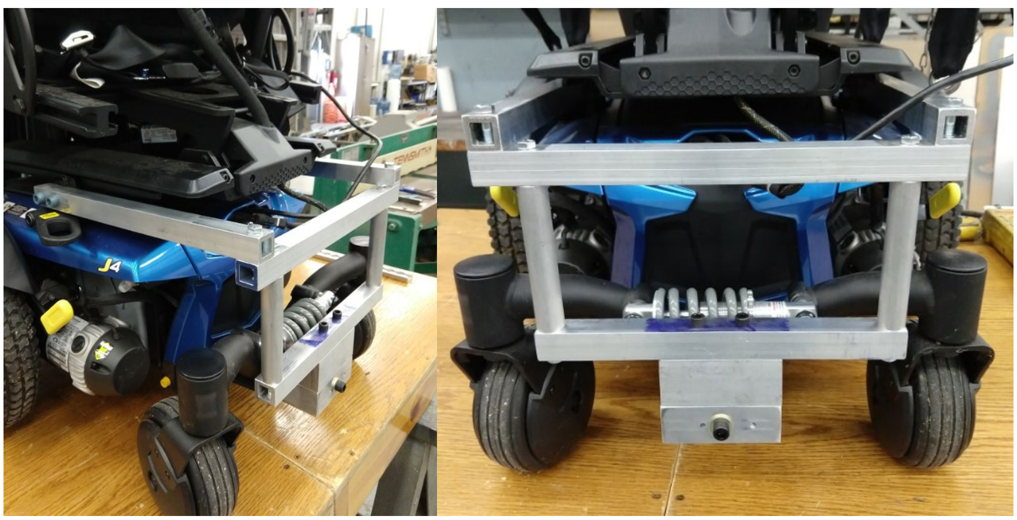


Figure 2. UDIG attachments for power wheelchair.

The vehicle UDIG anchorages are shown in Figure 3. The anchorages consist of two hooks that are initially positioned near the center of the fixture (left) and then powered by two separate actuators to move outward (right) until they engage with the UDIG attachments on the wheelchair. The actuators stop automatically when they engage with the attachments. The wheelchair user backs into the station until their attachments contact the front “bumper” (structure with top edge marked in green) that prevents them from damaging the actuators. Figure 4 shows examples of how the manual and power wheelchairs engaged with the anchorages.

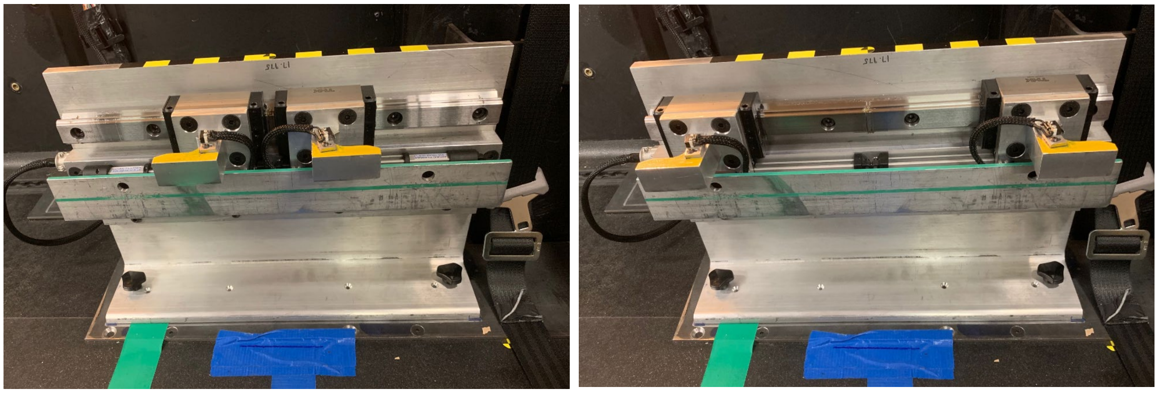


Figure 3. UDIG vehicle anchorages in initial (left) and extended (right) conditions.

Figure 4. Manual (left) and power (right) wheelchairs engaged with the vehicle UDIG anchorages.

For the automated restraint system portion of the NHTSA project, we modified an earlier prototype of an automated belt donning system that had been developed as part of a previous research project for a driver wheelchair station (Weir et al. 2011). The buckle end of the seatbelt was attached to the end of a rotating arm. The arm is initially be positioned upright, holding the seatbelt out of the way. When the occupant deploys the donning arm, it rotates down to the floor, placing the lap and shoulder belts across the driver’s body. For the current project, we iterated on this design (Figure 5, left) so the buckle end of the seatbelt is now attached to an extended structure on the rotating arm (Figure 5, right), such that it places the belt anchor closer to the occupant’s hip.

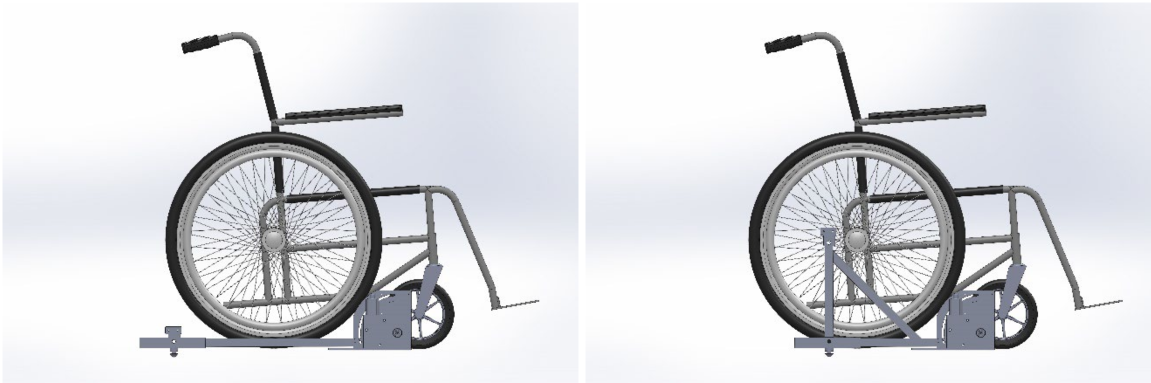


Figure 5. Original (left) and revised (right) designs of the seatbelt-donning system.

While the previous project demonstrated the crashworthiness of the donning arm when it was pinned to the floor, for the NHTSA project, we prioritized adjustability for volunteer assessment of usability. The geometry can be adjusted three ways, as illustrated in Figure 6. The geometry of the donning arm can be adjusted by shifting the vertical mount fore-and-aft on the arm, by shifting the belt attachment up-and-down on the vertical component, and by relocating the anchorage plate where the hinge and controlling actuator are connected. A requirement is that the wheelchair must have armrests that allow a space between the seatback and armrest.

Figure 6. Adjustability of donning arm geometry.

Computational Modeling

Computational modeling was used to identify the optimal location of the vehicle UDIG securement hardware relative to other interior vehicle components for both front and side crashes. Simulations analyzed how to balance the occupant position relative to belt anchorage locations and airbags, considering that wheelchair size will vary, whereas a vehicle seat would not. Simulations also considered placement of components relative to recommendations for space to accommodate wheelchairs and the amount of room needed to navigate into the wheelchair seating station.

In the NHTSA study, the restraint design optimization in frontal crashes was conducted using an integrated MADYMO model by combining the surrogate wheelchair base (SWCB) model, the Hybrid III midsize male ATD model, the model representing the UDIG design, a three-point seat belt system model, and airbag models. The first phase of modeling work focused on identifying the trends and effects from wheelchair location and belt anchorage location. Occupant injury risks with and without baseline airbag designs were investigated. Optimizations were conducted for both right-front and second-row-left locations. The results provide improved understanding on how seatbelts may interact with wheelchair-seated occupants in a wide range of UDIG and belt anchorage locations considering the size of the wheelchair, with and without airbags.

In the design optimization for side impacts, a set of MADYMO models similar to those used in frontal crashes was used for side impact simulations, except that ES-2re ATD replaced the HIII ATD, and a representation of a side door based on Dodge Caravan geometry was included. Because the UMTRI wheelchair model had not been previously validated in side impact testing, validation tests were conducted before proceeding with simulations to optimize side impact protection. Simulations examined wheelchair station location and belt geometry with and without airbags in near and farside impacts. Alternative belt configuration with an inboard rather than outboard D-ring were examined. Optimization results were harmonized with frontal optimizations. Because adequate restraint in farside crashes was not feasible with only belt restraint, modeling was used to design an innovative Center Airbag To Contain Humans (CATCH) in collaboration with colleagues from ZF.

The next modeling task developed MADYMO models representing the manual and power wheelchairs being used in volunteer and dynamic testing. Simulations evaluated the differences in frontal response using the SWCB and the two wheelchair models, using geometry for the wheelchair seating station and seatbelts that was feasible to achieve in the test vehicles. These simulations were used to identify test conditions for dynamic testing.

Volunteer Evaluation

In the NHTSA study, two test fixtures were used to assess the usability of the AWTORS by 8 volunteers. One was a 201 Dodge Caravan SE modified for use by occupants seated in wheelchairs, and the second was a body-in-white (BIW) of a Chrysler Town and Country that was also modified for component development and volunteer testing with wheelchair users. The NHTSA study evaluated right front and second row center positions in the BIW, as well as two configurations of a second-row left seating position in the minivan because they would be most feasible for access and restraint system design in a future AV.

Volunteer testing protocols and data collection tools were developed and approved by the University of Michigan Institutional Review Board. The main participant criteria were that participants must be regular users of wheelchairs but could transfer to the test wheelchairs that are equipped with the UDIG hardware.

After consenting, the participant transferred the test wheelchairs and performed the study tasks in the test fixture. Each volunteer entered the vehicle using a wheelchair ramp, maneuvered to the wheelchair space, secured the wheelchair using the automated docking station, and donned the automated seat belt. After documenting their position, posture, and belt fit with photographs and a 3-dimensional scan, the subjects then resumed the process by doffing the belt, disengaging the wheelchair from the docking station, and exiting the vehicle via the side ramp. Video was used to document the participants entry and exit from the vehicles.

Each participant performed these tasks with the manual and power wheelchairs, while entering the vehicle from curbside, and to first-row right and second-row left seating positions. Two different belt geometries were evaluated at each position. In addition to objective measures of docking efficiency and effectiveness, subjective feedback was gathered using questionnaires. Assessment included length of time between entry and being docked and restrained for travel as well as the number of attempts needed to dock and apply the seatbelt.

To allow safe testing of participants during the COVID19 pandemic, we developed an alternative procedure of using a Sense scanner to document the participant's posture as shown in Figure 7. Posture and belt fit were also documented through a series of photos.

Figure 7. Measuring volunteer belt fit with remote scanner instead of FARO arm.

Implementing Wheelchair Seating Stations in Test Fixtures

Figure 8 shows how the two locations for the UDIG in the Braun vehicle were selected. The process of lowering the floor to allow sufficient height for occupants seated in wheelchairs exposes the interior surface of the wheel wells. For the rearward (blue) conditions, we placed the UDIG anchorages as far rearward as space allowed, with the centerline located ~15 in inboard relative to the most prominent surface of the wheel well. This would allow the minimum 30 in width for the seating station required by ADA, which was needed to accommodate the width of the manual wheelchair. For the outboard (green) condition, the UDIG anchorage was placed directly in front of the wheel well, as close as possible to the left interior wall while still allowing room for the 30-in wide minimum seating space.

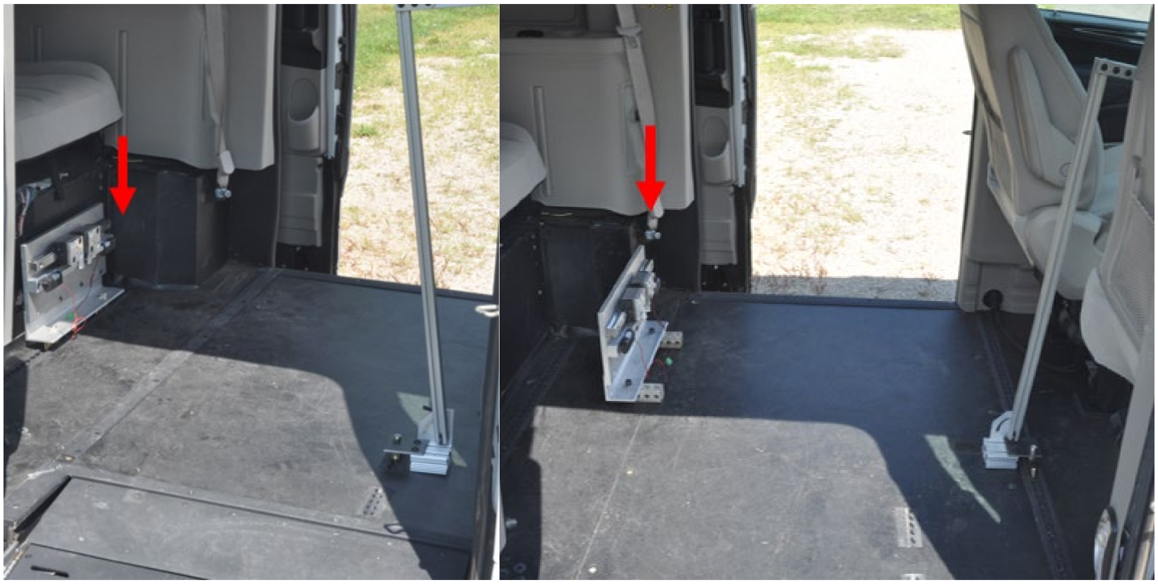


Figure 8. Two locations of the UDIG anchorages in the Braun vehicle: inboard of the left rear wheel well (left) and forward of the left rear wheel well (right).

The presence of the wheel well did not allow us to locate the outboard seatbelt anchor in the optimal location suggested by the simulations. Additional simulations showed better response with symmetric anchors. As a result, we placed the outboard anchor where it was feasible, and adjusted the donning arm geometry to place the inboard anchor in a matching location. For the blue conditions, we chose feasible lap belt anchor locations that provided an approximately 45-degree sideview lap belt angle for each of the two wheelchairs. Because the power wheelchair is longer than the manual chair, this resulted in a lap belt anchor position (dark blue) that was approximately 90 mm forward of the lap belt anchor position based on the manual chair (light blue). For the green condition, the same lap belt anchor was used in each condition. A fixture was added to the vehicle that allowed adjustment of the D-ring laterally, vertically, and fore-aft. For the blue conditions, we placed the D-ring close to the optimal locations in the X and Y directions. Vertically, we located the D-ring above the optimal location for the dark blue condition and below optimal location for the light blue condition. For the light green condition, we placed the D-ring in the optimal location. For the dark green condition, we placed the D-ring in a “practical” location that simulates using the existing D-ring location located on the C-pillar.

For the NHTSA study, the driver seat was removed, and tape used to mark locations 48 in, 54 in, and 60 in in front of the anchors. During testing, the experimenter noted how far forward the participant maneuvered while docking in the station.

For the purple conditions in the BIW second row, we wanted to compare the accessibility when the shoulder belt was located either inboard or outboard. We aimed for optimal belt anchorage placement, with the light based on manual and dark based on power. Both purple conditions used the same D-ring geometry, except the Y-location was inboard in the dark purple and outboard in light purple. A different design of belt-donning arm was used in the BIW, that allowed two degrees of freedom. As a result, it was not automated, but applied by the experimenter.

When setting up the test fixtures, ZF provided us with the longest typical seatbelts they had available. This was not sufficient length to allow maneuvering into the station, so we spliced about 18 in more webbing onto the belt system. Because of the weight of the extra length, the retractor spring was not strong enough to snug the webbing after donning. As a result, we instructed participants to snug the belts around themselves during testing.

Dynamic Testing

Ten frontal sled tests were performed to demonstrate differences with belt geometry and SCaRAB airbag presence, as well as to check the durability of UDIG anchors and attachments. Results showed a benefit of optimal geometry compared to a practical geometry representing a D-ring mounted to the C-pillar typically seen in accessible vans. Benefits of the airbag were greater with the practical geometry, and tests with the small female ATD had acceptable results using the restraint system optimized for the midsized male ATD. The initial UDIG attachments for the manual wheelchair performed well, as did a lighter weight version. The power wheelchair attachments shown in Figure 2 required strengthening to achieve successful performance.

Eight farside impacts were run to evaluate different versions of the CATCH bag, as well as to check durability of UDIG attachments in side impact. Tests demonstrated which characteristics provided reasonable retention within the wheelchair for both midsized male and small female occupants. The UDIG attachments designed for the manual chair were effective under farside impact conditions.

Methods: Laboratory Testing

Test Conditions

The current study measured 10 participants and duplicated the methods of the NHTSA study described above, with some exceptions detailed in this section. Table 1 lists the conditions tested. The four conditions in the Braun van used the same geometry as in the NHTSA study. For the BIW, a single second row condition was evaluated, with the belt geometry based on the test conditions with the NHTSA volunteers that provided the best overall belt fit across volunteers, which correspond to condition D for the lap belt anchors and condition A for the shoulder belt anchor. The belt geometries for these five conditions are shown in Figure 9, Figure 10, and Figure 11. On these plots, the origin is located at the top center point of the UDIG anchor fixture.

Table 1. Summary of UDIG and anchor locations.

Condition	UDIG Location	Lap belt anchors	D-ring location
A	Braun, 2nd row, rearward	Fixed, best possible	Optimal
B	Braun, 2nd row, outboard	45 degrees with manual	Above optimal
C	Braun, 2nd row, outboard	45 degrees with power	Below optimal
D	Braun, 2nd row, rearward	Fixed, best possible	Practical (C-pillar)
I	BIW, 2nd Row, center	Condition D	Condition A

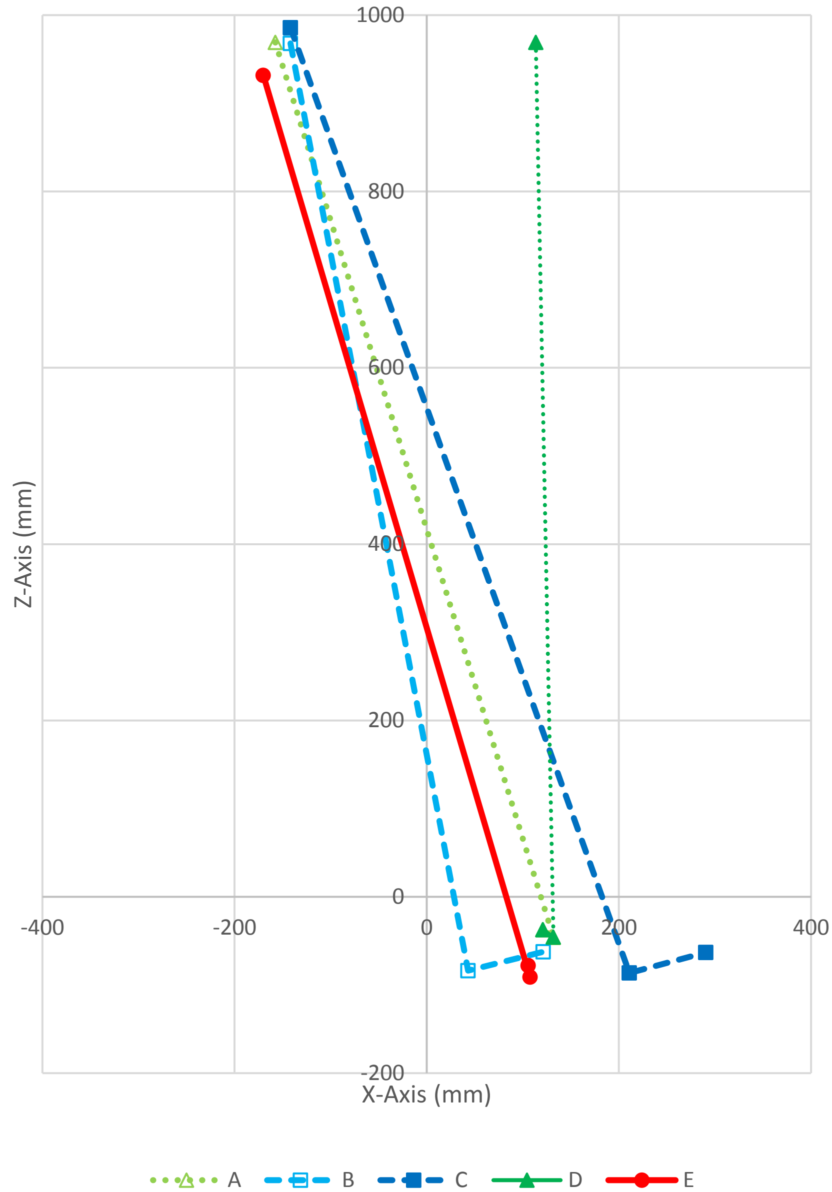


Figure 9. Belt geometry in X-Z plane (right side view).

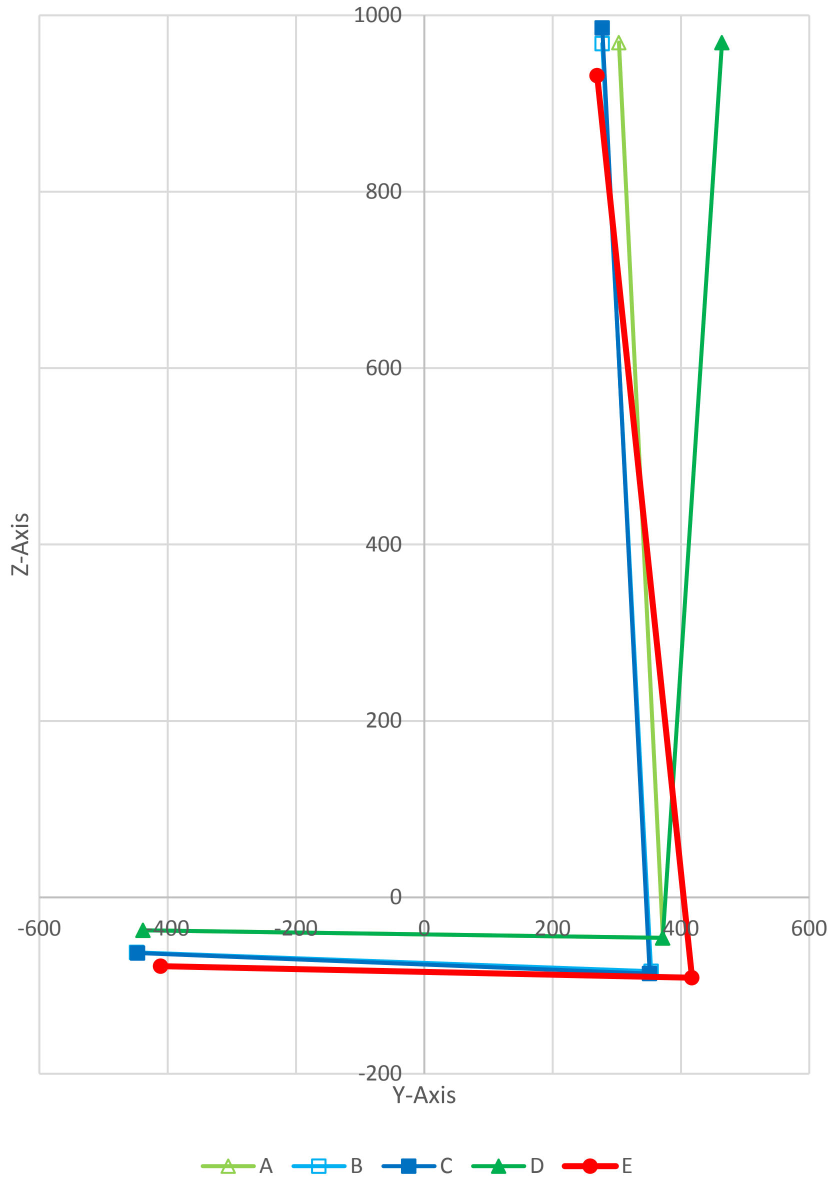


Figure 10. Belt geometry in Y-Z plane (front view).

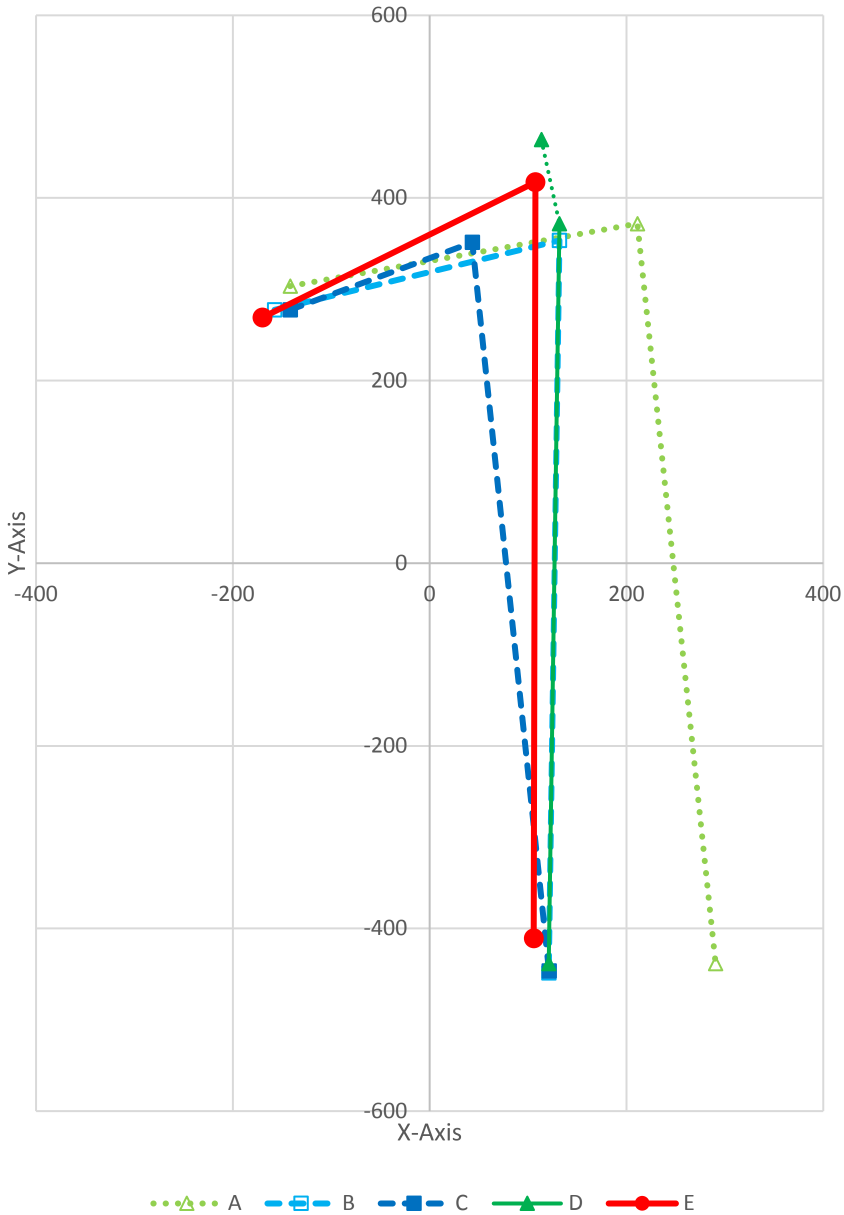


Figure 11. Belt geometry in X-Y plane (plan view).

