# REDESIGN, CLINICAL TESTING AND EVALUATION OF THE ENDEAVOR FOLDING WHEELCHAIR


by

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This thesis describes the history of the Endeavor folding wheelchair. In its current incarnation, it is an adjustable folding manual wheelchair conceptually based on a diamond shaped truss (similar to a bicycle). By disconnecting this truss at two points, the chair is able to fold flat enough to fit in the overhead bin of an airplane. It also features "airplane wheels" for maneuvering down the aisle of an airplane, taking the place of a boarding chair.

The main part of the study was a clinical trial to gain feedback on the current chair design. The first phase of the study involved users performing obstacles encountered on a daily basis using the Endeavor and their personal chair. In the second phase, users took the chair home to see how the chair would function in their everyday lives.

Because participants were comparing the Endeavor to their personal chairs, much of the feedback received was based primarily on the differences between the geometry and options of the Endeavor and their personal chairs.

Based on the clinical results, the most important features that the Endeavor is lacking are: a more forgiving seatpan, and a more effective range of adjustability. In the future, a more organized approach based on product development methods should be used to develop better design criteria.

The results of this study showed that in its current form, the Endeavor folding wheelchair may best be a special-purpose chair. By addressing all of the safety concerns, improving the

ranges of adjustability to match the dimensions of the users in our focus group, and adding usability related options the chair may be able to function as an everyday wheelchair for many users.

When our take-home participants were asked if they would like their chair better if they had "airplane wheels" five of the nine agreed. With some redesign to increase ease of use and decrease weight they could be marketed as their own product.

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# INTRODUCTION

Air travel for persons who use manual wheelchairs and cannot ambulate is full of challenges and legitimate fears. Rehabilitation grade wheelchairs are precisely fitted to a user's body size, weight, and level of function. They also interface with customized cushioning systems for the prevention of pressure sores which is unlike low-end chairs. Unsurprisingly they are expensive and difficult to replace. Damage or loss of a personal chair by an air carrier renders a wheelchair user less able to function and possibly unable to function at an acceptable level. Compounded by this, the wheelchair user quite often is in an unfamiliar location without any of the support systems necessary for providing an acceptable temporary solution. Persons who are not ambulatory also dislike using an airplane boarding chair to enplane and disembark. These chairs rarely fit the user, are in ill repair and therefore dangerous. Passengers cannot independently use these systems and often feel degraded by the experience.

After the passage of the Americans with Disabilities Act the physical environment within the United States has become more and more accessible for wheelchair users. A high level of accessibility is given within all government subsidized and large privately owned buildings including airports. This is not the case within the aircraft itself. Air carriers are protected from the financial burden of providing the same level of accessibility seen throughout United States [1]. Ironically these protections have made it impossible to ride in an airplane while sitting in your personal wheelchair but possible to do so on a public bus. Law and public policy are outside any one person's ability to change. Instead of trying to fix the system, it may be more productive to adapt to a less than ideal environment. This is the impetus behind the Endeavor folding wheelchair. The concept is:

- an everyday wheelchair with adjustable seating capable of providing a rehabilitation quality fit,
- able to fold small enough to fit within an overhead bin of an aircraft,
- which includes a second set of small wheels which; when deployed and large push wheels removed makes the chair narrow enough to function as an aisle chair.

Many factors are leading to greater usage of air travel by persons with mobility impairments. Persons with disabilities are participating in society at a greater level than ever before due to the societal changes brought about by the disability rights movement, increased societal expectations and acceptance for persons with disabilities. Rapidly aging mean populations, high gasoline prices, are also contributing. One very interesting emerging demographic is the aging businessman. In many career fields travel, specifically air travel is a necessity. As persons age, many develop mobility related disabilities. With the possible bankruptcy of the Social Security system looming as well as dissolving pension plans, many of these persons will need to continue working to maintain medical insurance and financial stability. This could lead to a boom in the number of wheelchair users traveling by air.

For brevity and clarity, some background and discussion information is located in the appendices. If you would like to find out more about literature and documentation pertaining to airline boarding procedures and chairs please see appendix B (page 109). Information on developments in boarding chairs, folding wheelchairs and wheelchair adjustability is located in appendix C (page 120). For a more detailed description of the design evolution please see appendix D (page 138). To view suggested design modifications visit appendix E (page 145).