The main difference in the test conditions in the Braun van was that the fore/aft wheelchair space was restricted to be 48 in for the green conditions and 54 in with the blue conditions, as illustrated by the white barrier in Figure 12. In addition, a laser level was positioned to mark the centerline of the wheelchair station rather than duct tape as shown in Figure 13.

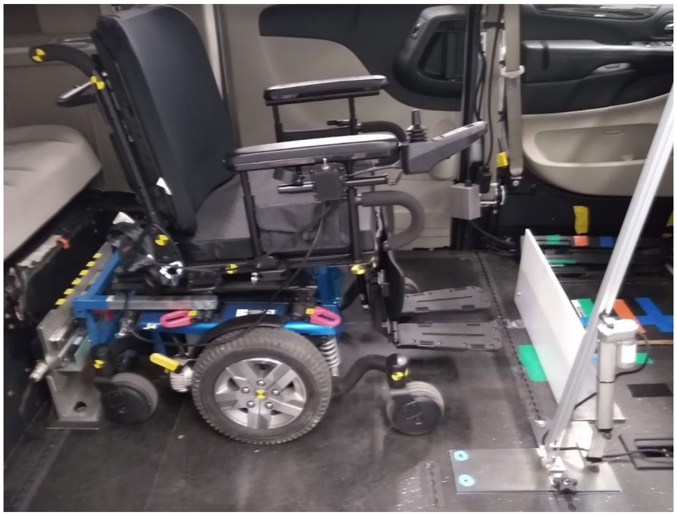


Figure 12. Illustration of barrier to restrict space in Braun van.

Figure 13. Replaced duct tape centerlines with a laser that shows alignment centerline on floor and cross on barrier.

Compared to the NHTSA testing, different conditions were used in the BIW fixture. The second-row seating station (condition I) was reconfigured to more closely resemble the second row left station in the Braun vehicle, and front row conditions were not evaluated. The same style of automated donning system was used, rather than an experimenter-operated system with two degrees of freedom. The seating station was also restricted to allow 60 in of fore/aft space in front of the UDIG anchorages, as shown in Figure 14. In addition, we added a forward LED panel that lights up when each securement anchorage hook is fully engaged with the wheelchair attachment.

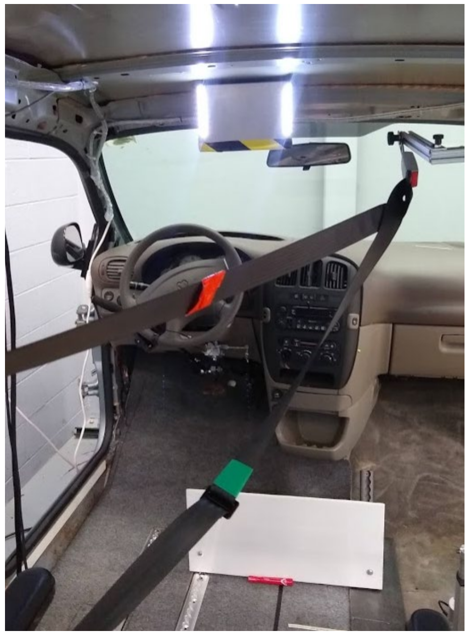


Figure 14. LED panel lights up on each side when UDIG hooks are engaged, plus barrier to restrict forward space.

In the body-in-white, our main focus was to compare belt fit across participants when they are in the manual, power, and their own wheelchair. We also wanted to identify how it might work if a seating station was equipped with both UDIG anchors and tiedown anchors. When using tiedowns, the ideal sideview angle of the rear tiedown is 45 degrees. Figure 15 shows how the traditional tiedown components were located adjacent to the UDIG anchors. In future installations, a WTORS supplier could offer this as a “combination” anchor package. Placing the traditional tiedowns in this location also helps to locate the occupant relative to the belt anchors optimized for someone using a wheelchair with UDIG attachments.

Figure 15. Traditional wheelchair tiedowns located adjacent to AWTORS fixture.

Up to three conditions were documented for the volunteers using their own wheelchair. In the first condition, we recorded the seatbelt fit with the baseline geometry in an “as donned” volunteer selected position. An example of condition I with a pilot volunteer is shown in Figure 16, where the belt is initially caught on the back of the armrest. For the second condition, I*, the belt is manually adjusted by the study team and/or volunteer to improve fit, as shown in Figure 17 while keeping the anchor positions the same as condition I. This often involved routing the belt optimally around wheelchair armrests to improve lap belt fit to the pelvis. In the third condition, I**, shown in Figure 18, we adjusted the belt anchor locations to improve fit, and recorded the locations of the shifted anchors using a FARO arm after the occupant test session. For example, anchors were often moved to allow the lap belt to insert between the wheelchair frame and manual drive wheel when the volunteer was in their own manual chair. This allowed better wrapping of the lap belt around the pelvis.

Figure 16. Belt fit of pilot volunteer in wheelchair with baseline geometry as donned; belt is caught on rear armrest.

Figure 17. Belt fit of pilot volunteer in wheelchair with baseline geometry, adjusted to improve fit.

Figure 18. Belt fit of pilot volunteer in wheelchair with belt geometry adjusted to provide better fit.

The final change compared to the previous NHTSA study was a redesign of the controller that operated the UDIG anchors. Some of the NHTSA volunteers lacked the dexterity to operate recessed buttons in the controller. Two soft knobs were added to the controller as shown in Figure 19.

Figure 19. Revised control buttons for people with limited dexterity.

Subject requirements and recruitment

The main screening criteria for the volunteers was that they regularly used a wheelchair in the past year but would be able to transfer to and operate the two wheelchairs purchased for the study. In addition, we attempted to recruit subjects divided among these stature ranges: ≤ 63 in, 64-69 in, ≥70 in. The main method of recruiting subjects involved posting the study on the website UMHealthResearch.org. To supplement this recruitment effort, flyers were also distributed by the Ann Arbor Center for Independent Living and were posted at the University of Michigan Wheelchair Seating Clinic. When potential subjects responded, they were interviewed by phone or email using the screening questions included in Appendix A.

Test protocol

To allow contact tracing, experimenters scanned into each lab space used for testing. The power wheelchair was set to a common starting position, with the seatpan angle at 5 degrees from horizontal and seatback angle at 10 degrees from vertical. The experimenters cleaned the fixtures, tools, and equipment with sanitizing wipes and recorded the effort on a checklist.

One experimenter prepared the paperwork, which consisted of two consent forms (included in Appendix A), an ethnicity form, a test matrix for each experimenter, and a checklist. The second experimenter set up the area where the participant self-applied reference targets, ensuring there was sufficient stickers and tape available, and placed a mirror on the participant table. Experimenter Two also prepared the scanner and laptop and placed it in position for use in the first test vehicle. To minimize interaction, Experimenter 1 worked in the Braun vehicle, while Experimenter 2 worked in the BIW. Each experimenter prepared the fixture for testing. Steps included:

- Check that tools are available and stowed
- Turn on lighting
- Set up first configuration
    - Check that actuators are working
    - Check that LED signals are working (BIW only)

    - Check connections if needed
- Mount GoPro on side panel (Braun only)
    - Mount iPad to steering wheel
    - Check that connection is working
- Set up video camera in correct spot
    - Check battery / plugged in
    - Check video card
    - Check camera angle / view
- Position laser level
- Check battery and place still camera on prep table
- Prep test labels for video/photos
- Move mirror to BIW after participant uses it for sticker placement

Participants were asked to pull up to the front of the building upon arrival and were met by an experimenter. The experimenter checked their health screening status and directed them to drive around the building to the high bay area. An experimenter then met them outside the high bay door and escorted the participant into the testing area.

The experimenter read the introduction script to the participant and gave them consent and demographic forms to fill out. After informed consent was obtained, the participant was shown a short video showing them what docking in the vehicle looks like. The participant then transferred to the first wheelchair and applied target stickers with the help of a diagram, verbal instructions, and a mirror. Next, a diagram of good belt fit was explained, and participants were informed that they could adjust the seatbelt if it got caught during application or request help if necessary. After the participant transferred into one of the testing wheelchairs, front and side photos were taken of the participant in front of a grid on the wall. In addition, 3-dimensional shape data were collected using a portable Kinect measurement system and then the subject began the trials.

Participants used a ramp to enter the vehicle mockups and then maneuvered their wheelchair into the docking stations. A laser level on the floor, mirrors, and a camera were used to help participants line up with the docking station located behind them. When the wheelchair was in position, the participant pressed a button to activate the UDIG hooks to latch onto the wheelchair hardware.

Once the wheelchair was locked in place, the participant pressed a button to activate the seatbelt to lower into position over their body. When measurements were complete, another button was pressed to raise the seatbelt out of the way and another to unhook the UDIG hardware from the wheelchair when the participant was ready to exit the vehicle mockup.

Each trial was video recorded during ingress and belt application. Photos of each participant were taken to record their position and belt fit for each condition, and then the participant was scanned with a handheld scanner. The participant began a survey (Appendix A) while belted in the vehicle, and then completed the survey after exiting the vehicle. The survey includes questions about ease of docking and belt application, as well as belt comfort. Video was also collected during belt doffing and vehicle egress.

There were four trials in the Braun van, with participants evaluating two configurations with the manual wheelchair, and two conditions with the power wheelchair. For the BIW, the volunteer evaluated the seating station with both the manual and power wheelchairs. In the last trial, the volunteer used their own wheelchair to enter the seating position, and their wheelchair was secured using 4-point strap tiedowns. The initial belt fit was documented. Then the belt fit was adjusted manually without moving anchors, and documented. Finally, the anchors were adjusted to improve fit and documented. The usability of the donning arm was checked with the shifted anchors. The participant then left the vehicle, and the position of the shifted anchors was measured with a FARO arm.

The test matrix was designed using a fractional factorial design based on 24 participants, although it was only possible to recruit 10 subjects during the time available to conduct the study. The planned test matrix for the volunteer identification numbers tested is shown in Table 2. Participants alternated between vehicles for each trial, completing three trials in one wheelchair before transferring to the second wheelchair, and then switching to their own wheelchair for the trials in the last condition. After transferring to the second wheelchair and their own wheelchair, front and side photos were again taken in front of a grid on the wall. They were also measured using the Kinect measurement system in each wheelchair. Odd-numbered participants had their first three trials in the manual wheelchair, followed by three in the power wheelchair. Even-numbered participants reversed this wheelchair order. Trial orders were randomized for each participant. If a volunteer was not able to independently operate the manual wheelchair, all trials were conducted in the power wheelchair.

Table 2. Planned test matrix for recruited participants

Volunteer#/Trial #	1	2	3	4	5	6	7	8	9
TW01	I	C	A	**I**	**D**	**B**	_I_	_I*_	_I**_
TW02	**I**	**C**	**A**	B	I	D	_I_	_I*_	_I**_
TW03	I	B	D	**C**	**A**	**I**	_I_	_I*_	_I**_
TW04	**I**	**B**	**D**	I	A	C	_I_	_I*_	_I**_
TW09	A	I	B	**C**	**D**	**I**	_I_	_I*_	_I**_
TW12	**B**	**I**	**C**	A	D	I	_I_	_I*_	_I**_
TW13	C	I	B	**I**	**A**	**D**	_I_	_I*_	_I**_
TW14	**C**	**I**	**B**	D	I	A	_I_	_I*_	_I**_
TW23	A	C	I	**D**	**I**	**B**	_I_	_I*_	_I**_
TW24	**B**	**C**	**I**	D	A	I	_I_	_I*_	_I**_

Power wheelchair Manual Wheelchair _Volunteer's wheelchair_

After all trials were complete, participants were given a Volunteer Questionnaire to fill out (Appendix A) that included questions about their personal travel experiences while using a wheelchair. They were given a payment form to fill out and were paid for their participation. Then they were escorted back to their vehicle.

The post-session lab protocol involved downloading video and photos for each subject. All electronic equipment was moved to the charging area. Experimenters repeated the laboratory cleaning checklist after each participant visit.

Results: Laboratory Testing

Participant Characteristics

Table 3 shows the characteristics of the study participants. Four volunteers were considered to have short stature, two tall, and three intermediate. Participant age ranged from 19 to 74, and the participants were fairly evenly divided among males and females.

Table 3. Participant characteristics.

ID	Age	Sex	Stature (cm)	BMI	Disability	Normal wheelchair
TW01	25	NI*	1524	53.7	Spinal bifida	Manual
TW02	19	M	1448	23.8	Neuropathy/tethered cord	Manual
TW03	31	F	1067	23.9	Limited endurance because of respiratory issues, muscle strength	Power
TW04	74	M	1600		Amputee	Manual
TW09	50	F	1613	26.1	Right foot amputee	Manual
TW12	32	F	1651	33.3	L3S1 SCI due to Spinal bifida	Manual
TW13	27	M	1422	26.9	Spinal bifida	Manual
TW14	49	F	1626	27.5	MS	Manual
TW23	65	M	1829	25.1	T12 Incomplete	Manual
TW24	28	M	1905	27.5	Spinal cord injury	Manual

*Preferred not to identify sex

All but one of the participants regularly used a manual wheelchair, and only three had previous experience with a power wheelchair. None of the volunteers' wheelchairs were equipped with WC19 compliant tiedown hooks. Nine of the volunteers had been using wheelchairs for three or more years. Eight participants regularly transferred from their wheelchairs to drive their personal vehicles; none drove in vehicles where they remained seated in their wheelchairs, although the participant who used the power wheelchair traveled regularly as a passenger while seated in their wheelchair. Likely as a result of our recruiting requirement that participants be able to transfer to our study wheelchairs, our volunteers had limited experience in traveling while seated in their own wheelchairs.

Test Matrix

The executed test matrix is shown in Table 4. The initial plan for testing was that each participant should have 9 trials, one in each condition, although they would not exit and enter the vehicle in between the different trials in their own wheelchair. However, for some participants, if the trials were taking longer, we skipped some trials in the study wheelchairs to ensure that they had sufficient time to be measured in their own wheelchairs. In addition, for some participants, their initial belt fit in their own wheelchair was sufficient that the adjustment condition, I*, was not necessary.

Table 4. Order of trials completed by each participant using each wheelchair.

	A	B	C	D	IM	IP	IV	I*	I**
TW01	3M	6P	2M	5P	1M	4P	7V	8V	9V
TW02	3P	5M	2P	-	4M	1P	7V	-	9V
TW03	6P	2P	5P	3P	-	4P	7V	8V	9V
TW04	5M	2P	6M	3P	4M	1P	7V	8V	9V
TW09	1M	3M	4P	-	2M	6P	7V	8V	9V
TW12	4M	1P	3P	5M	6M	2P	7V	-	-
TW13	5P	3M	1M	6P	2M	4P	7V	-	9V
TW14	-	3P	1P	4M	5M	2P	7V	-	9V
TW23	1M	6P	2M	4P	3M	5P	7V	-	9V
TW24	5M	1P	2P	4M	6M	3P	7V	-	9V
# Power	3	7	6	5		10	1	1	1
# Manual	6	3	4	3	9		9	3	8

Overall, there were 25 completed trials in the study manual wheelchair, and 31 completed trials in the study power wheelchair. For the trials using the volunteer's own wheelchairs, there were three with one volunteer in a power wheelchair, and twenty in nine different personal manual wheelchairs.

Belt Fit

Because of COVID-motivated protocols to reduce close proximity measurements, we assessed belt fit three ways to improve the quality of the measurement: still photos of participants, 3-D scan data, and participant videos. Shoulder belt score was calculated from the scan data, measuring the horizontal distance from the manubrium to the inboard point on the seatbelt. Figure 20 shows examples of the range of shoulder belt fit scores. For lap belt fit, a qualitative assessment of belt fit was made from the photos using the categories illustrated in Figure 21. Categories include touching thighs (no examples available), below ASIS, over ASIS, above ASIS, and on abdomen.

Figure 20. Examples of range of shoulder belt fit scores (mm).

Fit	Touching neck	Inboard	Centered	Outboard
Photo				
SBS	-39	0	30	82

Figure 21. Examples of qualitative lap belt fits.

Fit	Below ASIS	Over ASIS	Above ASIS	On Abdomen
Photo				
LBF	2	3	4	5

Appendix B contains photos of belt fit for all participant trials, while Figure 22 compares fit across all participants for condition I and the power wheelchair and Figure 23 does so for condition D. For a few cases, the SBS listed in the appendix may seem inconsistent with the photo; review of these cases showed that the participant moved the belt between the time of the photo and the time of the scan from which the scores were calculated. Condition I reflects the best geometry across participants in the NHTSA study. Here, shoulder belt appears positioned at the mid to inboard shoulder across all participants. Lap belt fit seems correlated with participant BMI, with better belt fit seen with lower BMI.

Condition D has the D-ring approximating using the vehicle D-ring location on the C-pillar, representing a practical belt geometry often used in van conversions. As expected, the shoulder belt was located on the outboard shoulder or upper arm with all participants. Lap belt fit again seems to be related to BMI with higher BMI subjects exhibiting poorer lap belt fit.

The mean shoulder belt score for each test condition, as well as overall and for each type of wheelchair, is shown in Figure 24. With the exception of condition D, mean belt fit was similar for each condition. The distribution of estimated lap belt fit by condition is shown in Figure 25. Again, there was not a drastic variation in the range of fits across each condition.

Figure 22. Belt fit of all participants in condition I, power wheelchair.

Figure 23. Belt fit of all participants in condition D.

	W02 Not tested	
	W09 Not tested	
		
		

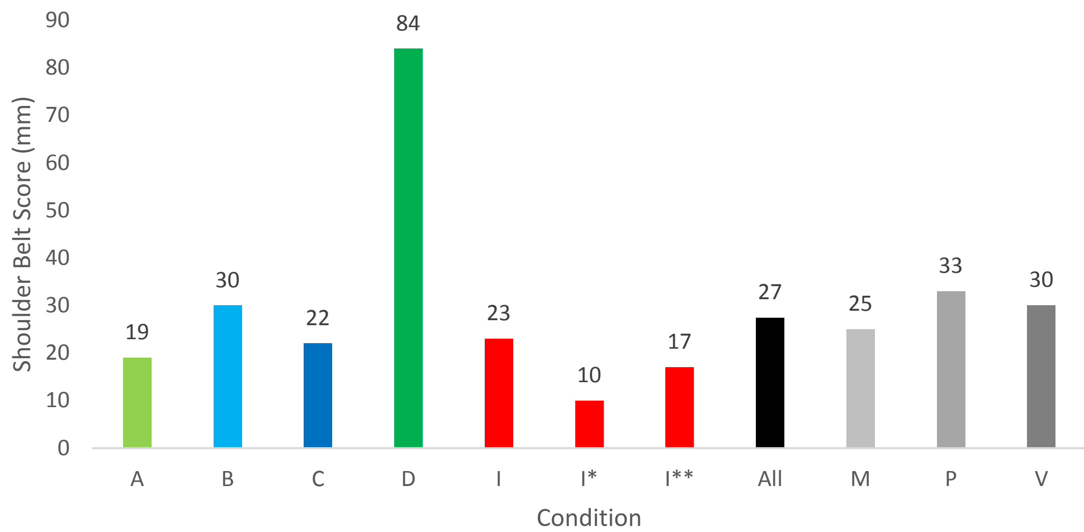


Figure 24. Mean shoulder belt score by condition and wheelchair type.

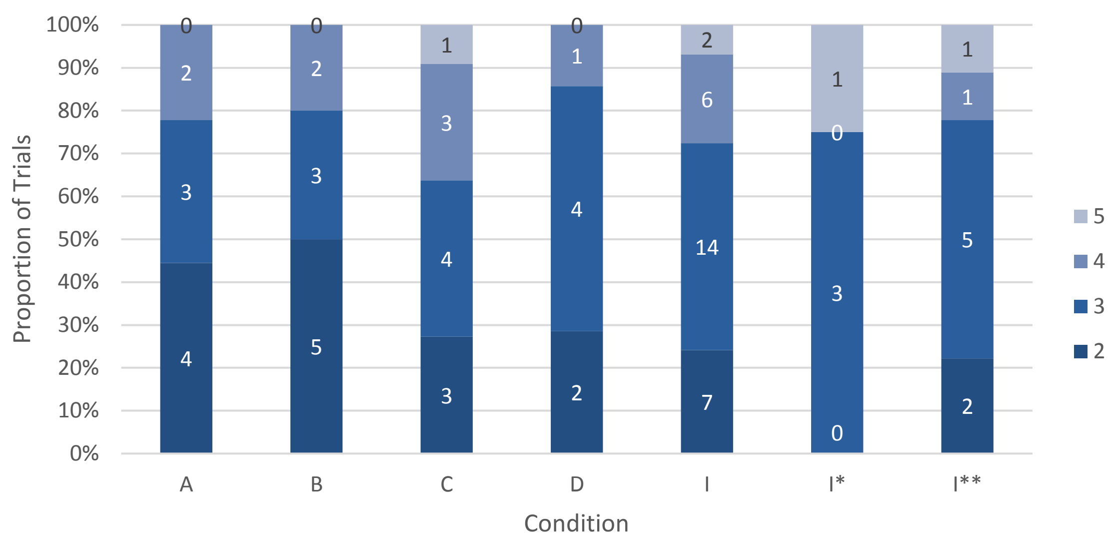


Figure 25. Distribution of lap belt scores by condition.

Ingress, Docking, Donning, Egress Analysis

The following items were coded from the video from each trial and participant:

Ingress:

- Approach direction on ramp
- Any problems maneuvering around seatbelt on entry?

Docking:

- Number of times they moved forward to align
- Was realignment needed after first engagement attempt?
- Time from entry to complete docking

Donning:

- Did seatbelt catch on any wheelchair structure during donning?
- Time from start to completion of donning
- How did participant adjust belt?
- Shoulder belt fit
- Lap belt fit

Doffing:

- Did seatbelt catch on any wheelchair structure during doffing?
- Did participant move belt during doffing?
- Time from start to completion of doffing

Egress:

- Number of times they moved backwards to exit station
- Any problems on maneuvering around seatbelt on exit?
- Time from unbelting to exit

Figure 26 shows the mean entry time for each configuration, across all conditions, for the power and manual conditions, as well as the volunteer's own wheelchair. The times are divided into docking time (from activating the actuator control to being fully docked), donning time (from reaching for the belt control to finishing adjusting the seatbelt), and positioning time (remaining time from leaving the ramp to being ready to go.) The average mean entry time was just over 2 minutes, and all phases averaged longer times in the power chair compared to the manual chair. Trials with the volunteer's own chair had shorter travel time, similar donning time, and docking time 3 to 4 times longer because 4-point strap tiedowns were used instead of the UDIG docking. Condition C had the highest mean entry time, which seems to be happening because it was easy to bump into the outboard lap belt anchor position. The minimum time for each task across all trials was 35 seconds. The maximum times were 139 s for docking, 166 s for donning, 319 s for positioning, and 385 total. The shortest total time was 65 s.

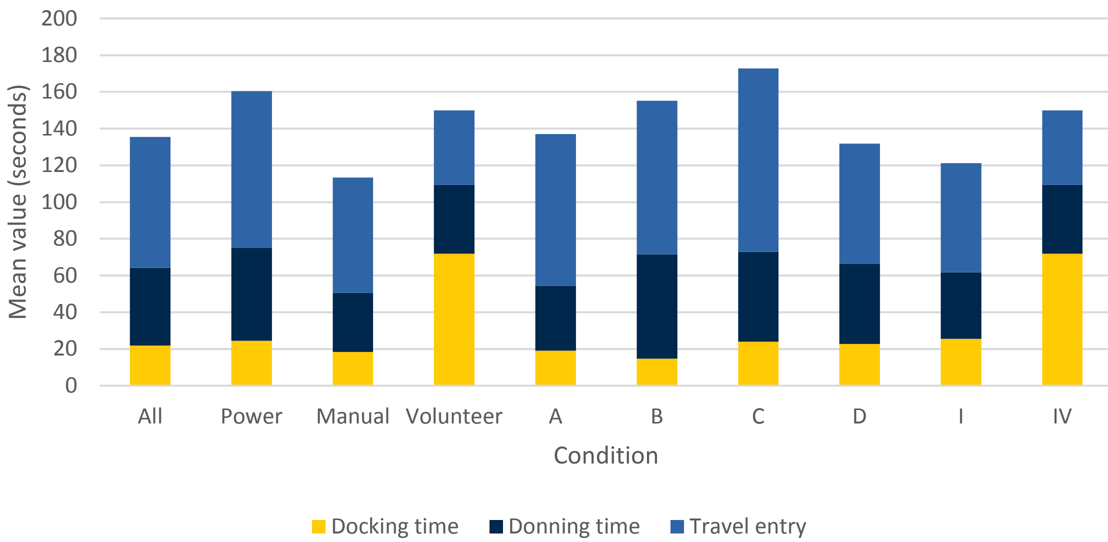


Figure 26. Mean entry time for each condition and type of wheelchair, divided by entry positioning, docking time, and donning time.

The same data are shown in Figure 27 for exiting the vehicle. The mean total exit time was just over a minute. Total exit time was lower for manual and volunteer chairs compared to the power chair. Undocking takes an average of 31 s for the 4-point strap tiedown and 10 s for the UDIG. The maximum exit times were 82 s for doffing, 32 s for undocking with UDIG (and 49 s for 4-point strap tiedowns), and 78 s for exit positioning.

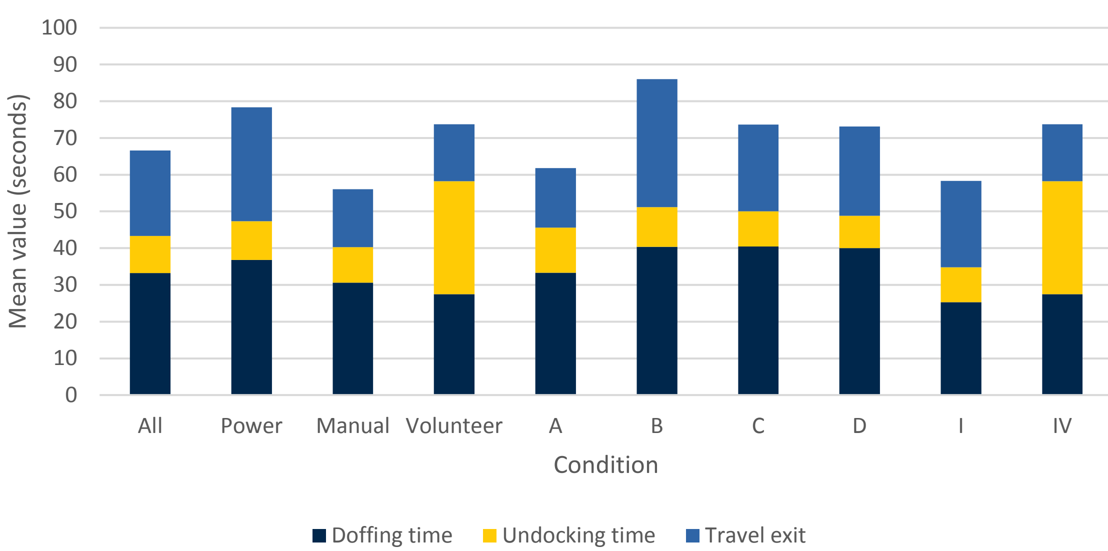


Figure 27. Mean exit time for each condition and type of wheelchair, divided by doffing time, undocking time, and exit positioning.

Table 5 lists several factors that were assessed in the video analysis and the percentage of trials where they were observed. In the majority of trials (98%), the participant traveled on the ramp facing forward. Only 3% had problems with the belt getting caught on the wheelchair while maneuvering; about 33% moved the seatbelt out of the way as they were entering. In 44% of trials, participants moved forward and backed up 3 or more times to align the wheelchair in position in front of the UDIG anchorages, including 2 trials with 10 and 17 attempts. In 48% of trials, participants had to move the wheelchair again after the first engagement attempt to allow full engagement of both hooks. In 27% of trials, the seatbelt caught on the armrest while donning. For exiting, participants were able to directly move out of the station onto the ramp without changing direction in 87% of trials. In 6% of trials participants had some issues maneuvering around the seatbelt on exit.

Table 5. Ingress, docking, and egress characteristics

Characteristic	% all trials
Traveled in forward position during entry	98%
Problems maneuvering around seatbelt during positioning	3%
Moved seatbelt out of the way during entry	33%
Took 3 or more attempts to align	44%
Realignment required after first engagement attempt	48%
Belt caught on armrest while donning	27%
Steered directly out of station on exit without changing direction	87%
Problems maneuvering around seatbelt on exit	6%

The available space was varied to be 48 in for conditions A and D, 54 in for B and C, and 60 inches for condition I. Participants were able to dock under all spacings with each wheelchair. Figure 28 shows a plot of mean entry times for each spacing for the manual and power trials. For the manual trials (where our volunteers had the most experience), time to enter/dock/doff decreased with increased amount of space. However, results for the power trials were inconsistent with the amount of available space, and may have been affected more by user experience than available space.

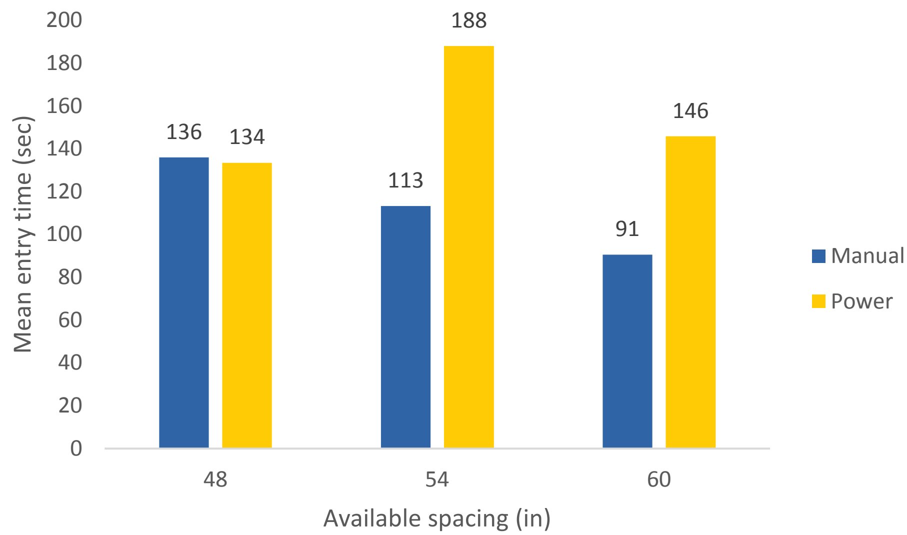


Figure 28. Mean entry time by available spacing and wheelchair type.

Questionnaire Responses

After each trial, the participant answered a series of questions regarding ease of use and comfort of the conditions, often comparing the test experience to their regular travel experience. Figure 29 shows responses to the question rating the difficulty maneuvering the test wheelchair in the vehicle compared to their personal wheelchair. For the manual wheelchair, just under half were within the easy categories, and just under half were within the difficult categories, with the remaining 4% indicating it was the same as using their personal wheelchair. For the trials using the volunteer’s own wheelchair, 40% rated the maneuvering as the same as in their normal travel situation, while 40% said it was easier and 20% moderately difficult. The power wheelchair had 77% of responses as slightly or moderately difficult compared to their own wheelchair, and 23% among the easy categories. This could be related to the shorter length of the manual wheelchair compared to the power wheelchair, or most participants (9/10) regularly using a manual wheelchair in their daily lives.

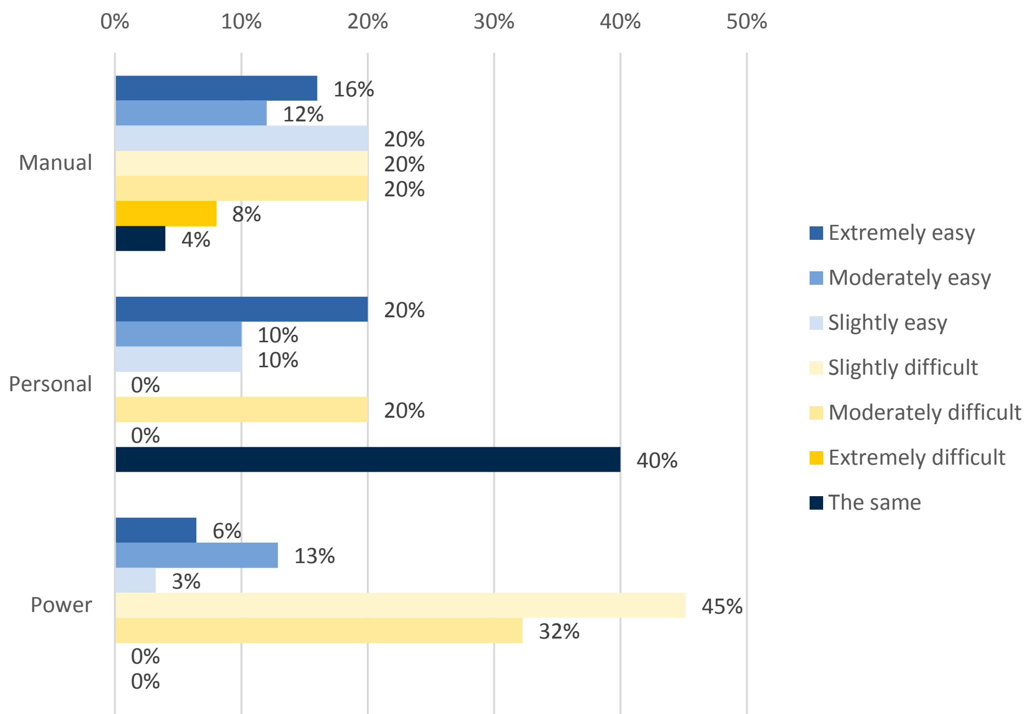


Figure 29. Level of difficulty maneuvering the test wheelchair compared to their personal wheelchair.

Answers to the question regarding ease of lining up the wheelchair with the UDIG anchorages are shown in Figure 30. Condition C had the most negative responses, condition I had the most positive responses, and condition B had the most "very easy" responses.

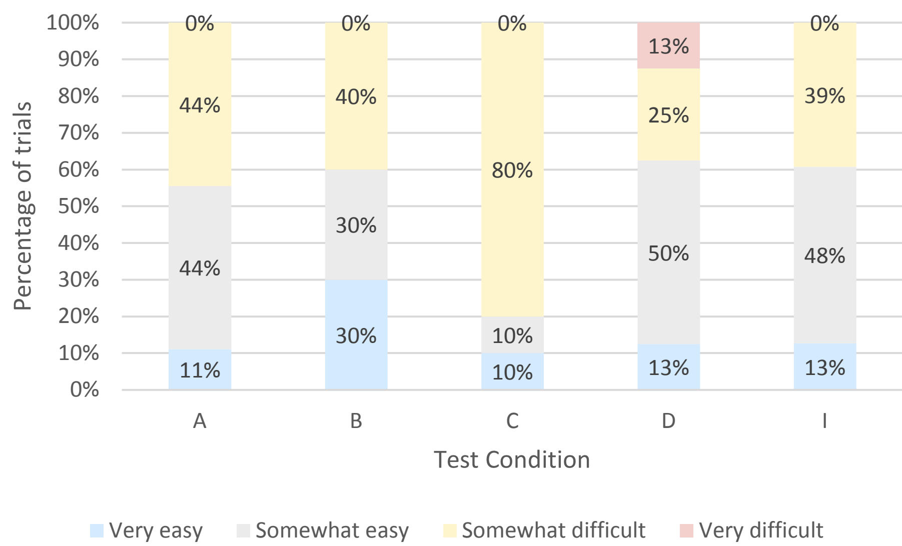


Figure 30. Ease of lining up wheelchair with UDIG anchors.

Participant ratings about their feeling of security once docked are shown in Figure 31. The 4-point strap tiedown system, used with their own wheelchairs, had the highest proportion of excellent and could be better responses. The UDIG anchors with the manual wheelchair had the lowest proportion of negative answers.

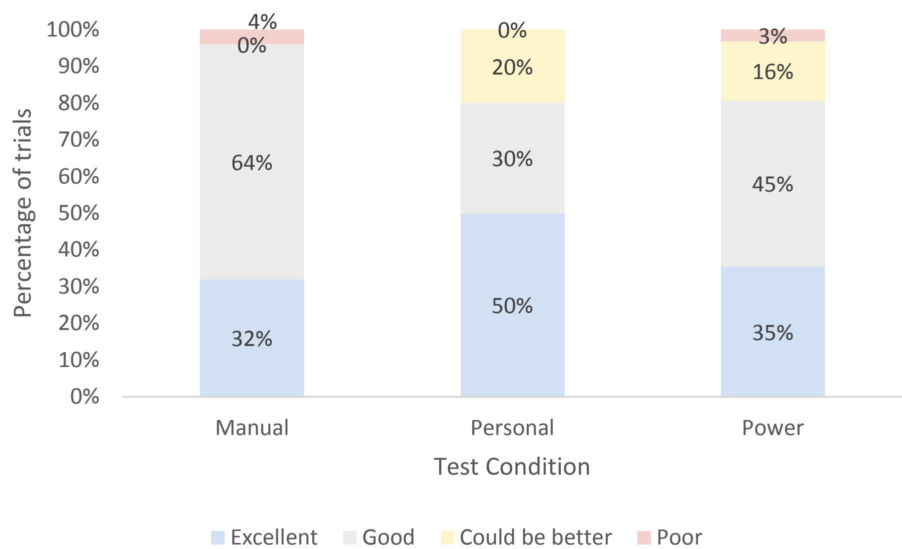
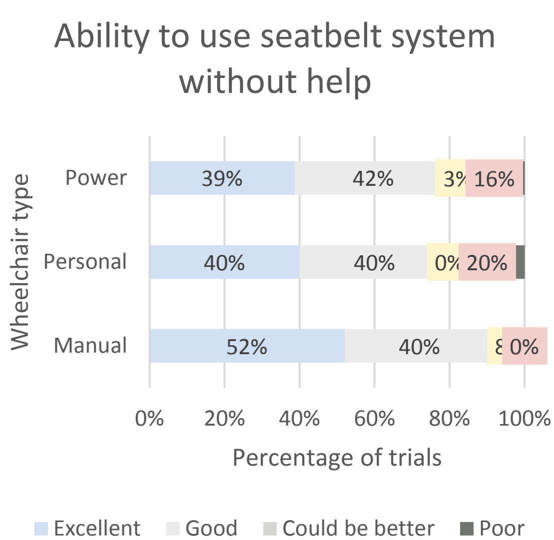


Figure 31. Feeling of security once docked by wheelchair type.

Participant rating of their ability to use the system independently is shown for the seatbelt system on the left side of Figure 32 and the docking system on the right side. About 25% of responses were poor/could be better for both systems, while the rest were good or excellent. For the seatbelt system, the manual wheelchair received more positive ratings than the power wheelchair or their personal chair, which were similar. For the docking system, the manual wheelchair received higher ratings than the power wheelchair.



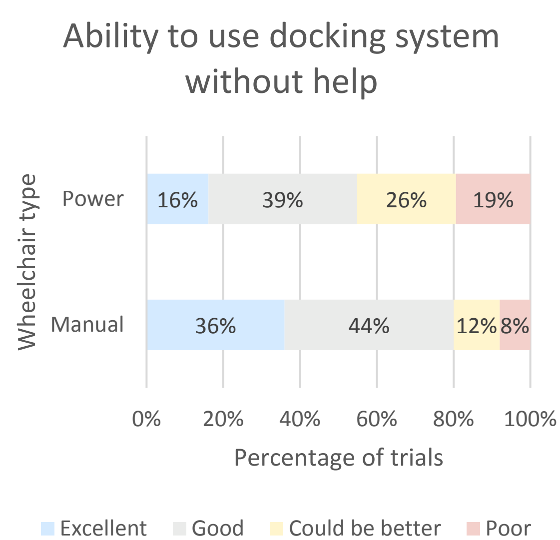


Figure 32. Rating of using the seatbelt system (left) and docking system (right) without help.

Figure 33 shows the distribution of responses to whether the participant would recommend the seatbelt system and the docking system in the configuration that was just tested. For the docking system, ratings were 7 or higher in 64% of manual trials and 58% of power trials. For the donning system, ratings were 7 or higher in 64% of manual trials, 54% of power trials, and 60% of personal wheelchair trials.

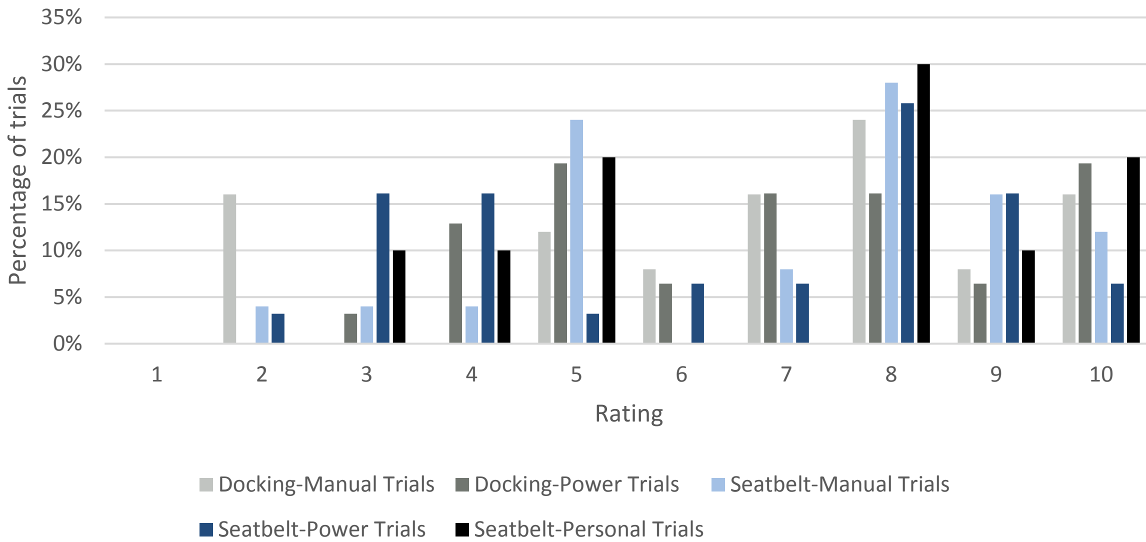


Figure 33. Participants' answers to whether or not they would recommend the seatbelt system and the docking system.

Qualitative Feedback/Assessment

Most participants did not provide additional feedback after each trial. Of those that did, many suggestions involved improvements in floor markings or other indicators that the UDIG anchors were engaged, such as the indicator lights used in the BIW. One person suggested padding of the shoulder belt for comfort.

In our study, we had two specific instances illustrating challenges of belt use with wheelchairs, as shown in Figure 34. One participant (W03) placed the shoulder belt under her arm because of discomfort in condition B. For participant W04, there was no gap between armrests and seatback that would allow appropriate routing of the belt using the automated donning system. For a paratransit situation where a driver is available to help, they could unbuckle the belt and reroute it under the armrests to improve lap belt fit. However, this could potentially reroute the shoulder belt under the armrest as well.

Figure 34. Seatbelt misuse conditions.

Volunteers' Wheelchairs: Geometry and Belt Anchorage Adjustment

Appendix C contains images showing the front and sideview posture of volunteers in their own wheelchairs, as well as the two study wheelchairs. The appendix also includes a scan of each volunteer's wheelchairs.

For our ten volunteers, only one regularly used a power wheelchair (and was unable to perform study tasks in the manual wheelchair.) Figure 35, Figure 36, and Figure 37 show comparisons of wheelchairs representing the maximum and minimum widths, depths, and heights of the nine manual wheelchairs used by participants. Among the manual wheelchairs, the maximum difference in width is 160 mm, in length 264 mm, height is 258 mm, and seat height is 106 mm. Although two of our participants had BMI above 30, their wheelchairs were not wider than 762 mm (30 in). For the single powerchair user with the lowest stature in our study, the width and length of her wheelchair were within the range of the manual chairs, but her seat height was 14 mm taller and overall wheelchair height was 73 mm taller.

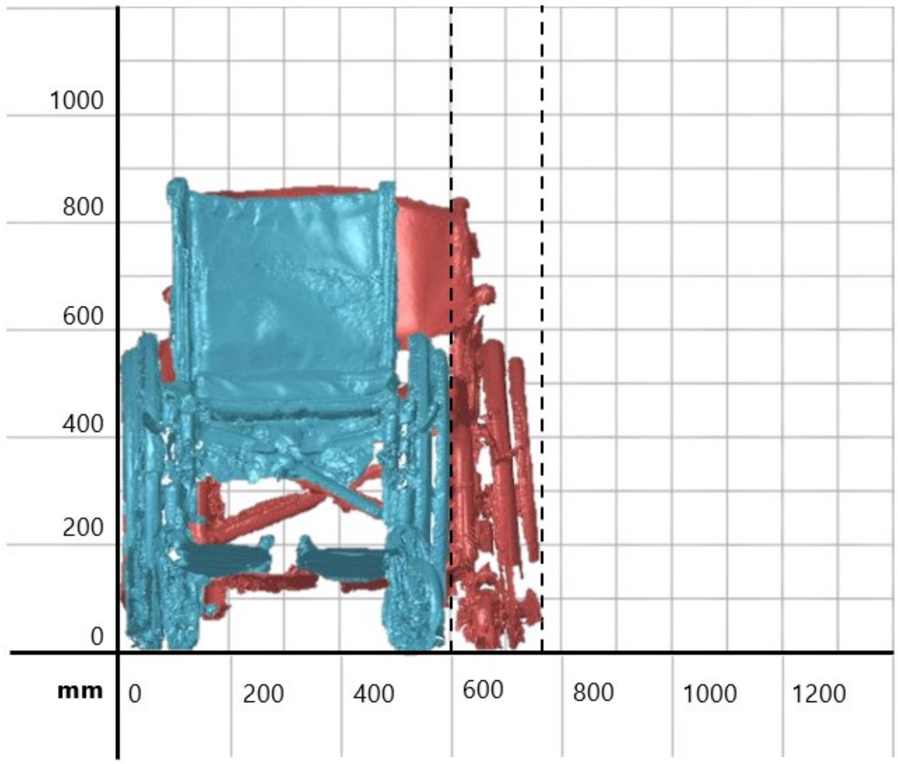


Figure 35. Comparison of narrowest and widest manual wheelchairs.

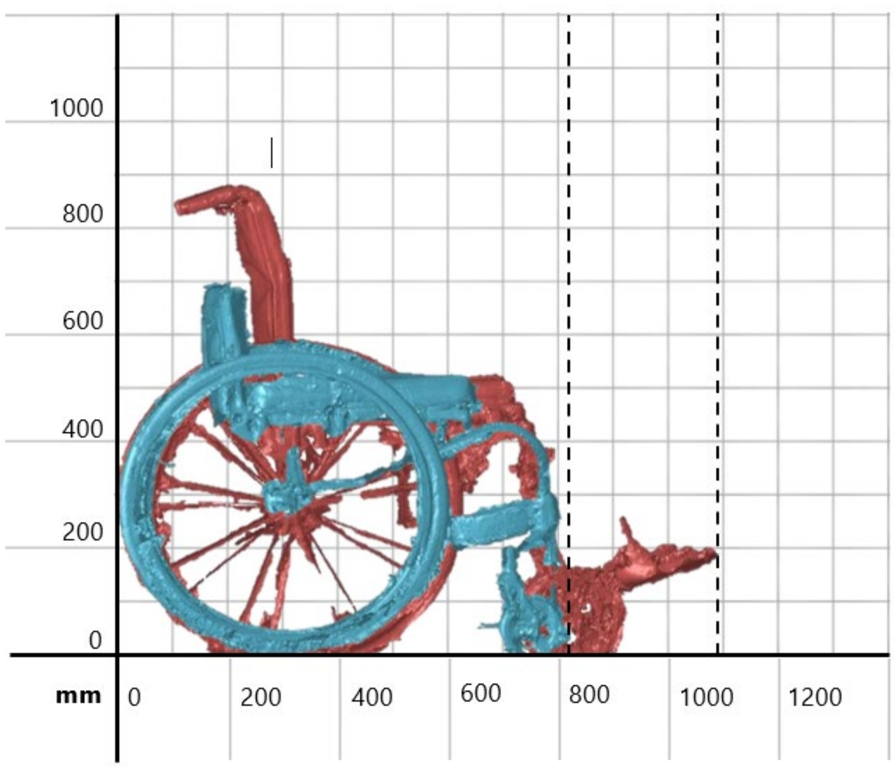


Figure 36. Comparison of shortest and longest (fore-aft) manual wheelchairs.

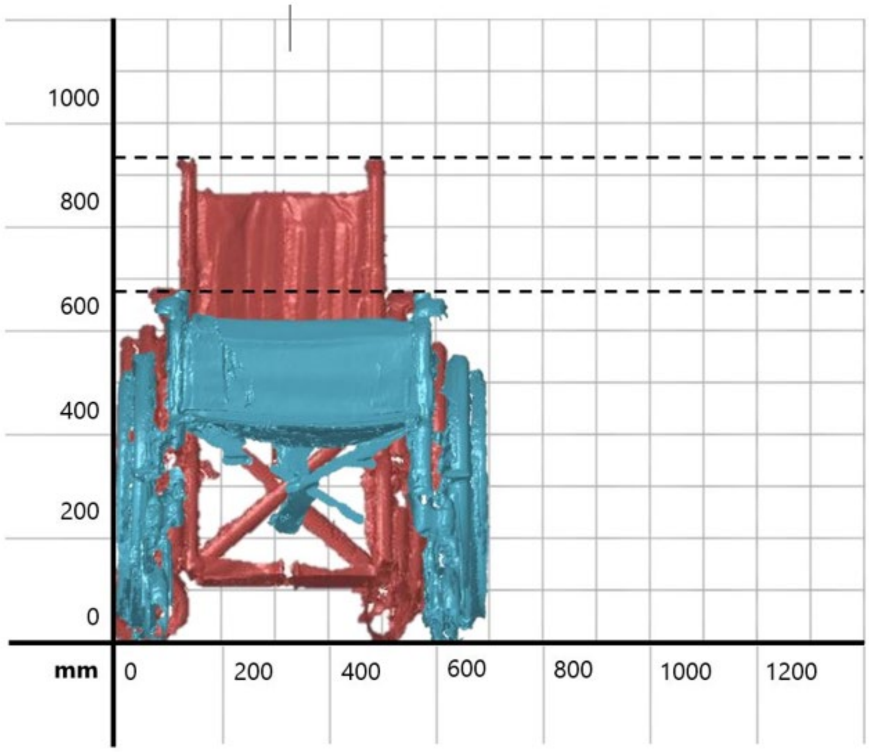


Figure 37. Comparison of shortest and tallest manual wheelchairs.