# 1.0 BACKGROUND

This folding wheelchair has been under development for more than eight years. It has evolved physically and in scope since its first conception in January of 2000 until completion of clinical testing in September of 2008. The first time the concept of a forward folding wheelchair was defined was in the 1998 book entitled Wheelchair Selection and Configuration [2]. For more information on the early evolution of the current chair please refer to appendix D (138). At first, the chair was as much designed for suspension as it was for folding. Minimizing space requirements, increasing adjustability and airplane access has eventually become it's focus.

Both phase I and phase II Small Business Initiative Research (SBIR) grants from the National Institute on Disability and Rehabilitation Research (NIDRR) have been used to further develop this chair. These grants are used to help bring products developed in the university setting (University of Pittsburgh) to market through collaboration with small businesses (Three Rivers Holding Company). The phase I period started in 2002. During this time, the adjustable steel prototype was developed and tested. The phase II period started in 2003. Originally, the plan was to have aluminum prototypes based on the adjustable steel prototype made by an outside machine shop. These prototypes would then be the subject of focus groups and be ANSI RESNA tested. The results from the testing and focus groups would be used to slightly modify the chair. This modified chair would be the subject of a round of clinical testing. Contracted prototype was delivered in December 2004. Very early in the durability testing the chair failed.

Three Rivers Holding Company decided to contract Human Engineering Research Laboratories to further develop and produce production grade prototypes for clinical testing. It took until December of 2006 to develop a chair which would pass standards. By the time it was done, it was nearly completely redesigned. Parts production, finishing and assembling the chairs as well as building of simulations for clinical testing took up all of 2007. Clinical testing started early 2008 and was completed in September of that year.

## 1.1 DEFINING A FORWARD FOLDING WHEELCHAIR

One paragraph in Dr. Cooper's book on wheelchair selection is devoted to forward folding wheelchairs. He describes a general "forward folding wheelchair" like this: “The design of a forward folding wheelchair involves hinging the front end of the wheelchair and the backrest. The backrest folds onto the seat and the front end of folds under the seat. Forward folding wheelchairs can be made very compact if the rear wheels are quick release. However, front folding wheelchairs require more operations and latches to fold them” [2]. This section will attempt to define the common characteristics of the Endeavor forward folding wheelchair lineage. For more historical perspective, information on early models is available in “Appendix D” (page 138).

The folding wheelchair studied in this document is basically a diamond shaped truss with four main links (A, B., C., and D.) and four nodes (labeled 1, 2, 3, 4) (Figure 1). These four links connect in alphabetical order with link D connecting to link A. to increase the stiffness in earlier versions and to make the system a truss in later adjustable versions a fifth link (link E.) runs between node 2 and 4.

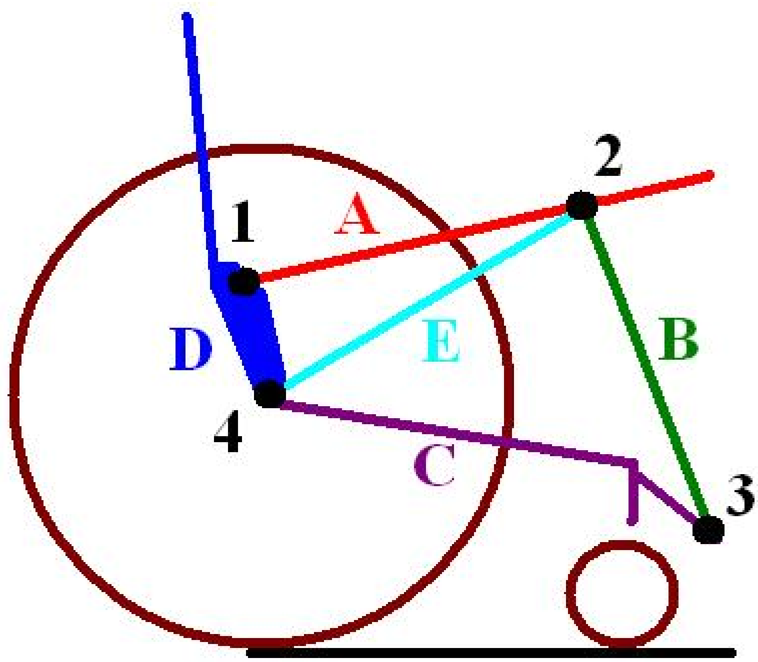



**Figure 1.** Diagram of a forward folding wheelchair

***This is a further defined list of the characteristics of each link.***

Link A. originates at node 1 and terminates at node 2. This link is the seat pan. After the first conceptual model, handles protruded past node two in line with the seat pan tubes. This link contains the attachment points of both link E. and link B. at the slightly imaginary node 2. On no prototype do link A., E., and B. actually cross. Even on later adjustable versions where these are pivot points, these pivots are not concentric.