None of the participants were using wheelchairs that meet voluntary WC19 standards for use as a motor vehicle seat (which can be identified by the presence of marked, dedicated hooks for tiedown attachments.) Of note is the wheelchair that had the shortest height. The seatback on this wheelchair is quite low, to avoid limiting the reach of the wheelchair user. Using this wheelchair in a vehicle could be problematic in a rear impact. WC19 does not currently include any requirements for rear impact. However, there is a maximum rearward displacement requirement for rebound in frontal impacts. Typically, wheelchairs where the seatback is lower than the 50th male ATD's scapula would not pass the rebound displacement requirement.

Review of the participant postures in their own wheelchair compared to the test wheelchairs did not indicate any drastic differences. Overall, most participants had a higher head CG location in the power wheelchair. The tallest participants had higher head CG locations in their own manual wheelchairs compared to the study manual wheelchair, but it varied for the rest of the participants. Key dimensions for the participant wheelchairs are listed in Table 6, together with an estimated percentile relative to the range of relevant wheelchairs (manual or power) collected in a larger study of wheelchair geometry reported by Steinfeld et al. (2010). With just nine participants using manual wheelchairs, the dimensions represent 12-99% of widths, 12-68% of lengths, and 1-61% of seat heights seen in the larger study. Another observation is that there is no consistency in dimensional percentiles for a particular wheelchair, meaning that a wheelchair that was particularly long was not necessarily particularly wide. Participant TW04 ranges from 1% in seat height to 90% width, while participant TW13 ranges from 12% in length to 41% in width.

Table 6. Key dimensions of volunteers' wheelchairs and comparison to Buffalo study

Participant	Width (mm)	UB %ile	Length (mm)	UB %ile	Seat Height	UB %ile	Height (mm)
TW01	765	99.7%	954	36%	499	21%	856
TW02	605	12%	1087	68%	522	42%	881
TW03	**669**	**76%**	**1032**	**27%**	**553**	**61%**	**1003**
TW04	705	90%	858	17%	440	0.9%	671
TW09	712	92%	832	14%	480	10%	822
TW12	660	56%	921	29%	433	0.5%	870
TW13	644	41%	823	12%	517	37%	693
TW14	631	29%	1078	66%	505	25%	930
TW23	674	69%	1022	53%	509	29%	717
TW24	653	49%	863	18%	539	59%	851
Range	160		264		120		332

The adjustments made to belt anchorage geometry to improve belt fit in each participant's wheelchair are shown in Figure 38 through Figure 40, while Table 7 shows the amount each anchor was adjusted in each direction relative to baseline. On these plots, the origin is the top center location of the UDIG anchorage fixture. (In the table, values less than 8 mm were presumed to be measurement errors and set to zero.) When reviewing the belt fit scores between the baseline and adjusted condition I scenarios, there is not a large difference in fit assessment, even if volunteers provided feedback on improved comfort.

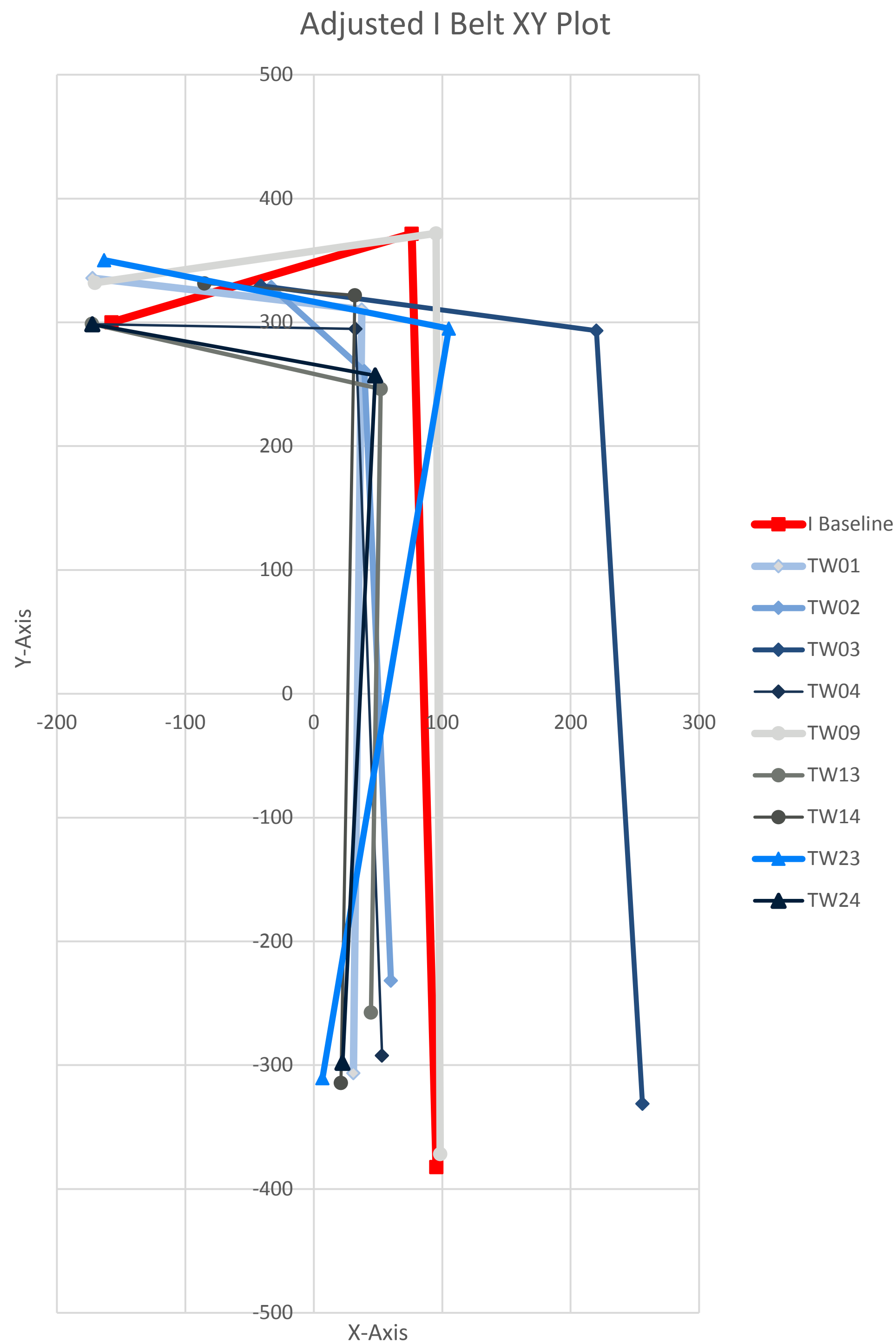


Figure 38. Top view geometry of baseline and adjusted belt anchors for each participant.

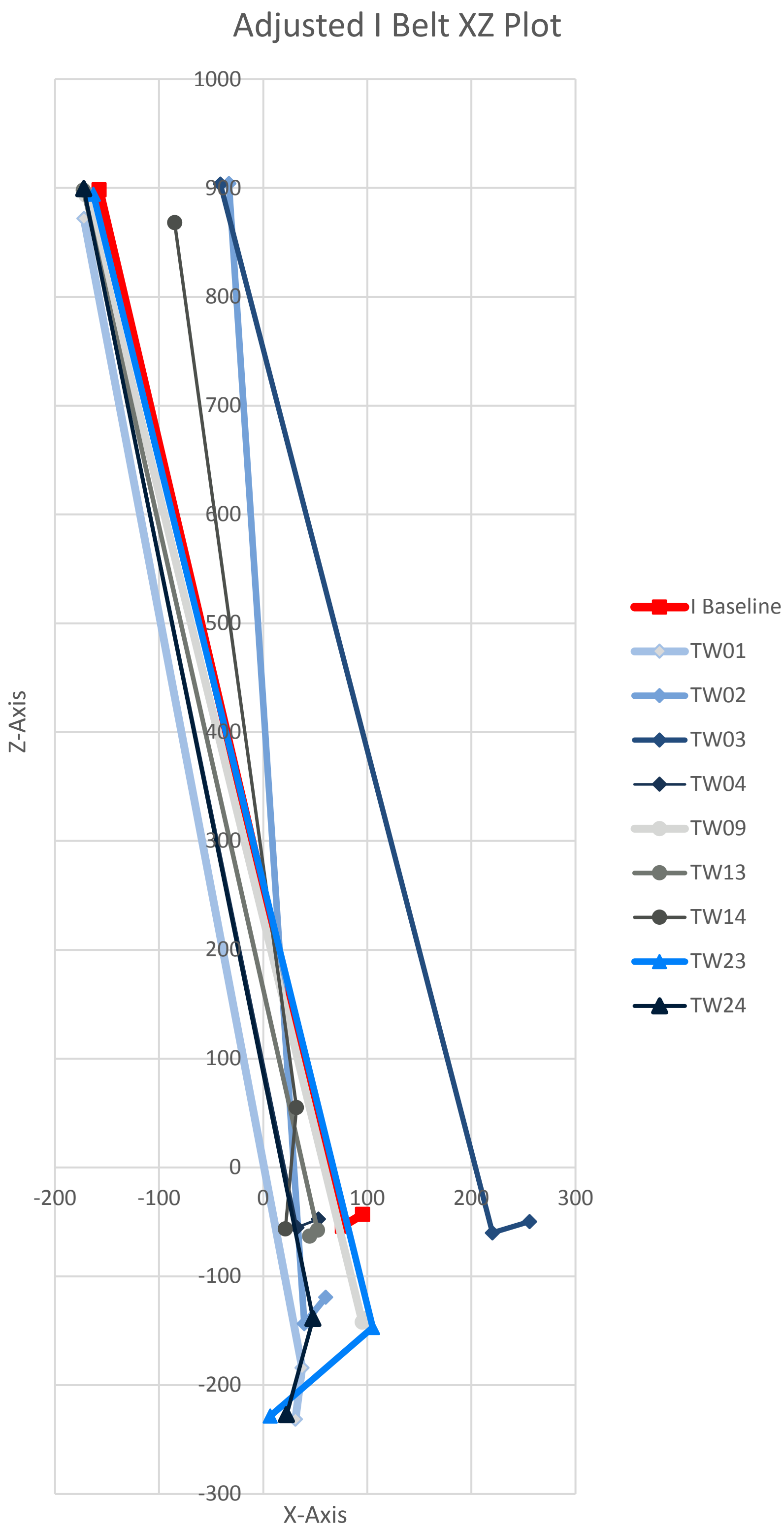


Figure 39. Sideview geometry of baseline and adjusted belt anchors for each participant.

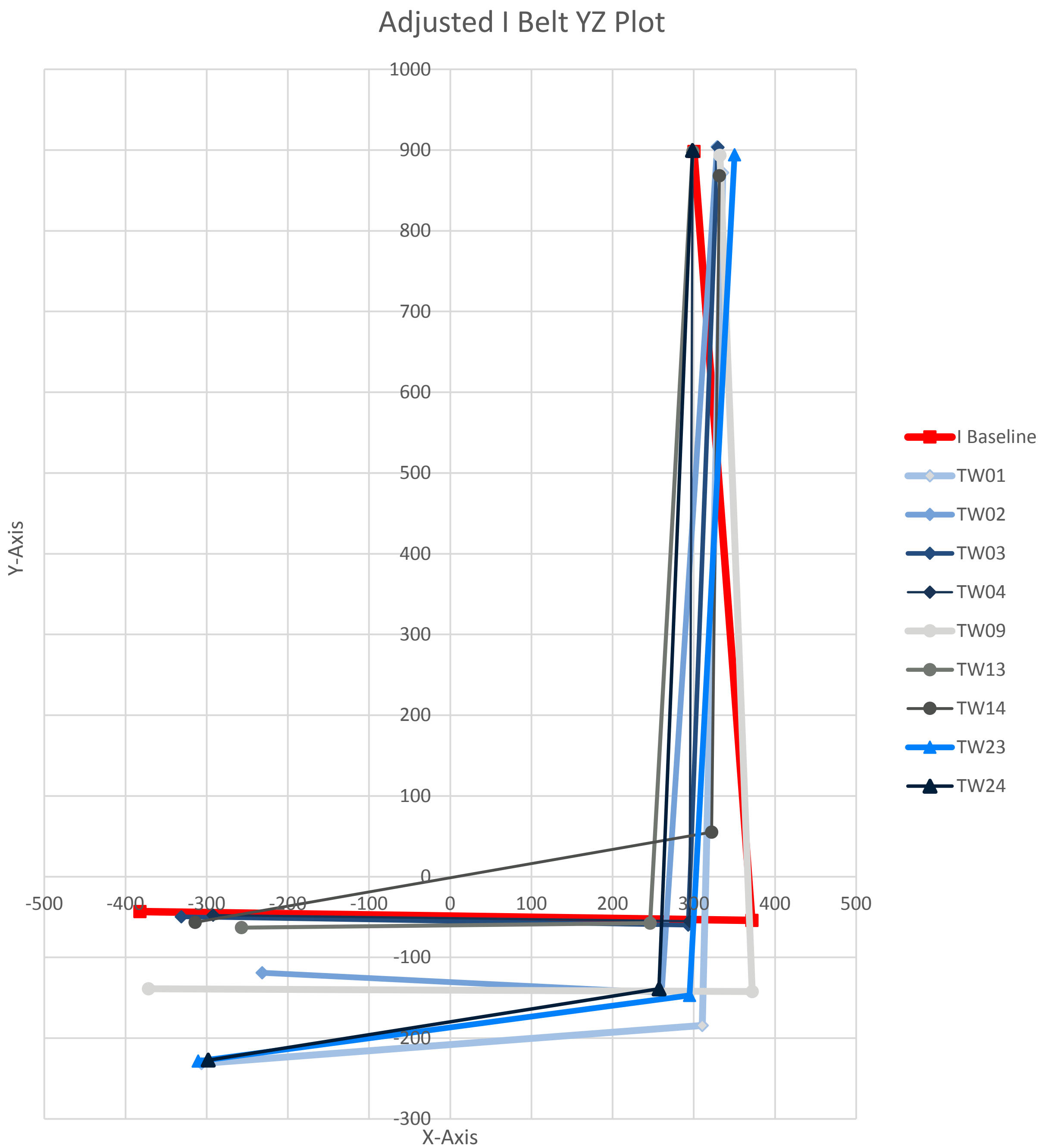


Figure 40. Front view geometry of baseline and adjusted belt anchors for each participant.

Table 7. Amount of adjustment to improve belt fit with volunteers' own wheelchairs.

Volunteer	X D-ring Bolt	X Inboard Lap Bolt	X Outboard Lap Bolt	Y D-ring Bolt	Y Inboard Lap Bolt	Y Outboard Lap Bolt	Z D-ring Bolt	Z Inboard Lap Bolt	Z Outboard Lap Bolt
TW01	-15	-65	-39	36	76	-61	-26	-130	-188
TW02	125	-35	-37	29	151	-111	0	-89	-76
TW03	116	160	144	30	51	-78	0	0	0
TW04	-15	-42	-44	0	90	-77	0	0	0
TW09	-13	0	19	32	11	0	0	-88	-96
TW13	-15	-51	-24	0	125	-125	0	0	-20
TW14	72	-74	-44	31	68	-50	-30	109	-14
TW23	0	-89	29	50	72	-77	0	-93	-185
TW24	-15	-73	-28	0	84	-114	0	-85	-184
Min	-15	-89	-140	0	10	-125	-30	-130	-188
Max	125	160	144	50	151	0	0	956	0
Mean	33	-26	-16	24	74	-73	-6	58	-76
Stdev	60	73	72	18	44	38	12	323	82

Volunteer Posture and Shape

The data collected with the Kinect system were used to improve understanding of how the seated posture of people in wheelchairs may differ from someone of the same size in a standardized vehicle seat posture, as well as trying to capture physical differences resulting from their disability. The first step involved generating an avatar using UMTRI's humanshape.org web tool, entering the age, height, and weight of each person. (For people with lower extremity amputations, they provided their stature before their amputation.) This provided a baseline occupant shape in a typical vehicle seated posture.

The next step involved using a beta version of an accessory being developed for the humanshape.org tool that allows posture configuration. With this tool, each body segment can be manipulated independently. The generated segments for each person were individually manipulated to represent the participants' postures.

Appendix D contains illustrations of the baseline and adjusted avatar for each person, as well as comparisons between the avatars and photos for reference.

Methods: Field Measurement

Data Collection

To collect data on the posture of people with disabilities spanning a wider range of conditions than those who were recruited to participate in the laboratory study, we developed a system to collect three-dimensional posture data in the field. The study was reviewed by the University of Michigan Institutional Review Board. Because one of their key concerns with participant data is privacy and storage of personally identifiable information, we proposed that participants wear masks and sunglasses to remain anonymous, since facial measurements are not critical to our effort. As a result, they approved our study as exempt, allowing us to simplify paperwork requirements and obtain oral consent only.

Data were collected outside of a Michigan Medicine facility that houses a Dialysis Center, a Prosthetics Department, and Wheelchair Seating Services; all organizations helped facilitate participant recruitment. Figure 41 shows the field measurement setup. We posted signs near two entrances, with the following advertisement "Help us design automated vehicles so they work with wheelchairs-$10 for 10 minutes." Experimenters passed out a flyer to anyone entering the facility who was using a wheelchair not provided at the site. The flyer, included in Appendix E, describes the study procedure. On exit from their appointment, interested volunteers were escorted to the measurement tent located next to the facility.

Figure 41. Pilot testing with field measurement setup.

The experimenters would first check to see if the participants had any questions about participating. They would then make sure the participant was wearing a mask, and provide them with disposable sunglasses. The participant would then navigate their wheelchair onto a platform scale and lock the brakes. We then gave the participant an iPad to fill out the survey, asking their age, height, weight, and main reason why they were using the wheelchair. If preferred, the experimenter filled out the form for participants with the participant's answers. The experimenter then entered the combined weight of the participant and wheelchair on the form.

Three-dimensional measurements were collected of the person seated in the wheelchair using a set of Kinect sensors mounted to a cart. Up to four postures were collected: in standard wheelchair position, with the nearest armrest moved out of the way, if possible (to better capture the person's posture), with the participant reaching up and to the left, and with the participant reaching sideways and to the right. Examples of each scan for one participant are shown in Figure 42.

Figure 42. Examples of three postures taken with Kinect measurement system.

Following the overall posture measurement with the Kinect sensors, an experimenter took pictures of each person from multiple angles. Examples are shown in Figure 43. Finally, an experimenter used a sense scanner to perform a more detailed scan of the person's wheelchair. An example is shown in Figure 43. The volunteer filled out a form to document receipt of a $10 Visa gift card as payment.

Figure 43. Examples of photos taken during field meaurement.

Figure 44. Example of Sense scan focusing on wheelchair geometry.

Data Analysis

The main data processing performed with the volunteer data involved creating avatars that reflect the posture of each person, as well as capturing physical differences resulting from their disability. The first step involved generating an avatar using UMTRI's humanshape.org web tool, entering the age, height, and weight of each person. (For people with lower extremity amputations, they provided their stature before their amputation.) This provided a baseline occupant shape in a typical vehicle seated posture.

The next step involved using a beta version of an accessory being developed for the humanshape.org tool that allows posture reconfiguration. With this tool, each body segment can be manipulated independently. The generated segments for each person were individually manipulated to represent the participants' postures.

Results: Field Measurement

Participant Characteristics

Over four days of field collection, ten people agreed to be in our study. A summary of their characteristics is shown in Table 8.

Table 8. Characteristics of field measurement volunteers.

ID	Sex	Age	Height	Weight	BMI	Type of wheelchair	Reason for wheelchair use
FWM001*	M					Manual	Amputation
FWM002	M	65	64	235	40.3	Manual	Amputation
FWM003	M	27	51	80	21.6	Power	Spine/respiratory
FWM004	M	82	70	185	26.5	Manual	Amputation
FWM005	F	68	67	350	54.8	Power	Blood clots in leg
FWM006	F	52	65	265	44.1	Power	Amputation, arthritis
FWM007	F	66	63	308	54.6	Scooter	Knee replaced
FWM008	F	53	59	102	20.6	Power	Cerebral palsy
FWM009	F	68	62	120	21.9	Power	Multiple sclerosis
FWM010	M	73	70	210	30.1	Manual	Injuries from crash

*error in recording responses

Volunteer Posture

Appendix F contains photos of volunteers in their own wheelchairs, as well as processed scan data. For volunteer 3, we were unable to generate a reasonable baseline avatar from humanshape.org because his height and weight were substantially below the range of values that the tool is based on.

Observations

None of the participants were using WC19 wheelchairs (recognized by the absence of marked, dedicated tiedown hooks.) Several of the people arrived via paratransit service, although we did not specifically track this for each volunteer. At least one volunteer was observed departing with his wheelchair secured but without using a seatbelt (as was his paratransit driver.) Others were usually escorted by a family member; we did not observe any volunteers driving their own vehicles from a wheelchair. When working with the three medical groups to facilitate recruitment of their patients, an administrator from the dialysis center commented that many of their patients will transfer from their personal wheelchair to one provided by the paratransit service.

Discussion

Laboratory Study

All but one of our participants regularly used a manual wheelchair, and none of them regularly traveled while seated in a wheelchair. We hypothesize that this is the reason trials with the power wheelchair took longer than those with the manual wheelchairs, as they were unfamiliar with operation of the power drive system. In addition, their feedback on both the docking system and the seatbelt system were not as favorable as the ratings given by the volunteers in the NHTSA study.

Compared to the NHTSA study, there was less variation in belt fit with the different seating conditions; the participants' BMI seemed to be a greater factor. The new test condition I used in this study did seem to provide reasonable shoulder belt fit across the range of occupants. Lap belt fit seemed to depend more on participants' BMI. Overall, the belts fit better on these participants compared to a previous study looking at belt fit in personal vehicles (van Roosmalen, Orton, and Schneider 2013). In addition, we see similarities between the lap belt fit on these participants in wheelchairs and a previous study performed at UMTRI on volunteers in vehicle seats, with lap belts often placed too high over the abdomen, particularly in obese participants. While knee bolsters or forward seat backs can partially compensate for poor lap belt fit in most vehicles, this option is not typically available for a wheelchair seating station where space is needed to maneuver the wheelchair.

Condition I demonstrated the feasibility of having combination docking station of a central UDIG and 4-point strap tiedown on either side. The benefit of having the rear tiedown anchors fixed in this location is that if the seatbelt geometry is optimized for the UDIG station, those using 4-pont strap tiedowns at this location would be in a similar fore-aft position.

For the trials performed in the participants' own wheelchairs, the configurations seemed to work in a similar manner as with the study wheelchairs. While we adjusted the belt anchorages to improve comfort and fit, the belt fit scores after adjustment were not substantially different from the baseline condition for most participants, even if they provided feedback during adjustment that they were more comfortable. The greatest adjustment from baseline was with the power wheelchair user, who was also the smallest participant. The large adjustment from baseline (~ 300 mm) demonstrates the potential range in belt anchors needed to accommodate people traveling in manual vs. power wheelchairs. According to the University of Buffalo study on wheelchair dimensions (Steinfeld et al. 2010b), the length of a 5th percentile manual wheelchair is 774 mm, while the length of a 95th percentile wheelchair is 1340 mm. If we approximate the occupant fore-aft torso location at the midpoint of each wheelchair length, and assume that each wheelchair is aligned with the rear boundary of the wheelchair station, this is a difference of 283 mm, consistent with our limited data.

Despite having a limited number of participants, the range in the manual wheelchair dimensions varied substantially. In addition, the measurements for each wheelchair demonstrate that it is likely not reasonable to approximate the size of an average wheelchair using a combination of average length, width, and seat height.

Field Measurements

This part of the study demonstrated a feasible method of performing field measurements of people seated in their wheelchairs that can provide insight on the challenges of designing integrated wheelchair seating stations that offer both accessibility and appropriate occupant protection. Traveling to a laboratory study can be challenging for wheelchair users, so the field study demonstrated a viable alternative for collecting additional posture and wheelchair geometry data. A challenge with the outdoor data collection was that on the brightest days, both the Kinect and Sense tools sometimes had trouble capturing the needed data.

Even with the limited number of participants, we were able to collect data on a more diverse group of people than we were able to observe in the laboratory part of the study, seen by the greater number of power wheelchair users: six out of ten in field study vs. one out of nine in laboratory. In addition, our field data collection had a higher proportion of obese occupants (50% vs. 22%). Both parts of the project were able to advance methods for adapting current posture modeling tools found in humanshape.org to people with atypical postures and physical differences.