Link B. originates at node 2 at the front of the seat pan and terminates at node 3 at the front of the bottom frame. In the final version, the foot rest is attached to this link. Folding is accomplished by disconnecting Link B. at node 2 in all chairs.

Link C. originates at node 3 and terminates at node 4 near the insertion point of the rear wheel. This is the main lower frame. In all cases, the caster housings have been rigidly mounted to this link and an "axle" tube has connected both side tubes of the frame at node 4.

Link D. originates at node four on the axle tube and terminates at node 1 at the back of the seat pan. In every version of the folding wheelchair, the backrest has been attached to this link. On the adjustable versions, the seat dump, backrest angle and the fore/aft axle adjustment occurred on this link.

Link E. originates at node 2 at the front of the seatpan and terminates at node 4 in the middle of the axle tube. The link disconnects for folding either at node 2 (in all nonadjustable chairs) or halfway through this link (in all adjustable chairs to date).

## 1.2 THREE RIVERS CHAIR- THE ENDEAVOR.

After developing the adjustable cromoly steel prototype, the plans for the chair were given to Three Rivers Holding Company (Figure 2). They contracted another company to build aluminum prototype chairs using the same design. It is important to note that this new chair used the suspension caster forks. It also had folding aluminum side guards. The springs were not properly installed in the locking mechanism for the airplane wheels and of the airplane wheels were too long for independent deployment.

**Figure 2.** Three Rivers *Endeavor*

### 1.2.1 ANSI-RESNA Testing of the Endeavor wheelchair

The first task was to test the static stability. These are a standardized set of informative tests which define tipping angles. Next, came durability testing. The first durability test required by the standards is the double drum. This apparatus consists of two 30cm diameter cylinders positioned horizontally and driven by an electric motor. The wheelchair is loaded with a 100kg test dummy and secured to the double drum by a system of straps and a mechanical linkage. Metal slats 12mm high are attached to both cylinders such that they provide cyclic harmonic impact loading for fatigue testing of the wheelchair frame. The test is made to simulate three to five years of use (200,000 cycles)[3]. Relatively early in the double drum testing of the chair failed (around 50,000 cycles). The frame failed at the weld attaching the caster housing to the frame (Figure 3). By looking at the visible microstructure it was concluded that a small crack started near the top of the weld and propagated through the cyclic loading until it nearly encircled the entire frame tube and then sheared off (Figure 3). This failure was blamed on the weakening of the material due to the welding process and/or inferior welds aggravated by multiple tube wall thicknesses at the heat affected zone[4].

**Figure 3.** Endeavor frame failure

### 1.2.2 Focus group results

A second copy was the subject of two focus groups one on March 12 and the second on March 14, 2005. In the focus groups many issues relating to design were brought up. Here's a list of some of the more important ones. It should be noted that these are picked with the benefit of hindsight. Because people tend to compare the chair to what they personally use this list may be more of be a general comparison of the differences between their personal chair and the Endeavor.

- The folding process is too complicated. It is much more complicated than the traditional cross brace folding chair.
- Folding requires two hands.
- The pinch disconnect is very difficult to operate especially with limited hand function.
- The middle tube disconnect is difficult to operate without a clear line of sight and noncontrasting colors.
- Putting the airplane wheels in the anti-tipper position requires too many hands.
- The front wheels are way too small for rough terrain. (Oblique angle caster fork)
- The caster barrels are too far apart (the front of the chair was very wide).
- The footrest is too high off the ground and not adjustable for people with other size leg lengths.
- The handles may get in the way during transfers but do serve to keep the legs from splaying apart.
- There's no way of changing the seat pan depth.
- The folding aluminum splash guards were generally well-liked

These options would be helpful:

- armrests
- camber
- folding backrest for car transport
- tie down points for public transit
- a strap to keep the chair together when folded
- a bar across the back to help lift the chair

- the ability to accommodate different seat depths

## 1.3 POST ENDEAVOR DESIGN AND TESTING

### 1.3.1 First Moc up Design

Starting in July of 2005 (prior even to the lead student's enrollment at the University of Pittsburgh) redesign of the Endeavor folding wheelchair started in earnest. The soon-to-be lead student was in charge of translating the selected design changes into a computer model of Cory Blauch's adjustable prototype[5]. As a way to cut down on parts to manufacture, many of the parts from the original chair were used in the first redesign.

The original design criteria were to further develop the aluminum framed Endeavor wheelchair from Three Rivers Holding Company to:

- optimize the folded geometry,
- shorten the wheelbase,
- incorporate footrest and axle position adjustability and
- pass the ANSI RESNA durability testing.

At first it was thought that all this could be accomplished by:

- redesigning the bottom frame,
- designing a new footrest assembly,
- changing the length of the link B. tubes
- modifying the hole in the seat pan to allow the middle bar to fold tighter to the frame.

It was decided that the best method of creating an adjustable footrest was to clamp the footrest onto the front folding tubes supporting the front of the seat pan (link B.). The second step was to incorporate the new design ideas into the frame using a computer aided solid modeling program (Figure 4). All of the initial computer design took place over a weeklong period in July 2005.

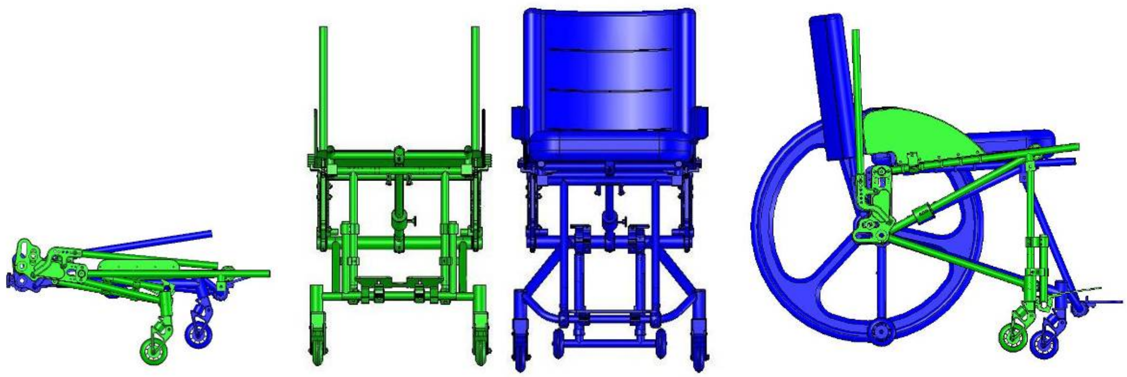


**Figure 4.** Comparison of Mock up chair (green) and Three Rivers Endeavor chair (blue)

### 1.3.2 Moc-up manufacture/evaluation

The next task was to make a physical prototype of the computer model on a brazed steel frame. This process illuminated a few geometric and mechanical problems. On the first frame, there was not enough clearance for the back end of the quick release assembly to pivot past the frame. This was due to a mistake in measuring the length of the axle tube. Next the angle adjustment clamps for the footrest could not maintain enough pressure to resist a tortional moment equivalent to that of a standing pivot transfer. This problem was remedied after a redesign of the geometry to mimic similar types of clamps from other assemblies. Finally, the first generation clamps which held the footrests to the frame were difficult to machine due to the lack of good reference angles to place the secondary holes. In the redesign, the clamps changed from pinch clamps to split clamps (Figure 5).

**Figure 5.** mock up version

After the mock up chair was finished, a wheelchair user with tetrapelegia evaluated it. He suggested that the wheelbase was still too long, specifically that the push wheel axle was positioned too far backwards. His second complaint was that there was not enough space for his feet between the footrest tubes.

### 1.3.3 Final redesign

Much of the redesign and subsequent manufacture can be credited to long hours by Jeremy Puhlman and Mark McCartney. Because of the lead student's limited design experience his responsibilities were relegated to incorporating the design changes carried out into the computer model. He did his best to provide help when advice on complicated geometry problems that could be easily solved using computer aided drafting. He also observed some of the manufacture, drew up part drawings and imported geometry into computer aided manufacturing programs.