The humanshape.org tool creates avatars using data collected on hundreds of adult participants, appropriate for estimating shape for people in the stature range from 1400 mm to 1900 and a BMI range from 18 to 40. One challenge in using the humanshape.org tool was that the BMI of several people were outside this range, so the accuracy of the baseline configuration may be lower, although visible comparison of photos and avatars showed that the shapes seem reasonable despite being used out of the recommended range. Our study also identified the need to have an option to remove a body segment to better represent people with amputations. Because of the limited number of participants in our study, it was feasible to create the adjusted occupant postures manually. Larger studies would benefit from automated segment adjustment capabilities (which are under development.)

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Appendix A: Volunteer Testing Documents

Participant Screening Script

Consent form

Post-trial survey

Participant Screening Script

Email to interested participants

Thank you for your interest in our study about traveling in vehicles while seated in a wheelchair. We would like to schedule a time where we can call you to tell you more about our study. Can you please let us know your availability on xx days? And can you confirm that we can call you at xx number?

We prefer to talk to you to answer any questions, but if it would be easier for you to fill out a form instead, please let us know.

Participant Screening Script

Volunteer Participant AWTORS Study

Thank you for volunteering for this study about traveling in vehicles while seated in a wheelchair. I need to ask you several questions to see if you qualify for our study.

How old are you?

Reject if less than 19 or older than 65

Are you pregnant?

Reject if pregnant

Do you use a wheelchair regularly?

Reject if they are not a wheelchair user.

Can you and are you comfortable transferring from your wheelchair into another wheelchair independently or with minimal assistance?

Reject if no.

What is your name, email address and/or contact number?

Let me tell you a little more about the study. You will be coming to our lab on north campus. We will ask you to transfer to a different wheelchair and get in and out of a parked van, dock the wheelchair, and apply a seatbelt. We will take videos and pictures of you throughout the process, as well as some measurements with a handheld scanner. Then we will ask you to complete a survey about your experience. Do you think you will be able to do this several times over the course of two hours?

To keep everyone safe during testing, everyone entering the building needs to go through a health check and temperature screening by our building greeter. We have set up our tests so our researchers will be less than 6 feet from you for less than 15 minutes over the two-hour test session. Our experimenters will be wearing fabric face masks and plastic face shields. We will also give you a fabric mask to wear during testing that you can keep, and ask you to wear a plastic face shield during testing. We will reschedule testing if you or any of the researchers have any symptoms of illness. We will disinfect our wheelchairs and equipment before and after each test session. Does this sound OK?

Reminder Email

This is a reminder about your appointment to participate in our research study at UMTRI tomorrow at xx. If you have any symptoms of illness, please contact us to reschedule your session. When you arrive at UMTRI, please park in a visitor’s spot, and enter through the main doors. Our greeter will perform the health check required for everyone to enter the building. They will also give you a parking pass and a facemask to wear during the study. Please call xx if you have any questions or need to reschedule.

UNIVERSITY OF MICHIGAN

CONSENT TO BE PART OF A RESEARCH STUDY

1. KEY INFORMATION ABOUT THE RESEARCHERS AND THIS STUDY

Study title: Development of an Automated Wheelchair Tiedown and Occupant Restraint System

Principal Investigator: Kathleen D. Klinich, PhD, University of Michigan Transportation Research Institute

Study Sponsor: National Highway Traffic Safety Administration

You are invited to take part in a research study. This form contains information that will help you decide whether to join the study.

1.1 Key Information

Things you should know:

- The purpose of the study is to evaluate new hardware and seatbelt designs that should make it easier and safer to travel in vehicles while seated in a wheelchair.
- If you choose to participate, you will be asked to transfer from your wheelchair to a wheelchair that has special docking attachment hardware. We will then have you try out different wheelchair docking hardware and seatbelt designs in a vehicle mockup. Photos, videos, and scanned measurements will be taken during these trials and a survey will be given following each trial. At the end of all of the trials, a questionnaire will be given regarding your transportation experiences. The test session will take up to two hours.
- Risks or discomforts from this research include frustration when trying out different hardware designs, or discomfort from using a seatbelt that might not fit well. There is a risk of falling from the wheelchair as you maneuver in our test fixture. Breach of confidentiality is also a risk.
- There are no direct benefits for you to participate in this study.

Taking part in this research project is voluntary. You do not have to participate and you can stop at any time. Please take time to read this entire form and ask questions before deciding whether to take part in this research project.

2. PURPOSE OF THIS STUDY

When traveling while seated in a wheelchair, it is important to attach the wheelchair to the vehicle. We are trying to design a way for people to do this without help. We are also designing a seatbelt you can put on by yourself. These designs will be needed to allow safe and independent travel in automated vehicles, where there won’t be a driver to help.

3. WHO CAN PARTICIPATE IN THE STUDY

3.1 Who can take part in this study? People 19 to 64 years old who regularly use a wheelchair, but are able to transfer to one of our study wheelchairs, are eligible to participate. You cannot participate if you are pregnant.

4. INFORMATION ABOUT STUDY PARTICIPATION

4.1 What will happen to me in this study?

- Testing will occur in our laboratory at UMTRI.
- We will tell you about the study and obtain your consent.
- We will make sure you can safely transfer to our study wheelchairs, and that you are comfortable using them.
- We will show you where to put stickers on different parts of your body.
- We will take some photos and scans to document your body dimensions.
- We will have you enter the vehicle mockup, and use the hardware to attach the wheelchair and put on the seatbelt. Seatbelt tightness will be varied and we'll ask you about the comfort. Photos and video and will be recorded during this process.
- Then we will document your posture and position using a 3D scanner and photos.
- Then you will remove the seatbelt, undock the wheelchair and exit the mockup. Photos and video and will be recorded during this process. You will fill out a form about the trial.
- We will repeat the trials using at least 8 different configurations, and potentially more if time and comfort allows.
- You will fill out a survey about your personal travel experiences.

4.2 How much of my time will be needed to take part in this study? Up to 2 hours.

5. INFORMATION ABOUT STUDY RISKS AND BENEFITS

5.1 What risks will I face by taking part in the study? What will the researchers do to protect me against these risks?

The highest risk is being frustrated if hardware is difficult to use. There may also be risk of discomfort if our seatbelt system doesn't fit you well. There is also a risk of you falling out of the wheelchair as you drive it in and out of the vehicle mockup. The researchers will try to minimize these risks by padding surfaces and having an experimenter close by to help if needed. You can also choose not to keep the seatbelt on if it is too uncomfortable. You do not have to answer any questions you do not want to answer. Breach of Confidentiality is a risk and the study team will follow data handling procedures and safeguards to minimize this risk.

5.1.1 What happens if I get hurt, become sick, or have other problems because of this research?

The researchers have taken steps to minimize the risks of this study. Please tell the researchers if you have any injuries or problems related to your participation in the study. The University may be able to assist you with obtaining emergency treatment, if appropriate, but you or your insurance company will be responsible for the cost. By signing this form, you do not give up your right to seek payment if you are harmed because of being in this study.

5.2 How could I benefit if I take part in this study? How could others benefit?

You may not receive any personal benefits from being in this study. You might benefit in the future from being in the study. Results from the study will be used to design hardware that should make it easier and safer to travel while seated in a wheelchair.

6. ENDING THE STUDY

6.1 If I want to stop participating in the study, what should I do?

You are free to leave the study at any time. If you leave the study before it is finished, there will be no penalty to you. If you decide to leave the study before it is finished, please tell one of the persons listed in Section 9. “Contact Information”. If you choose to tell the researchers why you are leaving the study, your reasons may be kept as part of the study record. The researchers will keep the information collected about you for the research unless you ask us to delete it from our records. If the researchers have already used your information in a research analysis, it will not be possible to remove your information.

If you are unable to use the test wheelchairs safely, we will end your participation in the study.

7. FINANCIAL INFORMATION

7.1 Will I be paid or given anything for taking part in this study? You will receive $40 to for your participation in the study. If you decide to withdraw from the study early, we will pay you $15/hour, rounded to the nearest 15 minutes.

8. PROTECTING AND SHARING RESEARCH INFORMATION

8.1 How will the researchers protect my information?

We will give you a subject code number. All of your data will only be identified with this code. Information with your name on it, such as recruitment and payment forms, will be stored separately you’re your data and destroyed after 1 year. All of your data and video recordings will be stored on a password-protected server. If you give consent on this form and we use pictures of you in a report or presentation, we will blur the images whenever possible.

8.2 Who will have access to my research records?

There are reasons why information about you may be used or seen by the researchers or others during or after this study. Examples include:

- University, government officials, study sponsors or funders, auditors, and/or the Institutional Review Board (IRB) may need the information to make sure that the study is done in a safe and proper manner.

8.3 What will happen to the information collected in this study?

We will keep the information we collect about you during the research for future research projects. Datasets that will be made available to the public through archive (using Deep Blue) will include measurements and survey responses but not video or photos where you could be identified. Information, video and photos will be saved locally and will only be shared with collaborators to guide future design improvements if consent has been given by you on this form.

The results of this study could be published in an article or presentation, but will not include any information that would let others know who you are.

8.4 Will my information be used for future research or shared with others?

We may use or share your research information for future research studies. If we share your information with other researchers it will be de-identified, which means that it will not contain your name or other information that can directly identify you. Potentially identifying information, video and photos will only be shared with collaborators to guide future design improvements if consent has been given by you on this form. Future research may be similar to this study or completely different. We will not ask for your additional informed consent for these studies.

Datasets will be made available to the public through the repository Deep Blue and will include measurements and survey responses but not video or photos where you could be identified. The repository contains information about many people. Your information will be labeled with a code, instead of your name or other information that could be used to directly identify you.

9. CONTACT INFORMATION

Who can I contact about this study?

Please contact the researchers listed below to:

- Obtain more information about the study
- Ask a question about the study procedures
- Report an illness, injury, or other problem (you may also need to tell your regular doctors)
- Leave the study before it is finished
- Express a concern about the study

Principal Investigator: Kathleen D. Klinich, PhD

Email: kklinich@umich.edu

Phone: (734) 936-1113

Study Coordinator: Nichole Orton

Email: nritchie@umich.edu

Phone: (734) 936-1107

If you have questions about your rights as a research participant, or wish to obtain information, ask questions or discuss any concerns about this study with someone other than the researcher(s), please contact the following:

University of Michigan

Health Sciences and Behavioral Sciences Institutional Review Board (IRB-HSBS)
2800 Plymouth Road
Building 520, Room 1169Ann Arbor, MI 48109-2800
Telephone: 734-936-0933 or toll free (866) 936-0933 Fax: 734-936-1852

E-mail: irbhsbs@umich.edu

10. YOUR CONSENT

Consent to Participate in the Research Study

By signing this document, you are agreeing to be in this study. Make sure you understand what the study is about before you sign. We will give you a copy of this document for your records and we will keep a copy with the study records. If you have any questions about the study after you sign this document, you can contact the study team using the information in Section 9 provided above.

I understand what the study is about and my questions so far have been answered. I agree to take part in this study.

Print Legal Name: ____

Signature: ____

Date of Signature (mm/dd/yy): ______________________________________

Consent to use and/or share your identifiable information for future research

The researchers would like to use your identifiable information (pictures and video) for future research that may be similar to or completely different from this research project. We may also use your pictures and video in reports and presentations. Identifiable means that the data will contain information that can be used to directly identify you, although we will not share your name with anyone. The study team will not contact you for additional consent to this future research. We may also share your identifiable information with other researchers. You can contact us at any time to ask us to stop using your information. However, we will not be able to take back your information from research projects that have already used it.

_____ Yes, I agree to let the researcher(s) use or share my personally identifiable information for future research.

_____ No, I do not agree to let the researcher(s) use or share my personally identifiable information for future research.

Print Legal Name: ____

Signature: ____

Date of Signature (mm/dd/yy): ______________________________________

Consent to be Contacted for Participation in Future Research

Researchers may wish to keep your contact information to invite you to be in future research projects that may be similar to or completely different from this research project.

_____ Yes, I agree for the researchers to contact me for future research projects.

_____ No, I do not agree for the researchers to contact me for future research projects.

Toyota Wheelchair Trial Survey

Start of Block: Default Question Block

Q27 Participant ID

____

Q18 Wheelchair Used

- ◯ Power (4)
- ◯ Manual (5)
- ◯ Personal (7)

Q20 AWTORS Configuration

- ◯ A (4)
- ◯ B (5)
- ◯ C (7)
- ◯ D (8)
- ◯ I (9)

End of Block: Default Question Block

Start of Block: Test Wheelchair

Q22 Rate the level of difficulty involved in maneuvering the test wheelchair compared to your own wheelchair:

- ○ Extremely easy (12)
- ○ Moderately easy (13)
- ○ Slightly easy (14)
- ○ Slightly difficult (16)
- ○ Moderately difficult (17)
- ○ Extremely difficult (18)
- ○ The same (19)

End of Block: Test Wheelchair

Start of Block: Entering Docking System

Q34 The following questions are in reference to entering the vehicle space and using the docking system.

Q16 Rate the level of difficulty involved in turning the wheelchair into the UDIG space compared to other securement systems you have used:

- ◯ Very easy (1)
- ◯ Somewhat easy (2)
- ◯ Somewhat difficult (4)
- ◯ Very difficult (5)

Q24 Rate the level of difficulty involved in backing into the UDIG space compared to other securement systems you have used:

- ◯ Very easy (1)
- ◯ Somewhat easy (2)
- ◯ Somewhat difficult (4)
- ◯ Very difficult (5)

Q28 Rate the ease of lining up the wheelchair with the UDIG anchors:

- ◯ Poor (1)
- ◯ Could be better (2)
- ◯ Good (3)
- ◯ Excellent (4)
- ◯ Not applicable (5)

Q29 Rate the feeling of security once docked:

- ◯ Poor (1)
- ◯ Could be better (2)
- ◯ Good (3)

○ Excellent (4)

Q30 Rate the ability to use the docking system without help:

○ Poor (1)

○ Could be better (2)

○ Good (3)

○ Excellent (4)

○ Not applicable (5)

Q15 Rate the level of difficulty using and understanding the UDIG docking system controls while engaging/locking the UDIG mechanism compared to other securement systems you have used:

○ Very easy (1)

○ Somewhat easy (2)

○ Somewhat difficult (4)

○ Very difficult (5)

○ Not applicable (6)

End of Block: Entering Docking System

Start of Block: Seatbelt System

Q35 The following questions are in reference to the seatbelt system.
Q31 Rate the ease of positioning the lap belt on your body:

- Poor (1)
- Could be better (2)
- Good (3)
- Excellent (4)

Q32 Rate the ease of positioning the shoulder belt on your body:

- Poor (1)
- Could be better (2)
- Good (3)
- Excellent (4)

Q33 Rate the feeling of safety once belted:

- Poor (1)
- Could be better (2)
- Good (3)
- Excellent (4)

Q37 Rate the ability to use the seatbelt system without help:

- Poor (1)
- Could be better (2)
- Good (3)
- Excellent (4)

Q31 How comfortable is the lap belt?

- Extremely comfortable (1)

- ○ Very comfortable (2)
- ○ Moderately comfortable (3)
- ○ Slightly comfortable (4)
- ○ Not at all comfortable (5)

Q17 How comfortable is the shoulder belt?

- ○ Extremely comfortable (1)
- ○ Very comfortable (2)
- ○ Moderately comfortable (3)
- ○ Slightly comfortable (4)
- ○ Not at all comfortable (5)

End of Block: Seatbelt System

Start of Block: STOP

Q27 Please stop and hand the tablet to the investigator.

End of Block: STOP

Start of Block: After Exit (Seatbelt/Docking Systems)

Q25 Rate the level of difficulty using and understanding the UDIG docking system controls while releasing the UDIG mechanism compared to other securement systems you have used:

- ◯ Very easy (1)
- ◯ Somewhat easy (2)
- ◯ Somewhat difficult (4)
- ◯ Very difficult (5)
- ◯ Not applicable (6)

Q33 On a scale from 0-10, based on your experience today, how likely are you to recommend this docking system to a friend or colleague?

- ◯ 0 (0)
- ◯ 1 (1)
- ◯ 2 (2)
- ◯ 3 (3)
- ◯ 4 (4)
- ◯ 5 (5)
- ◯ 6 (6)
- ◯ 7 (7)
- ◯ 8 (8)
- ◯ 9 (9)
- ◯ 10 (10)

Q22 On a scale from 0-10, based on your experience today, how likely are you to recommend this seatbelt system to a friend or colleague?

- ◯ 0 (0)

○ 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 (7)

○ 8 (8)

○ 9 (9)

○ 10 (10)

Q34 Please leave any additional comments about how we can improve the docking or seatbelt system or process in the space provided below.

____

____

____

____

____

End of Block: After Exit (Seatbelt/Docking Systems)

Toyota Wheelchair Volunteer Questionnaire

Start of Block: Default Question Block

Q21 Participant ID

____

End of Block: Default Question Block

Start of Block: Welcome

Q1 Thank you for volunteering to participate in our study. Please answer the following questions regarding your personal transportation experiences.

End of Block: Welcome

Start of Block: Your Devices

Q25 How often do you use a manual wheelchair?

- ○ Always (1)
- ○ Usually (2)
- ○ Sometimes (3)
- ○ Never (4)

Q26 How often do you use a power wheelchair?

- ○ Always (1)
- ○ Usually (2)
- ○ Sometimes (3)
- ○ Never (4)

Q27 How often do you use a scooter?

- ○ Always (1)
- ○ Usually (2)
- ○ Sometimes (3)
- ○ Never (4)

Q28 How often do you use a walker?

- ○ Always (1)
- ○ Usually (2)
- ○ Sometimes (3)
- ○ Never (4)

Q29 How often do you use a cane?

- ○ Always (1)

○ Usually (2)

○ Sometimes (3)

○ Never (4)

Q3 What is the primary medical reason you use an assistive device?

____

____

____

____

____

Q4 How long have you used a wheelchair or scooter?

- ◯ Less than 1 year (1)
- ◯ 1-2 years (2)
- ◯ 3-5 years (3)
- ◯ 6-10 years (4)
- ◯ More than 10 years (5)

Q5 Do you have any of these items attached to your wheelchair when you travel in vehicles?

- ▢ Oxygen tank (1)
- ▢ Tray (2)
- ▢ Lateral supports (3)
- ▢ Headrest (4)
- ▢ Chest postural supports (5)
- ▢ Pelvis postural supports (6)

End of Block: Your Devices

Start of Block: Travel Methods

Q30 How often do you travel by public bus?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q31 How often do you travel by paratransit van?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q32 How often do you transfer from your wheelchair to drive?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)

- 4-5 times per week (6)
- Almost every day (8)

Q33 How often do you transfer to a vehicle as a passenger?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q34 How often do you drive while seated in your wheelchair in a modified vehicle?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q35 How often do you travel as a passenger while seated in your wheelchair in a modified personal vehicle?

- Never (1)
- About once a month (2)

- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q36 How often do you travel by other means of transportation?

- Never (1)
- About once a month (2)
- 2-3 times per month (3)
- About once a week (4)
- 2-3 times per week (5)
- 4-5 times per week (6)
- Almost every day (8)

Q7 When traveling in personal vehicles, where do you usually sit?

- Driver seat (1)
- First row right (2)
- Second row left (3)
- Second row right (4)
- Second row center (5)
- Third row center (6)
- Other (7)

Q8 If you transfer from your wheelchair, how do you usually stow it?

◯ Stow it myself in back seat (1)

◯ Automatic rooftop storage (2)

◯ Secured on platform outside vehicle (3)

◯ Unsecured in occupant area (4)

◯ Someone else stows it in the trunk or cargo area (5)

◯ Do not transfer (6)

End of Block: Travel Methods

Start of Block: Travel Experiences

Q37 How often have you been injured while entering or exiting a vehicle?

- Never (1)
- Sometimes (2)
- Often (3)
- Usually (4)

Q38 How often is a ramp too steep to navigate safely?

- Never (1)
- Sometimes (2)
- Often (3)
- Usually (4)

Q39 How often do you have difficulty maneuvering to the wheelchair station?

- Never (1)
- Sometimes (2)
- Often (3)
- Usually (4)

Q40 How often do you have difficulty securing your wheelchair to the vehicle?

- Never (1)
- Sometimes (2)
- Often (3)
- Usually (4)

Q41 How often do you experience uncomfortable seat belt fit?

- Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q42 How often does your wheelchair move too much during travel?

○ Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q43 How often do you shift too much in your wheelchair during braking or turning?

○ Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q44 How often do you have difficulty buckling the seat belt?

○ Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q45 How often do the wheelchair parts interfere with the seat belt?

○ Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q46 How often are you unable to see the vehicle travel path?

○ Never (1)

○ Sometimes (2)

○ Often (3)

○ Usually (4)

Q47 Think of the most common way you travel in vehicles and rate how independent you feel.

○ Great (1)

○ Good (2)

○ OK (3)

○ Bad (4)

○ Terrible (5)

Q48 Think of the most common way you travel in vehicles and rate how safe you feel.

○ Great (1)

○ Good (2)

○ OK (3)

○ Bad (4)

○ Terrible (5)

Q49 Think of the most common way you travel in vehicles and rate how usable it is.

○ Great (1)

○ Good (2)

○ OK (3)

○ Bad (4)

○ Terrible (5)

End of Block: Travel Experiences

Start of Block: Travel Safety

Q55 Do you remain seated in your wheelchair while traveling in a personal vehicle?

○ Yes (23)

○ No (24)

Skip To: Q11 If Do you remain seated in your wheelchair while traveling in a personal vehicle? = Yes

Skip To: Q13 If Do you remain seated in your wheelchair while traveling in a personal vehicle? = No

Display This Question:

If Do you remain seated in your wheelchair while traveling in a personal vehicle? = Yes

Q11 How do you secure your wheelchair to the vehicle?

○ Wheelchair not secured (1)

○ 4-point-strap tiedown (2)

○ Docking station (3)

Display This Question:

If Do you remain seated in your wheelchair while traveling in a personal vehicle? = Yes

Q12 What type of seat belt do you use? Select all that apply.

- ☐ None (1)
- ☐ Lap belt attached to my wheelchair (2)
- ☐ Harness system attached to my wheelchair (3)
- ☐ Shoulder belt attached to the vehicle (4)
- ☐ Shoulder and lap belt attached to the vehicle (5)

Q13 In your most common method of travel when using a shoulder belt, how does it fit? Select all that apply.

- ☐ Upper end centered on shoulder (1)
- ☐ Upper end touching neck (2)
- ☐ Upper end crossing upper arm (3)
- ☐ Connects to lap belt near centerline of body (4)
- ☐ Connects to lap belt near opposite hip (5)
- ☐ Too tight (6)
- ☐ Too loose (7)
- ☐ Snug (8)

Q14 In your most common method of travel when using a lap belt, how does it fit? Select all that apply.

- ☐ Contacts tops of thighs (1)
- ☐ Crosses abdomen below my belly button (2)

- ☐ Crosses abdomen above my belly button (3)
- ☐ Crosses at chest level (4)
- ☐ Too loose (5)
- ☐ Too tight (6)
- ☐ Snugness just right (7)

Q15 In the most common situation when you wear a seat belt, how do you put it on?

- ○ Drive myself into it (1)
- ○ Someone helps buckle me in (2)
- ○ I buckle myself (3)

Q16 Do you know if your wheelchair has passed tests showing that it is safe to use as seating in vehicles? This might be described as having the "transit option" or passing "WC19" tests.

- ○ Yes, it has been tested (1)
- ○ No, it has not been tested (2)
- ○ I don't know (3)

Q17 Have you heard about the "transit option" or WC19 tests before this survey?

- ○ Yes (1)
- ○ No (2)
- ○ Not sure (3)

Q54 Do you travel in a vehicle adapted for wheelchair use?

- Yes (23)
- No (24)

Skip to: Q50 if Do you travel in a vehicle adapted for wheelchair use? =Yes

Skip to End of Block if Do you travel in a vehicle adapted for Wheelchair use? =No

Q50 Has the steering wheel airbag been removed or modified in the adapted vehicle?

- Still there (1)
- Removed (2)
- Modified (3)
- Not sure (4)

Display This Question
If Do you travel in a vehicle adapted for wheelchair use?=Yes

Q51 Has the front passenger airbag in the dashboard been removed or modified in the adapted vehicle?

- Still there (1)
- Removed (2)
- Modified (3)
- Not sure (4)

Display This Question
If Do you travel in a vehicle adapted for wheelchair use?=Yes

Q52 Have the curtain airbags been removed or modified in the adapted vehicle?

- Still there (1)
- Removed (2)
- Modified (3)
- Not sure (4)

Display This Question
If Do you travel in a vehicle adapted for wheelchair use?=Yes

Q53 Has the original seat belt been removed or modified in the adapted vehicle?

- Still there (1)
- Removed (2)
- Modified (3)
- Not sure (4)

End of Block: Travel Safety

Start of Block: Demographic Information

Q19 What is your age?

____

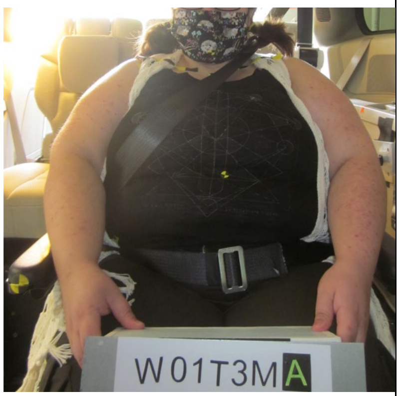
Q20 What is your gender?

- Female (1)
- Male (2)
- Prefer not to identify gender (3)

End of Block: Demographic Information

Appendix B: Photos of Participant Belt Fit

Volunteer TW01

A: SBS 13 LBS 3	B: SBS 23 LBS 4	C: SBS 7 LBS 4
		
D: SBS 62 LBS 4	I:M: SBS 21 LBS 4	I:P: SBS 7 LBS 4
		
I:V: SBS 10 LBS 3	I:V*: SBS 23 LBS 3	I:V**: SBS 16 LBS 2
		

Volunteer TW02

A: SBS 15 LBS 4	B: SBS 28 LBS 3	C: SBS 15 LBS 3
		
D	I:M: SBS 0 LBS 4	I:P: SBS 0 LBS 4
Not tested		
I:V: SBS 65 LBS 3	I:V*	I:V**: SBS 0 LBS 4
	Not adjusted	

Volunteer W03

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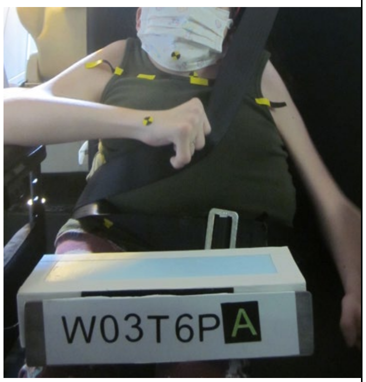
<tr><td>
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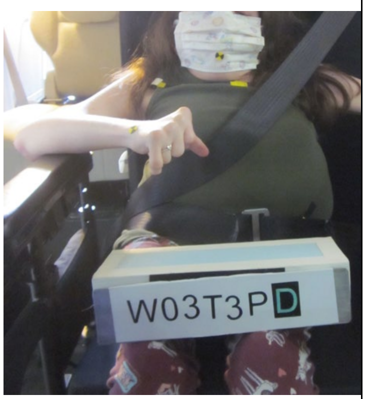
<tr><td>D: SBS 63 LBS 3</td><td>I:M</td><td>I:P: SBS 26 LBS 3</td></tr>
<tr><td>
</td><td>Not tested</td><td>
</td></tr>
<tr><td>I:V: SBS 88 LBS 4</td><td>I:V*: SBS 21 LBS 3</td><td>I:V**: SBS 75 LBS 3</td></tr>
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</table>

Volunteer W04

A: SBS 11 LBS 3	B: SBS 27 LBS 3	C: SBS 46 LBS 3
		
D: SBS 124 LBS 3	I:M: SBS -8 LBS 3	I:P: SBS 35 LBS 3
		
I:V: SBS -19 LBS 5	I:V*: SBS -43 LBS 5	I:V**: SBS -40 LBS 5
		

Volunteer W09

A: SBS -21 LBS 4	B: SBS -12 LBS 4	C: SBS 17 LBS 5
		
D	I:M: SBS -12 LBS 3	I:P: SBS 12 LBS 5
Not tested		
I:V: SBS 12 LBS 5	I:V*: SBS 40 LBS 3	I:V**: SBS 17 LBS 3
		

Volunteer W12

<table>
<tr><td>A: SBS 0 LBS 3</td><td>B: SBS 20 LBS 2</td><td>C: SBS -39 LBS 4</td></tr>
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<tr><td>D: SBS NA LBS 3</td><td>I:M: SBS 12 LBS 3</td><td>I:P: SBS 30 LBS 4</td></tr>
<tr><td>
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</td><td>
</td></tr>
<tr><td>I:V: SBS 57 LBS 2</td><td>I:V*</td><td>I:V**</td></tr>
<tr><td>Their

</td><td>Not adjusted</td><td></td></tr>
</table>

Volunteer W13

A: SBS 51 LBS 3	B: SBS 32 LBS 2	C: SBS 52 LBS 2
		
D: SBS 70 LBS 2	I:M: SBS 56 LBS 2	I:P: SBS 30 LBS 2
		
I:V: SBS 44 LBS 2	I:V*	I:V**: SBS 52 LBS 2
	Not adjusted	

Volunteer W14

A	B: SBS 41 LBS 3	C: SBS 35 LBS 3
Not tested		
D: SBS 136, LBS 3	I:M: SBS 91 LBS 2	I:P: SBS 49 LBS 3
		
I:V: SBS 31 LBS 2	I:V*	I:V**: SBS 7 LBS 3
	Not adjusted	

Volunteer W23

A: SBS 0 LBS 2	B: SBS 0 LBS 2	C: SBS 10 LBS 2
		
D: SBS 52 LBS 2	I:M: SBS 15 LBS 2	I:P: SBS -17 LBS 3
		
I:V: SBS -17 LBS 3	I:V*	I:V**: SBS 0 LBS 3
	Not adjusted	

Volunteer W24

<table>
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<tr><td>D: SBS 82 LBS 3</td><td>I:M: SBS 20 LBS 3</td><td>I:P: SBS 0 LBS 3</td></tr>
<tr><td>
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</td></tr>
<tr><td>I:V: SBS 27 LBS 2</td><td>I:V*</td><td>I:V**: SBS 27 LBS 2</td></tr>
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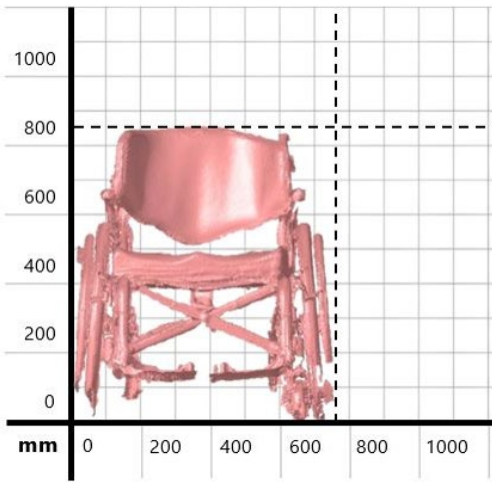
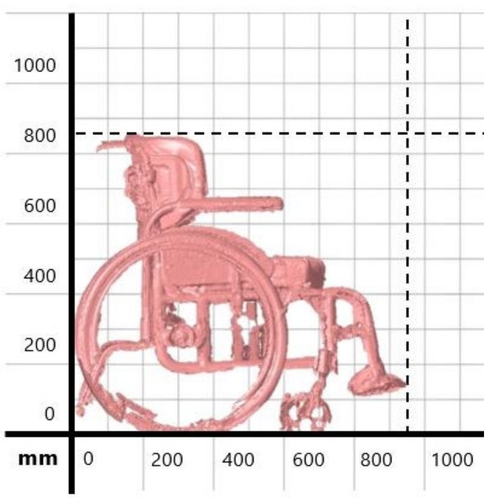
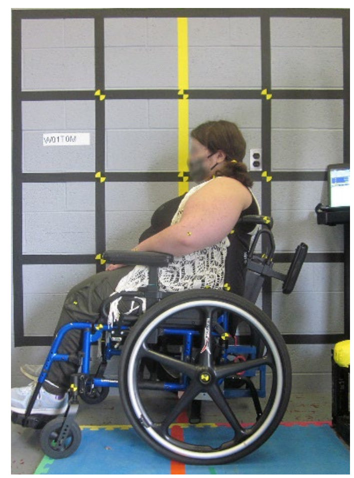
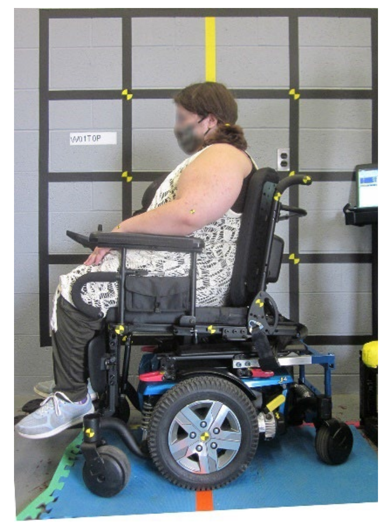
Appendix C: Images of Volunteers in Wheelchairs

TW01

View	Scan Personal WC	Personal WC	Manual WC	Power WC
Front				
Side				

TW02

<table>
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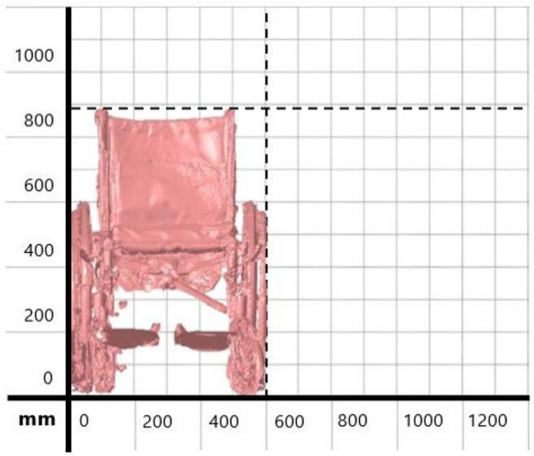
<tr><td>Front</td><td>
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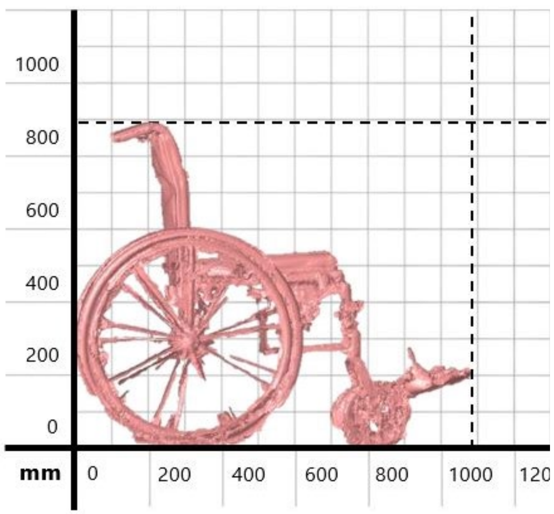
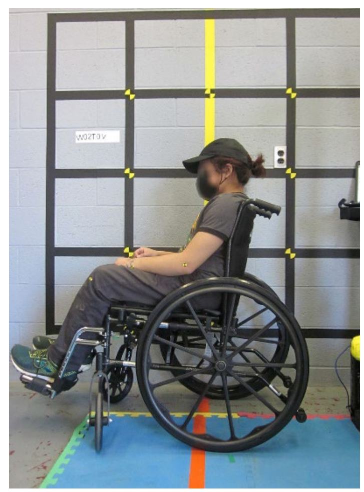
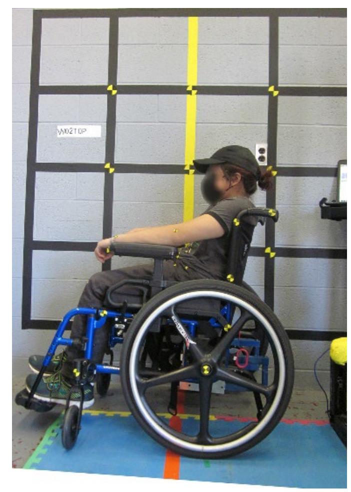
<tr><td>Side View</td><td>
</td><td></td><td></td><td></td></tr>
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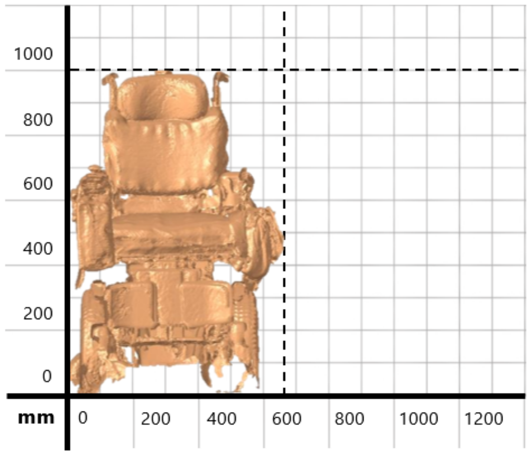
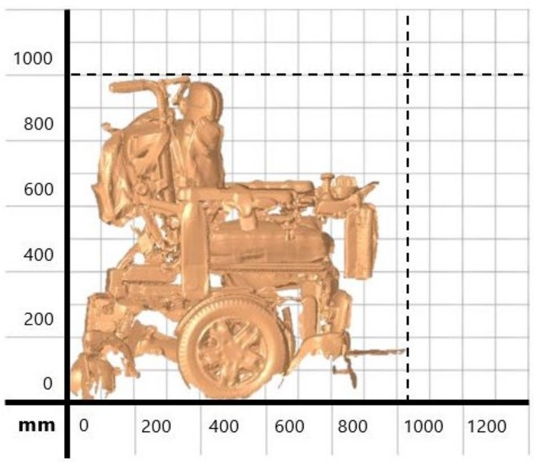
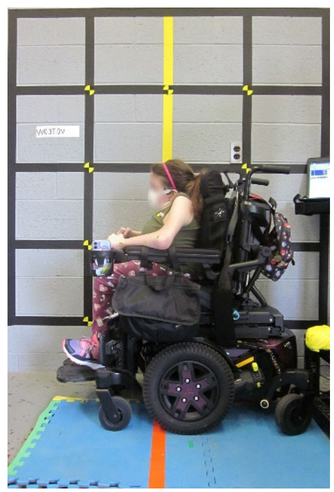
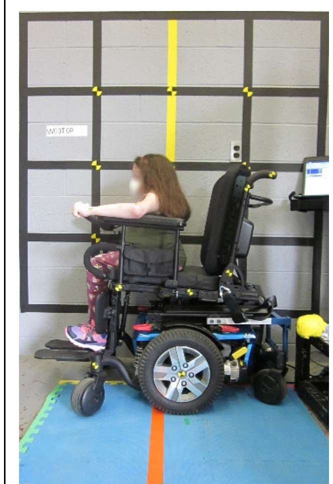
 1000 800 600 400 200 0 mm 0 200 400 600 800 1000 1200		NA	
 1000 800 600 400 200 0 mm 0 200 400 600 800 1000 1200		NA	

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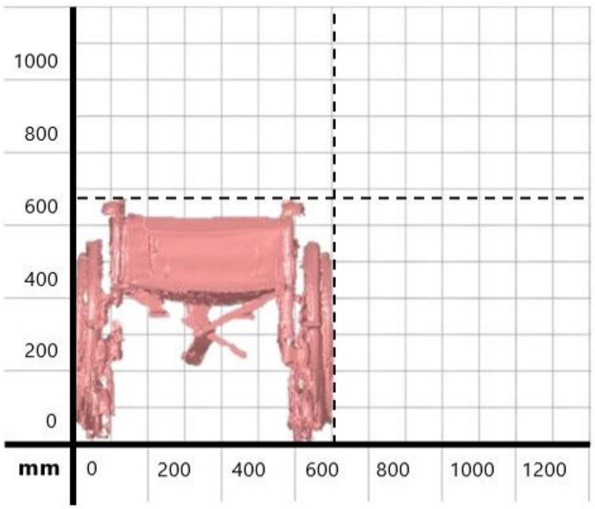
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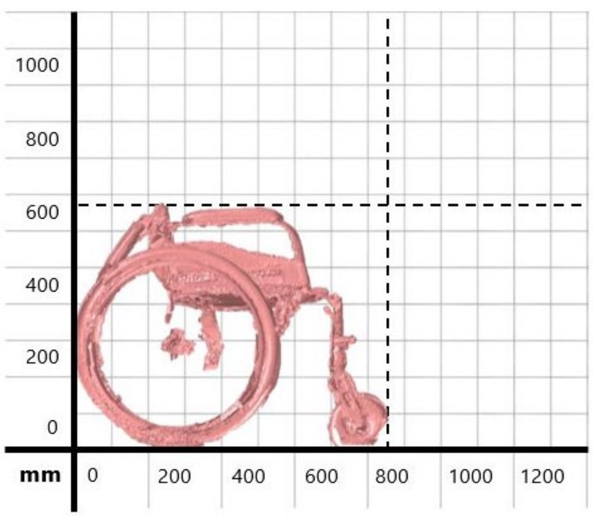
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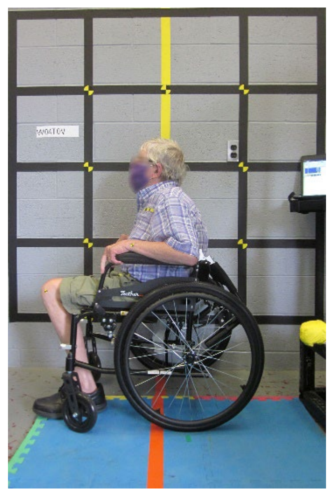

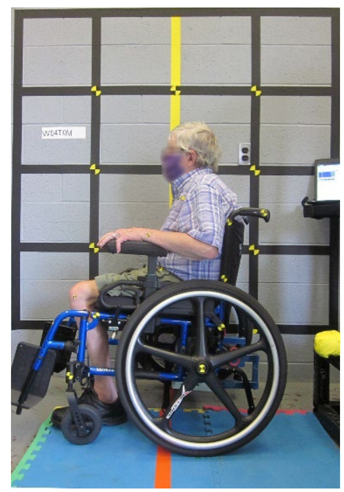

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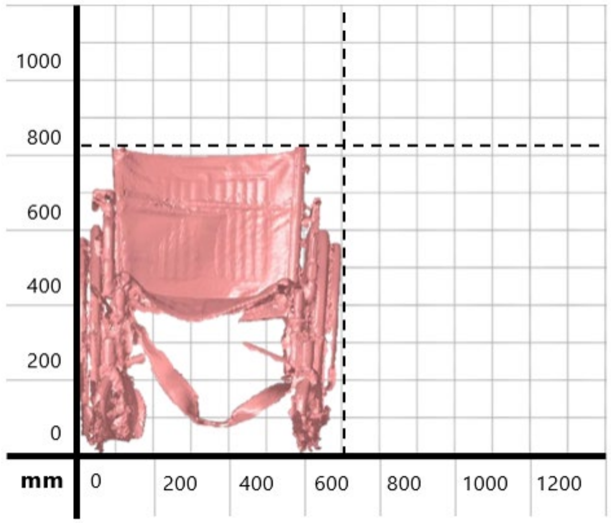
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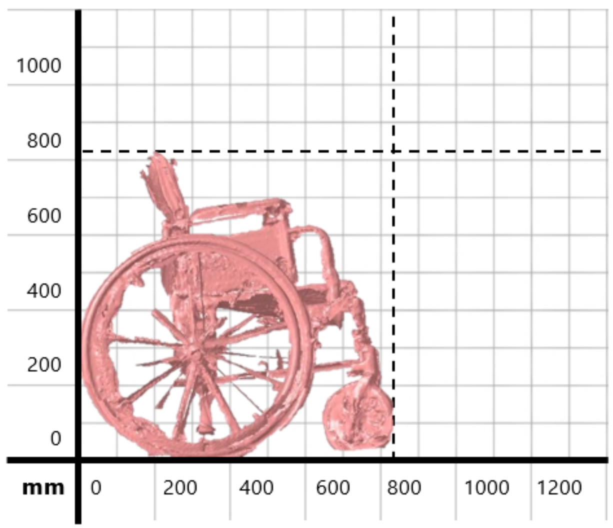
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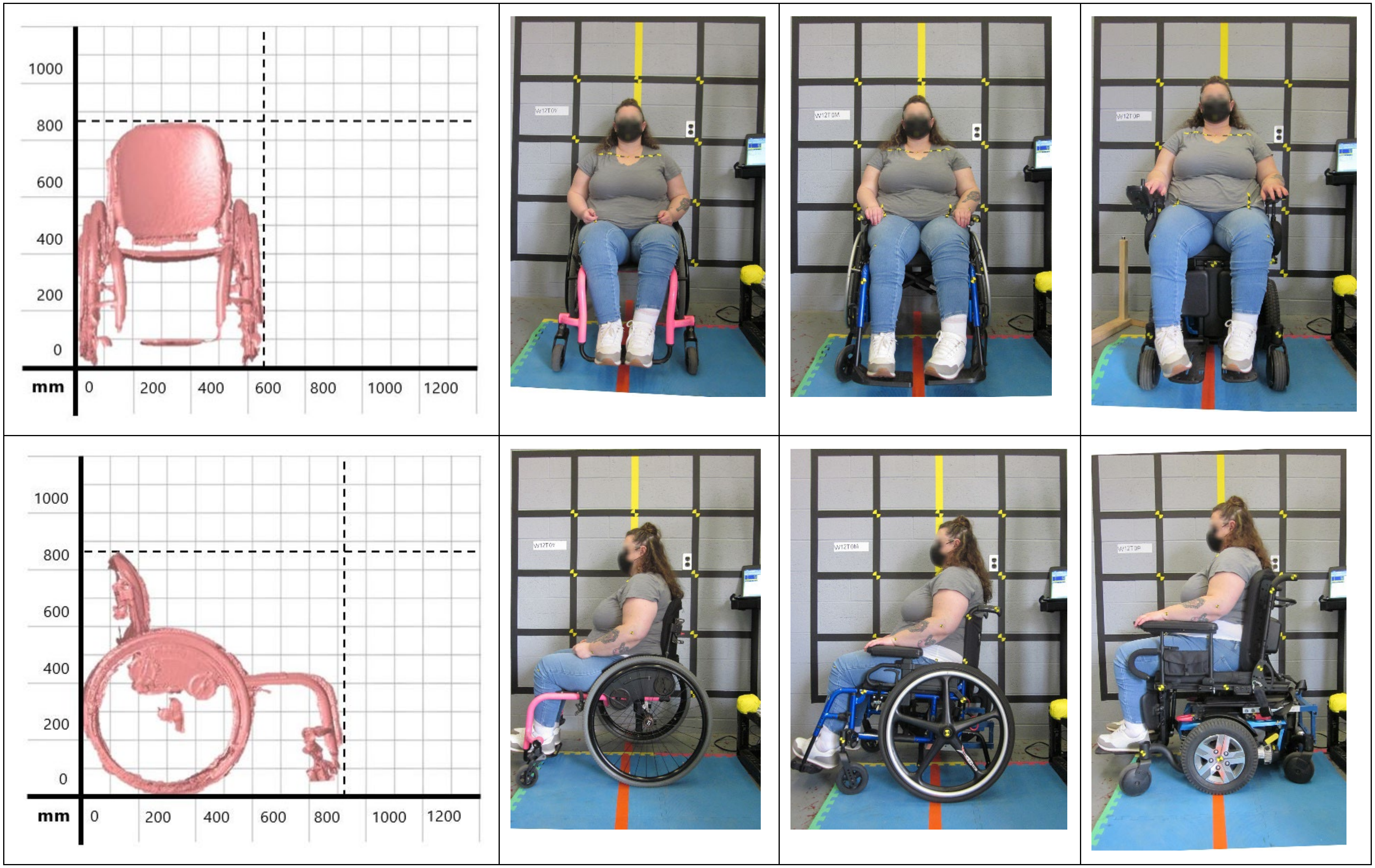

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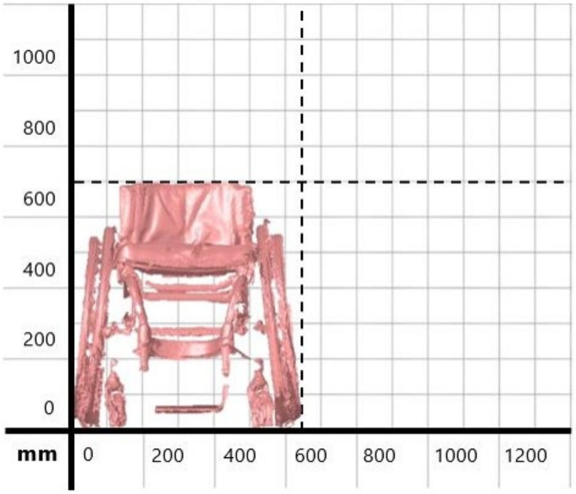
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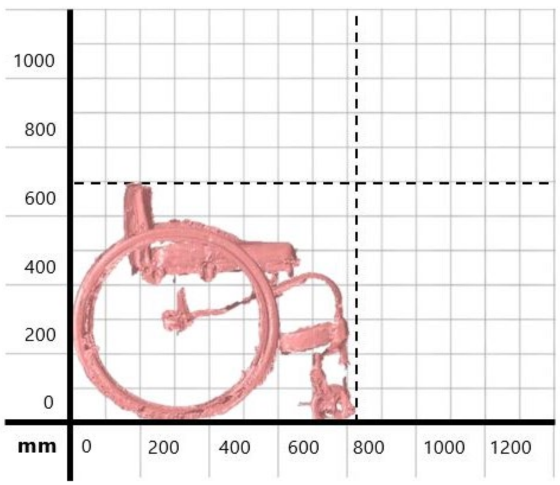
TEAM REEVE


TEAM REEVE


TEAM REEVE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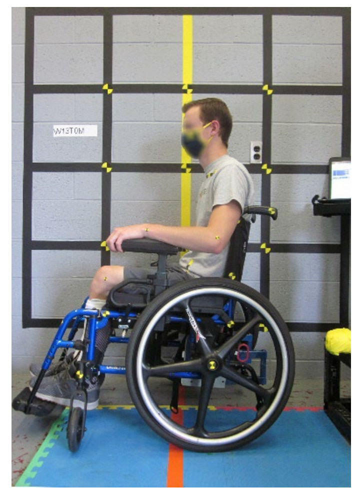

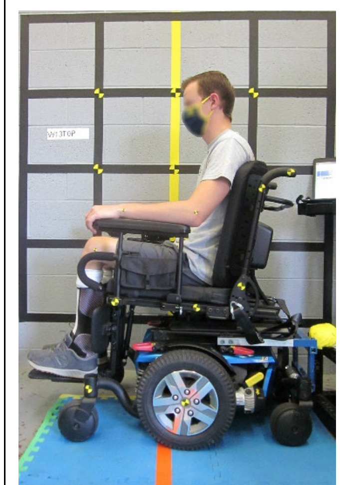

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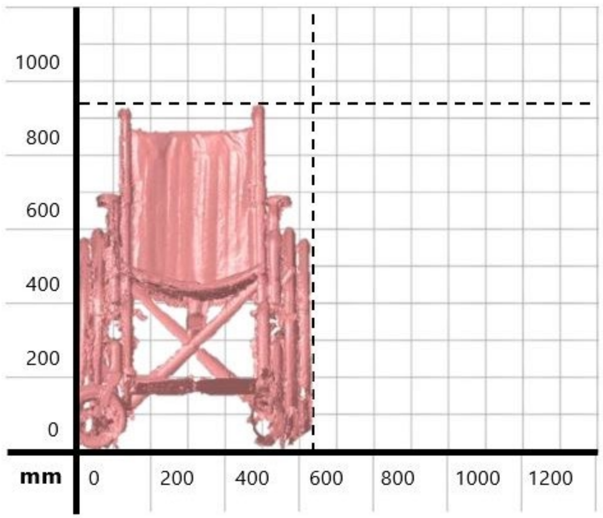
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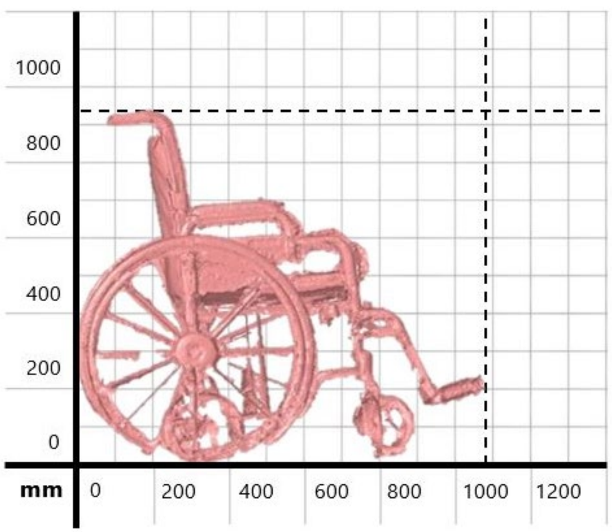
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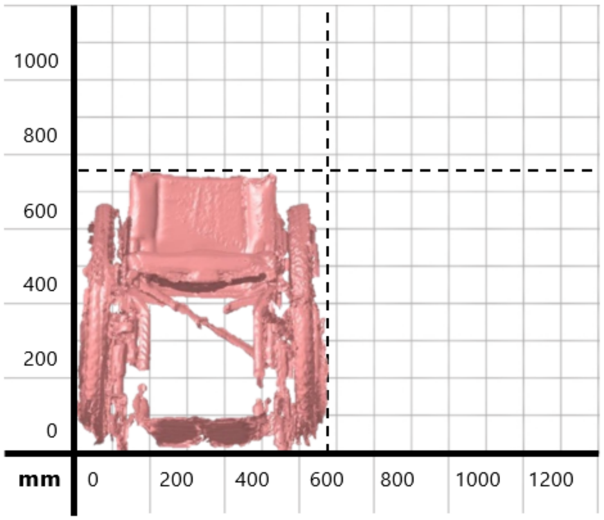

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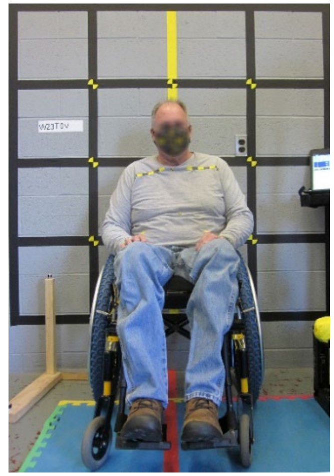

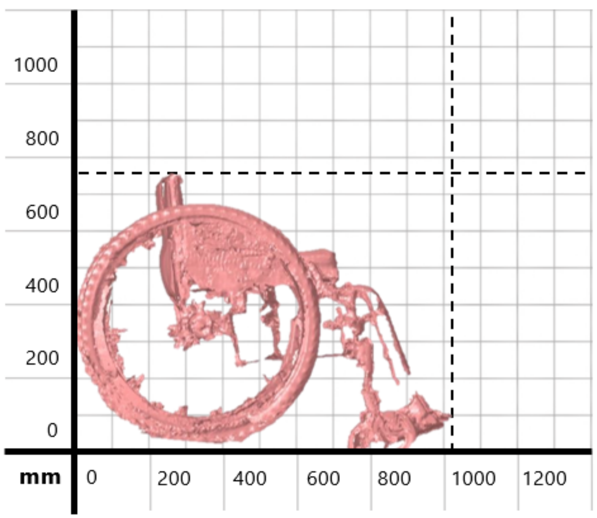

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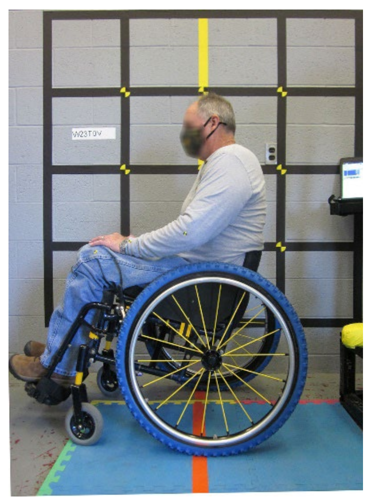

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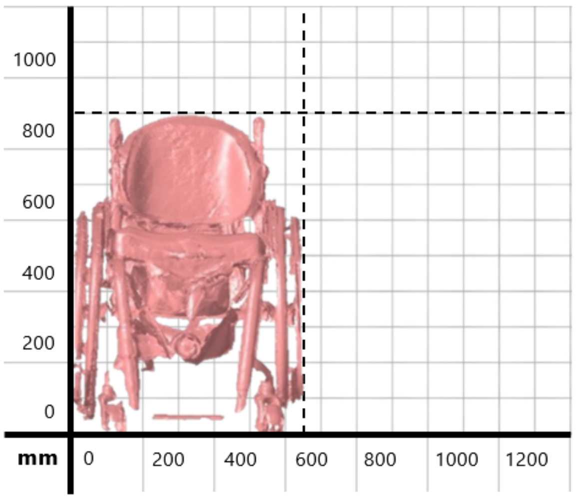
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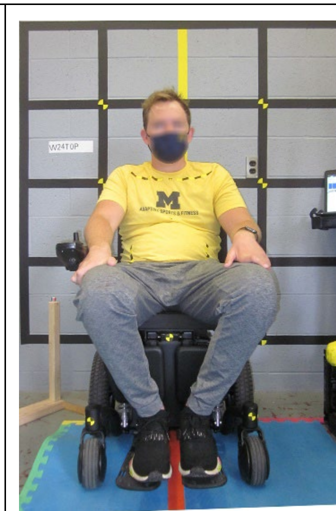

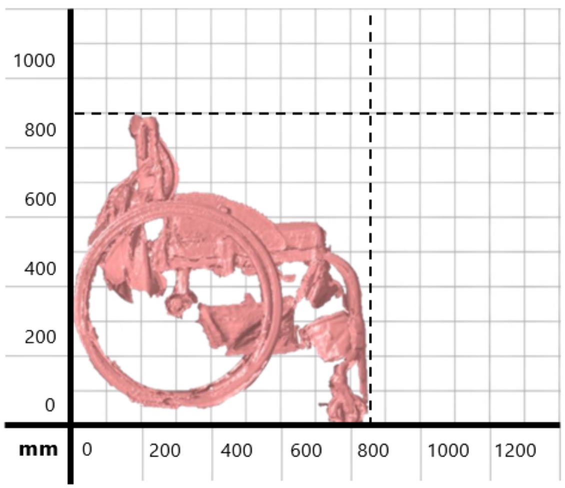
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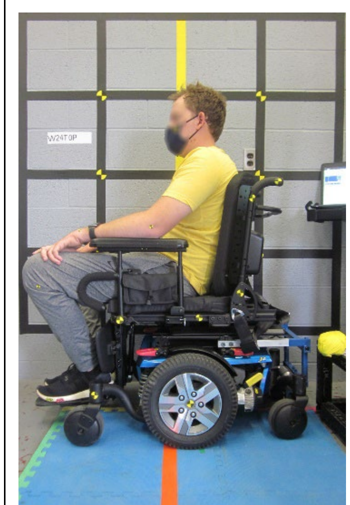
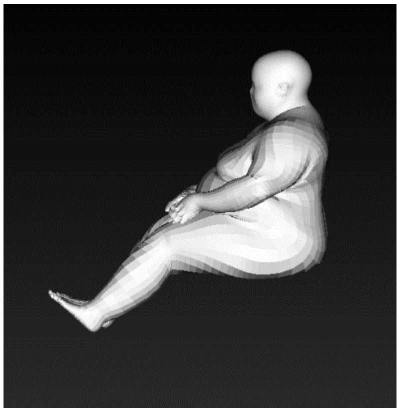
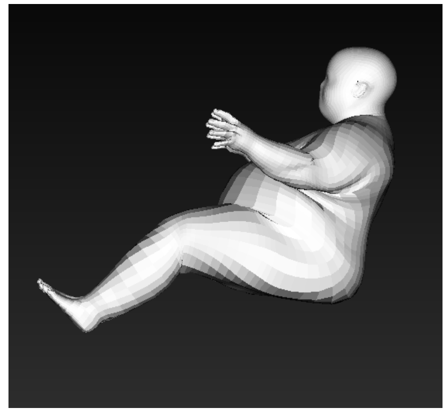
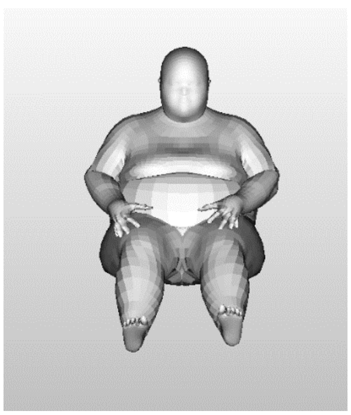
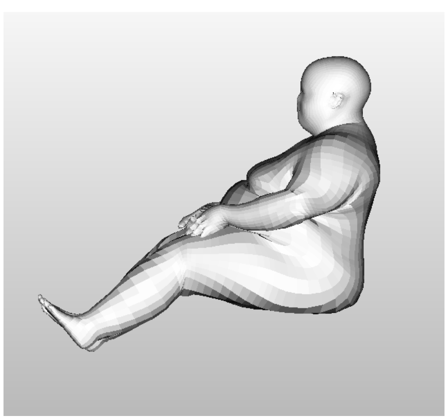


Appendix D: Avatars from Laboratory Postures

TW01

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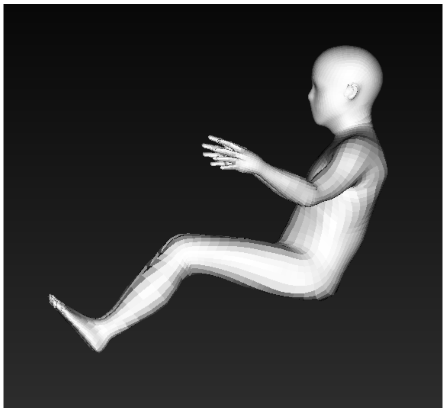	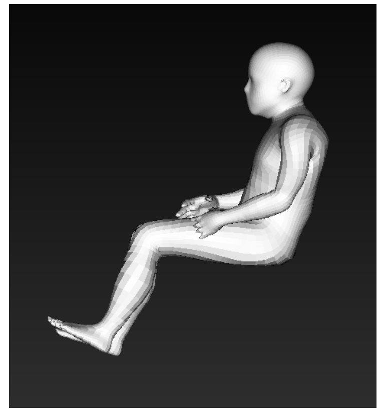
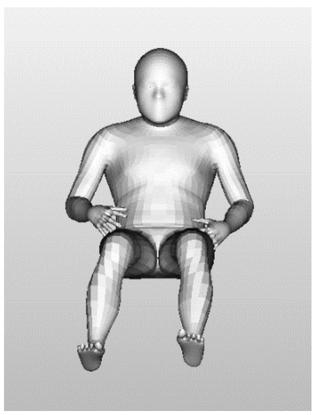	
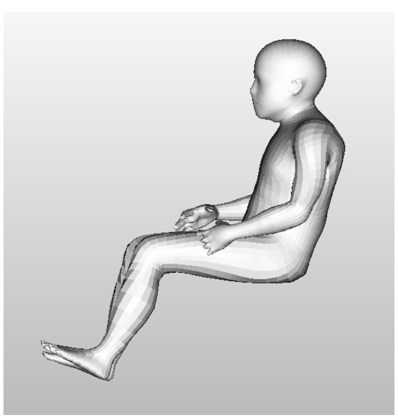	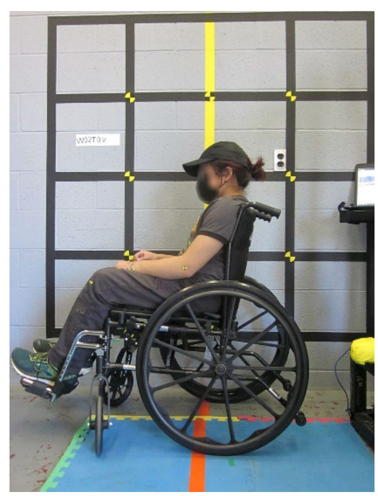

TW03

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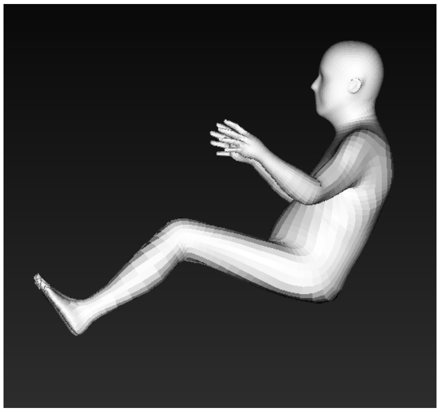
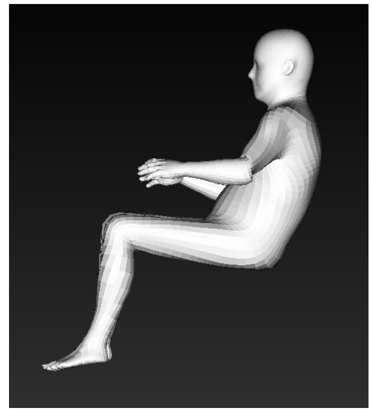
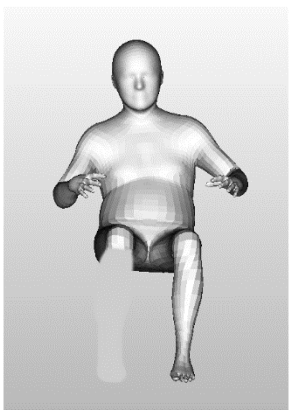
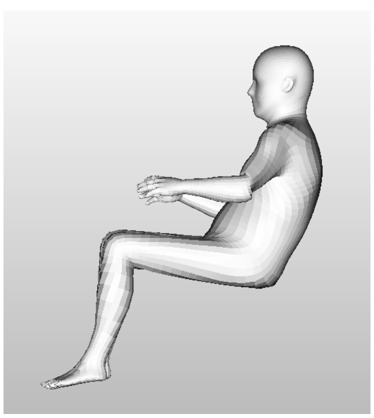
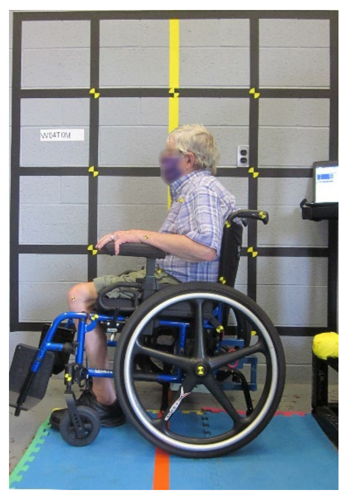
TW04

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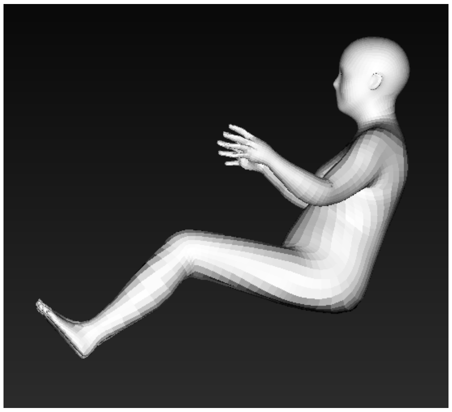	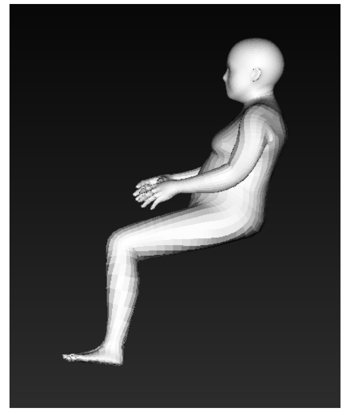
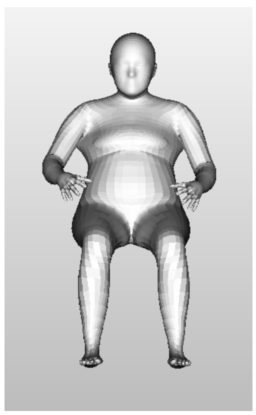	
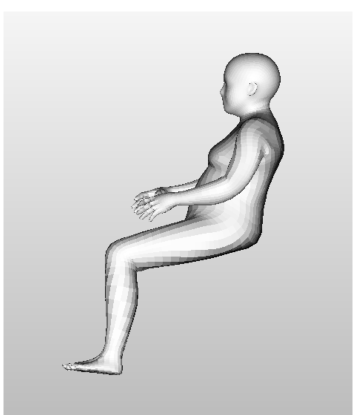	

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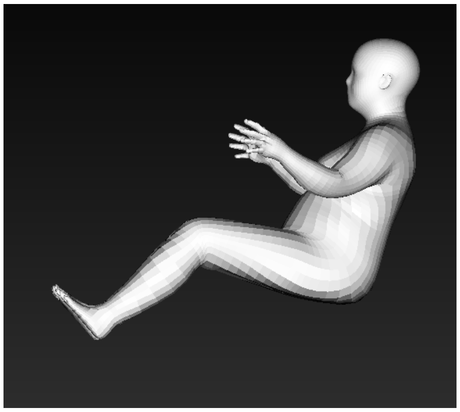	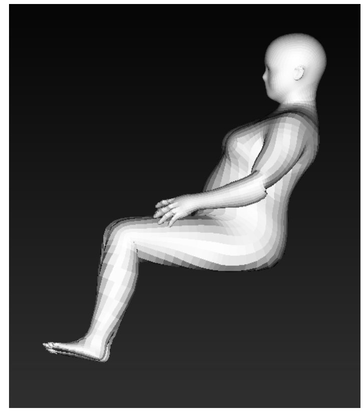
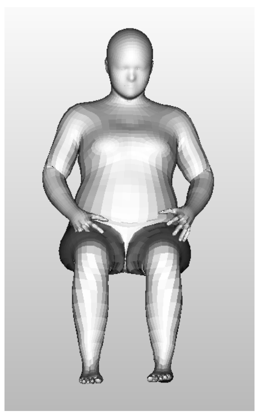	
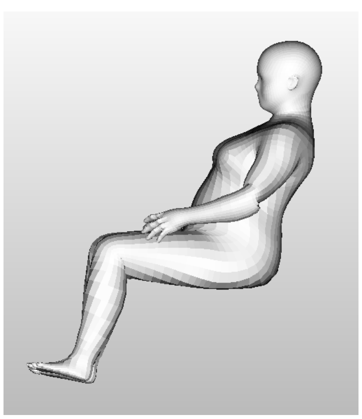	

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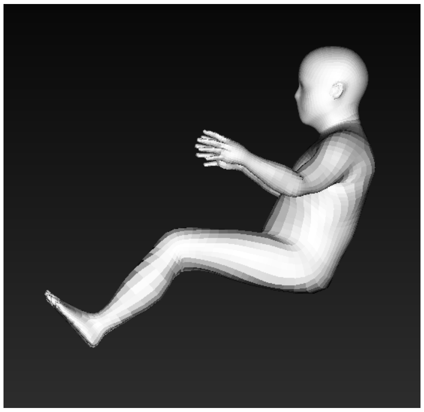	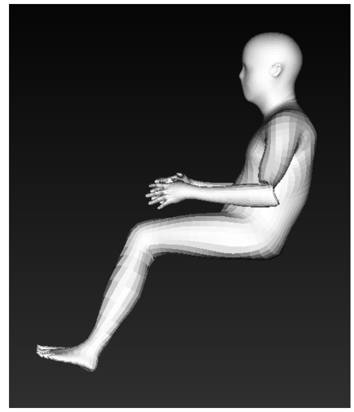
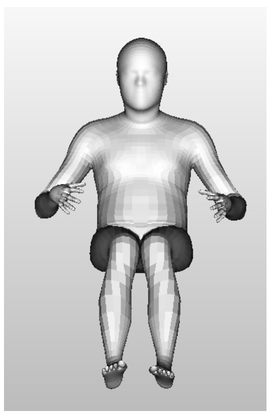	
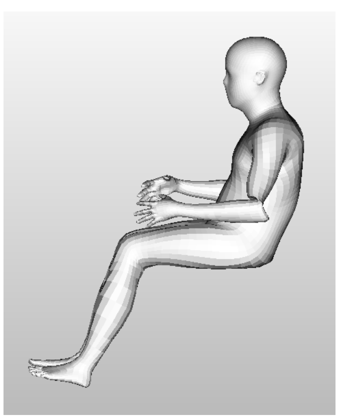	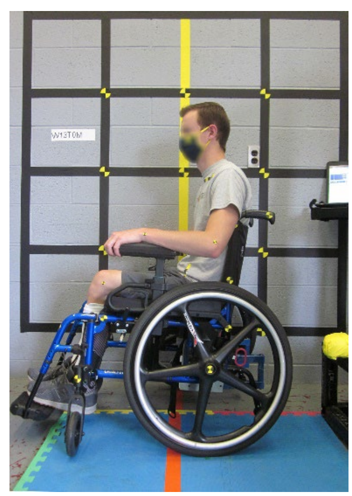

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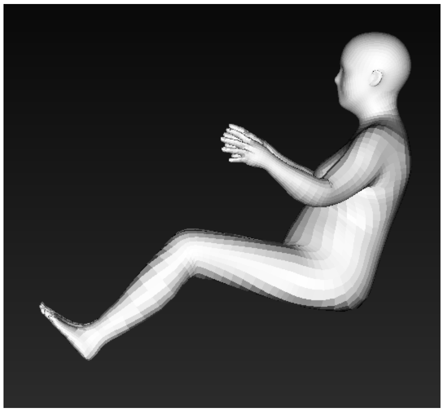	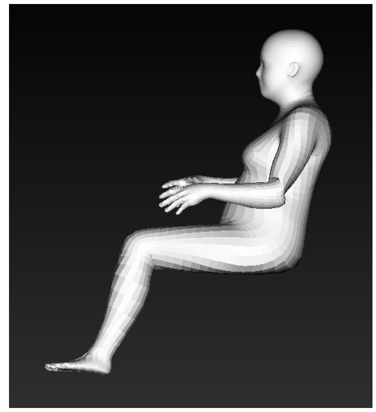
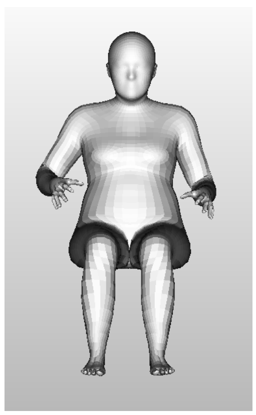	
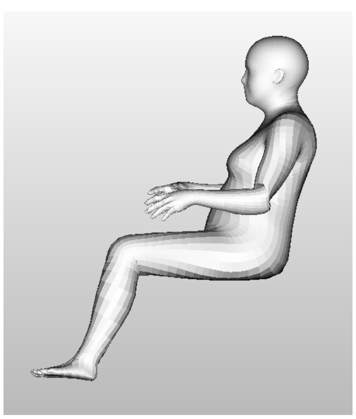	

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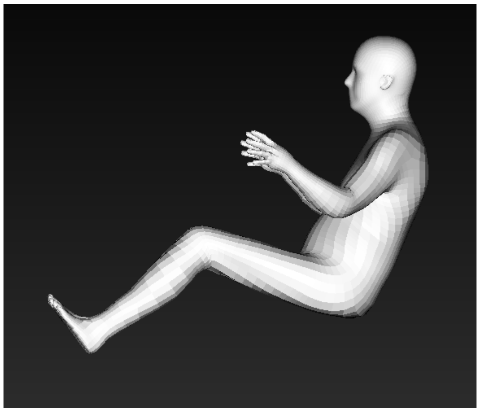	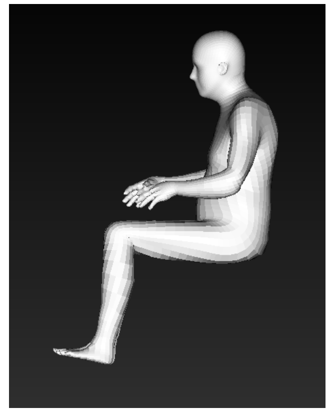
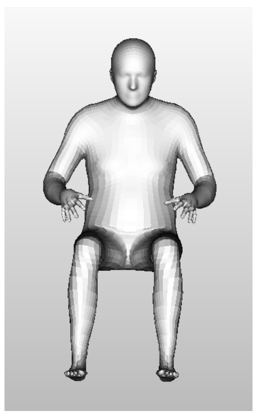	
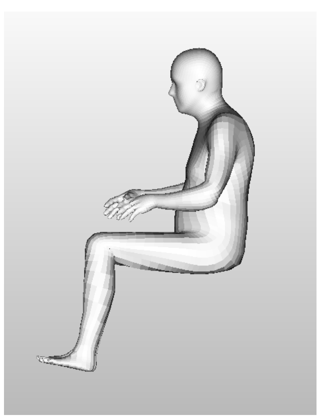	

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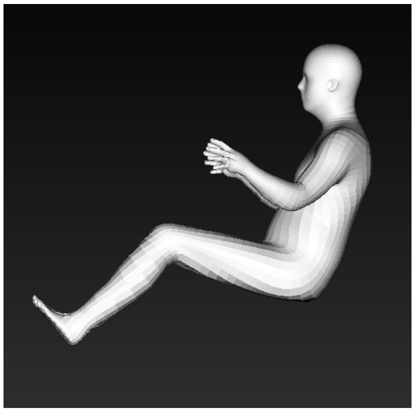
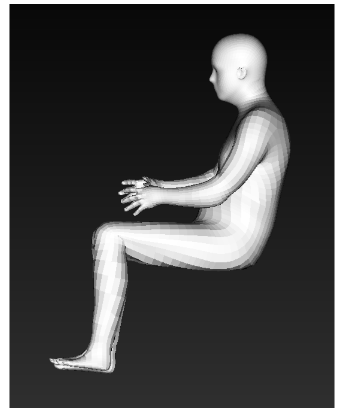
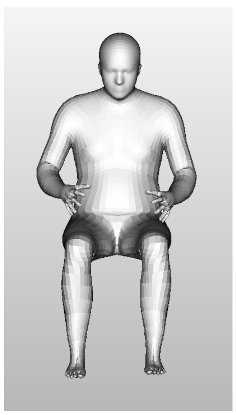
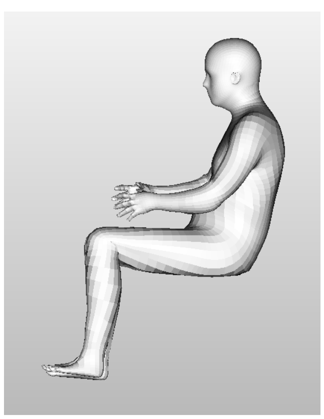
	
	
	

Appendix E: Field Measurement Documents

Help us design automated vehicles so they work with wheelchairs!

Why?

Vehicle manufacturers are trying to design automated vehicles that will work for a wide range of wheelchair and passenger sizes.

Who?

Anyone using their own wheelchair age 18 and older.

Where?

Outside the building.

When? How long?

As you are leaving, about 10 minutes.

How much?

We will give you a $10 Visa gift card for participating.

What about privacy?

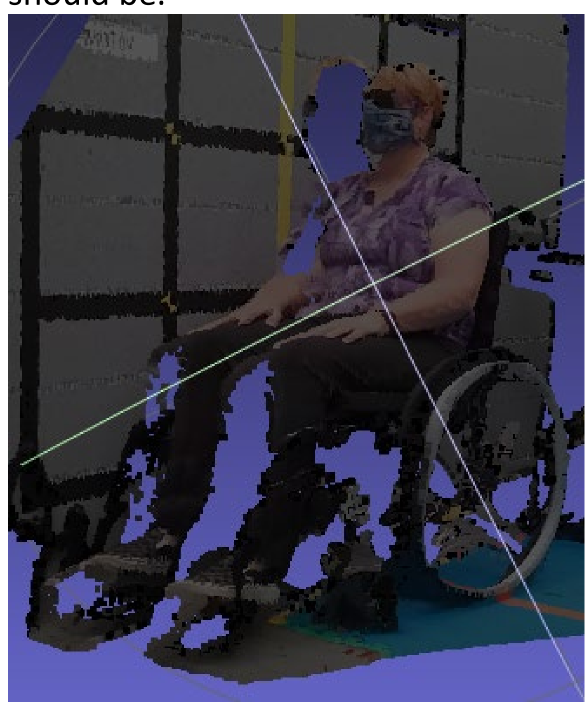
We will have you wear sunglasses and a mask during the scan so you can't be recognized. We will store individual scans on a secure server, and will not share individual scans outside of the research team.

How does it work?

We will ask you your age, height, weight, and reason for using the wheelchair. We will record the wheelchair make and model.

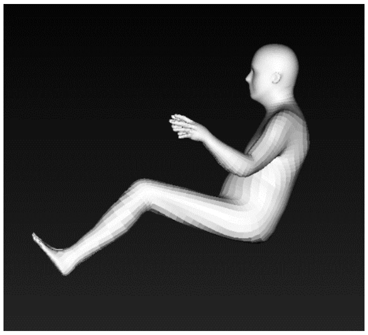
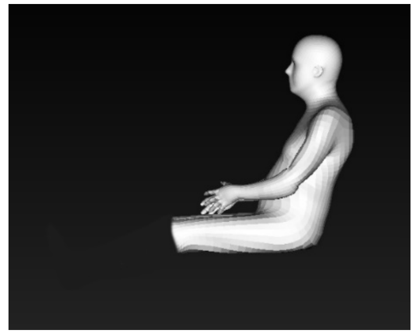
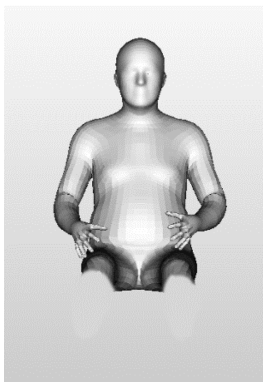
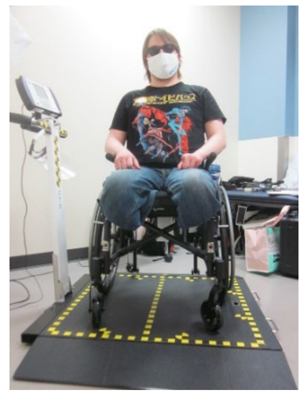
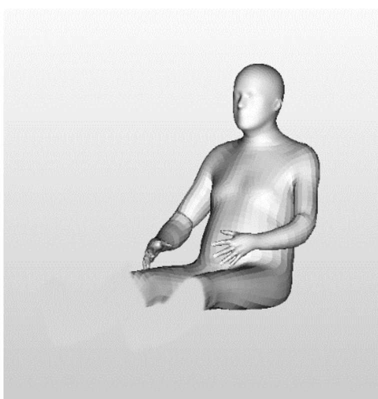
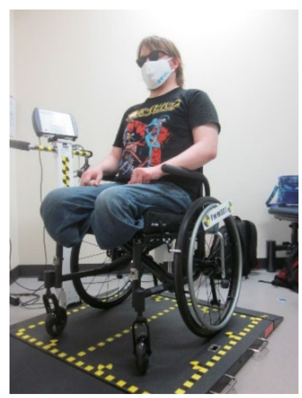
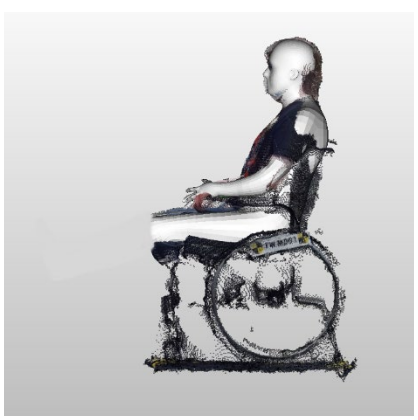
We will weigh you and your wheelchair on a portable scale.

We will use our portable measurement system (based on Kinect video-game technology) to capture a 3-D picture of you in your wheelchair. The picture shows what it looks like. We will also measure you while reaching in different directions to help figure out where controls should be.

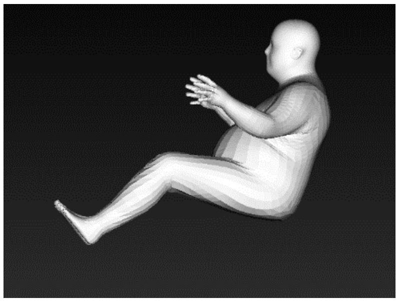
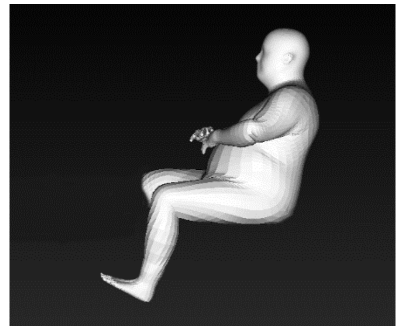
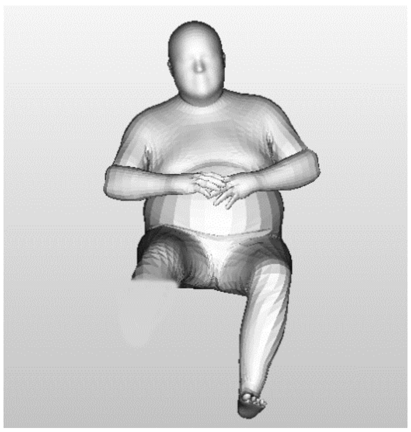
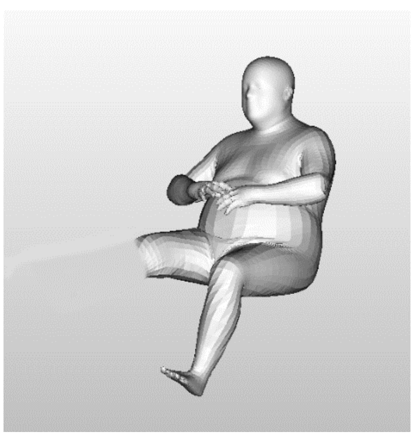
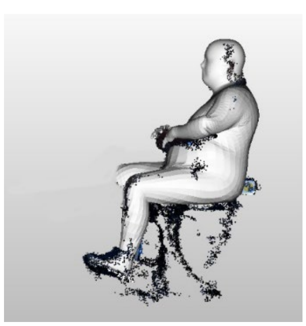


Appendix F: Avatars from Field Measurements

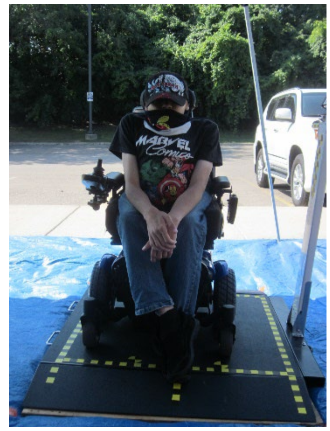
FWM01

FWM02

	
	
	N/A
	

FWM03

Dimensions outside model range	
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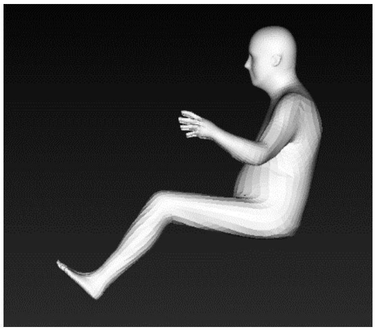
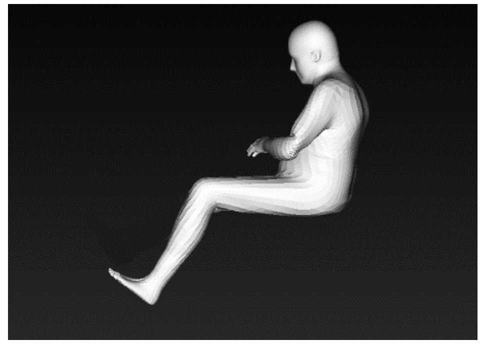
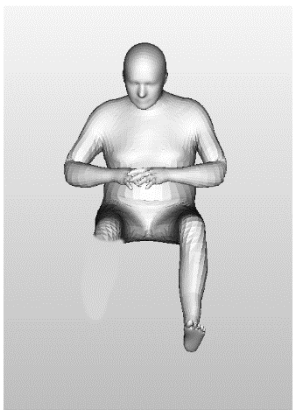
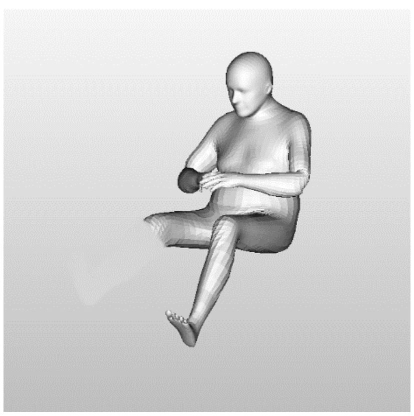
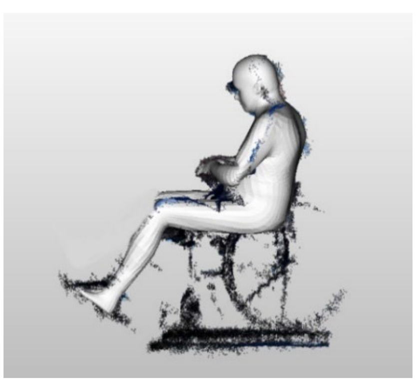
FWM04

	
	
	**N/A**
	

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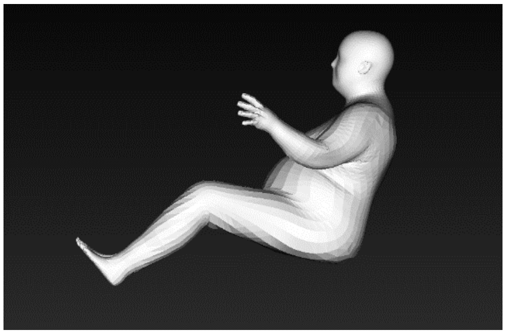	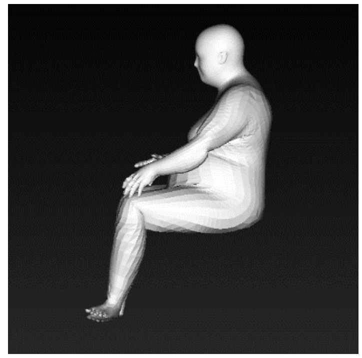
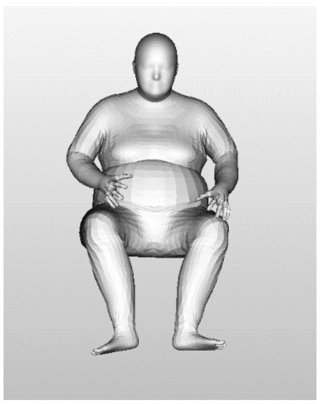	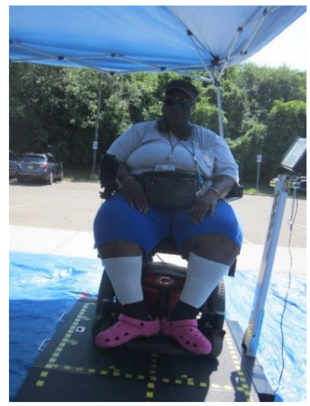
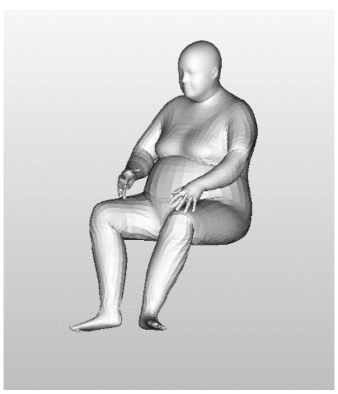	**N/A**
	

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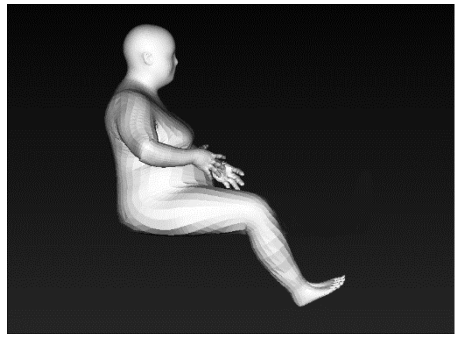
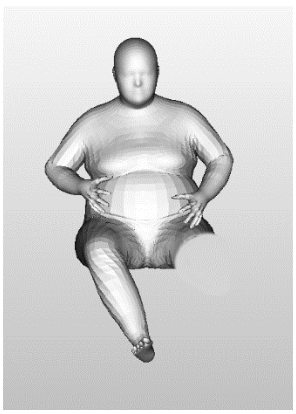
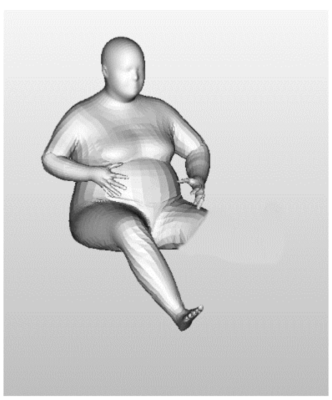
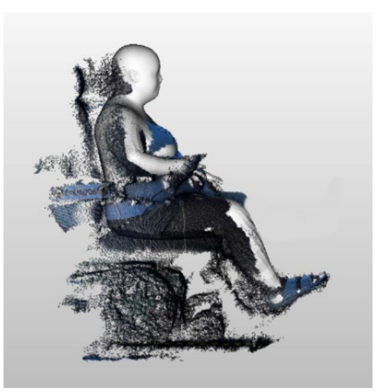
	
	
	**N/A**
	

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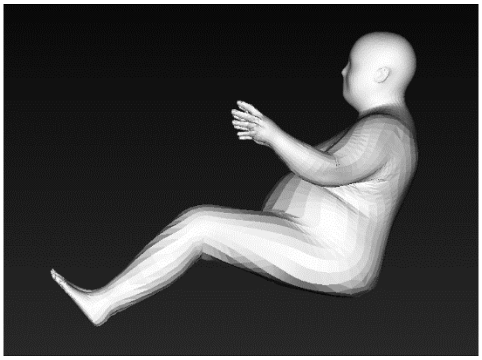
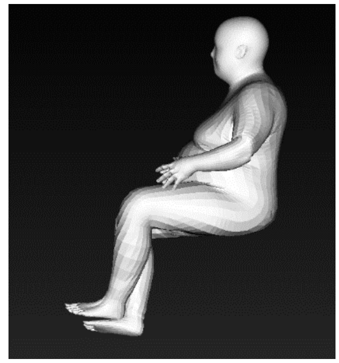
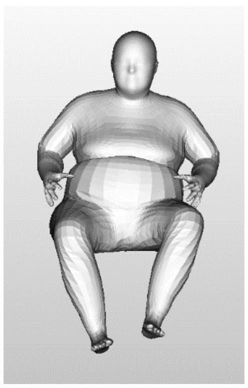
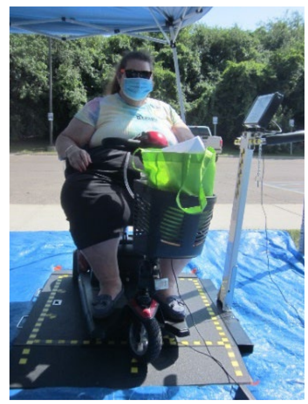
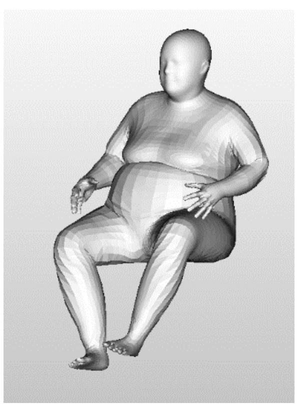
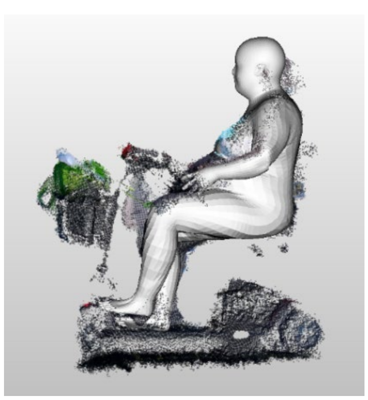
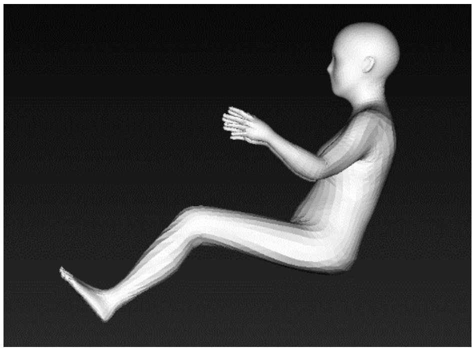
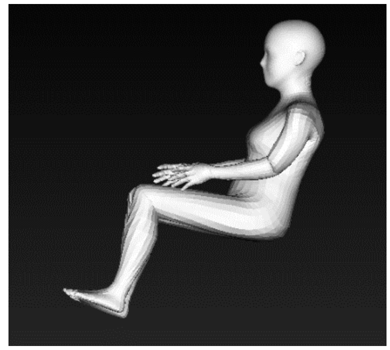
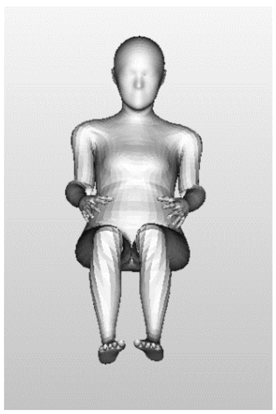
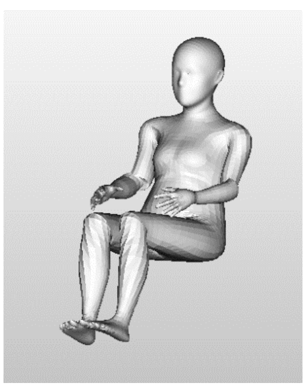
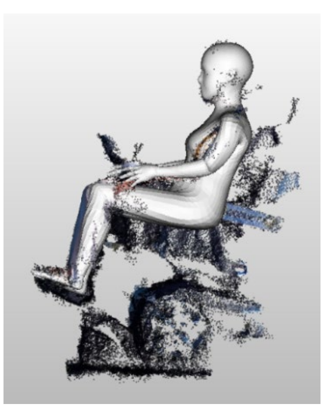
	
	
	**N/A**
	

FWM08

	
	
	**N/A**
	

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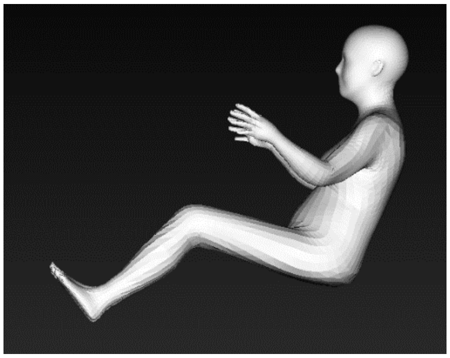
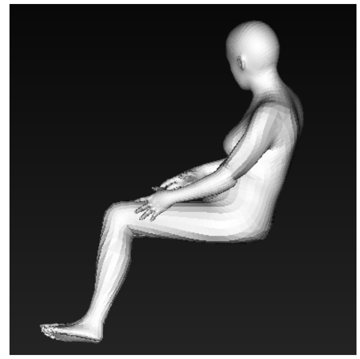
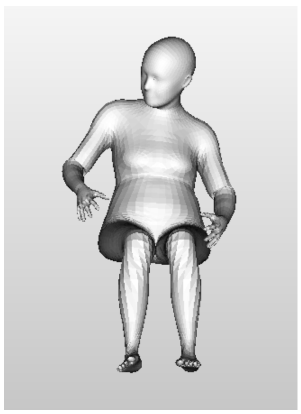
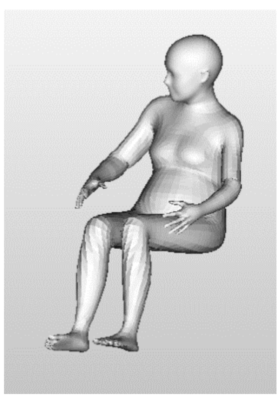
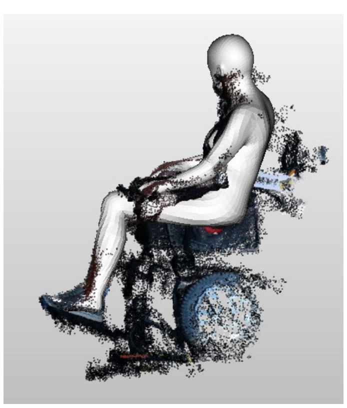
	
	
	**N/A**
	

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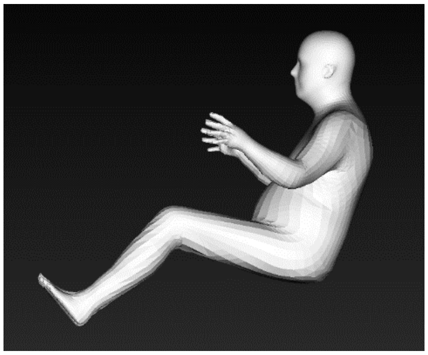	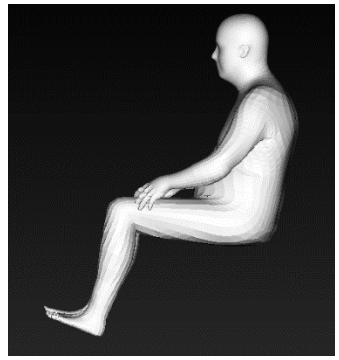
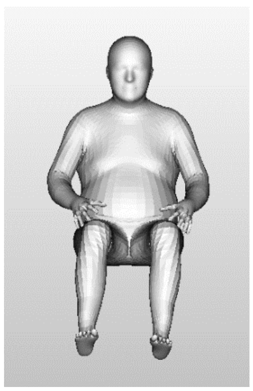	
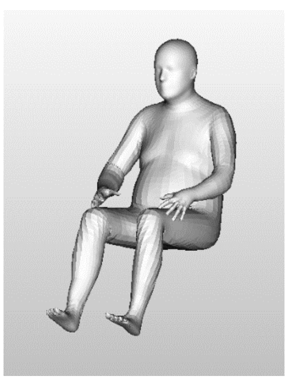	**N/A**