To give the proper amount of forward adjustment, the axle plates were redesigned yet again. To address the problem of the cramped footrest, the only plausible design solution was to angle the side tubes of the main frame outwards from the axle tube to give enough space for the caster to spin freely when enlarging the footrest pad. This redesign required the middle tube of the main frame (link 3) to be moved backwards in respect to the casters. Because this is one of the pivot points of the folding frame the seat pan needed to be redesigned also (Figure 6). To avoid the failure at the caster weld experienced when testing the Three Rivers manufactured chair and allow vertical housing adjustment, it was decided that our redesign would incorporate a milled caster housing clamp (Figure 7).

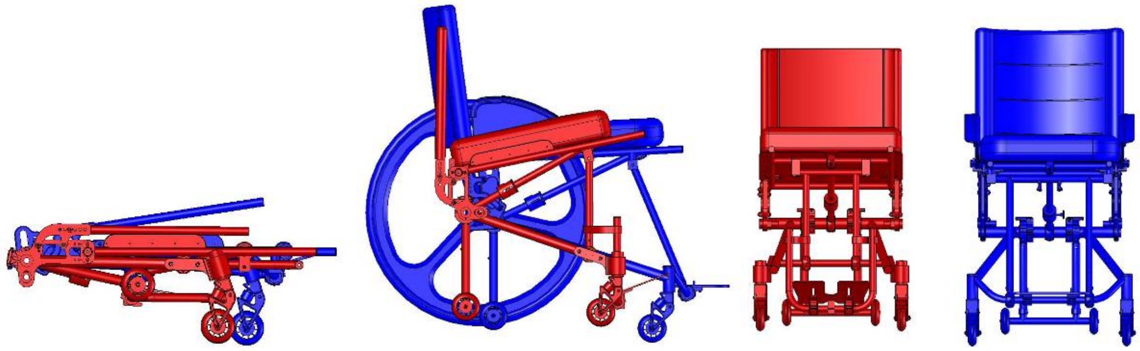


**Figure 6.** Comparison between Endeavor (blue) and final upgrade geometry (red)

**Figure 7.** Milled caster housing clamp

### 1.3.4 Redesign manufacture

After these design modifications, part production started. There were many parts that needed to be made by several different processes. For ease of manufacturing a production run of 15 wheelchairs many duplicate parts were made prior to completion of the testing phase of the second third-generation prototype.

Manufacturing a welded aluminum frame requires greater skill than when making a frame from steel. The materials are also more expensive. A professional welder was contracted to assemble the frames which were precut in house.

During the welding process an interesting phenomenon was witnessed. When completing the second weld of the seat frame middle tube, the air inside of the middle tube heated and expanded causing the liquefied metal to blow out, ruining the weld. To avoid this problem, a very small hole was drilled in the middle of the tube allowing the expanding air to escape. Both seat and main frames for all wheelchairs were made at this time.

### 1.3.5 Redesign ANSI-RESNA durability testing

After the parts for one chair were finished along with a frame, the chair was placed on the double drum (Figure 8). It failed after only 400 cycles because the steel tube inside of the axle tube was missing. After installing the steel axle tube, the chair was restarted on the double drum.

**Figure 8.** Double drum

At 49,000 cycles the chair failed again. This time the middle tube of the seat frame deformed (node 2) due to loading by the middle tube (Link E.) (Figure 9). The geometry of the five link truss design is such that as backward force is put on the seat back (rearwards rotation of link D. around node 4 in respect to link C.) it drives the middle tube in to the seat frame (Figure 10). The lead student had unwittingly played a major part in creating a seat frame breaking machine. This problem probably could have been anticipated by some simple computer simulations on the part prior to manufacture. This problem took much time and redesign work to fix. The eventual arrival at a working solution can be credited to much collaborative brainstorming, trial and error by many persons.

*First attempt* It was decided that the solution to this problem was to share the backwards loading up by locking the seat back at 90° using an L-shaped steel bracket which looped under the side tube of the main frame (Figure 11). The axle plate also needed to be redesigned to take into account the rigidity of the locked design and provide place for mounting holes for the L-shaped bracket.

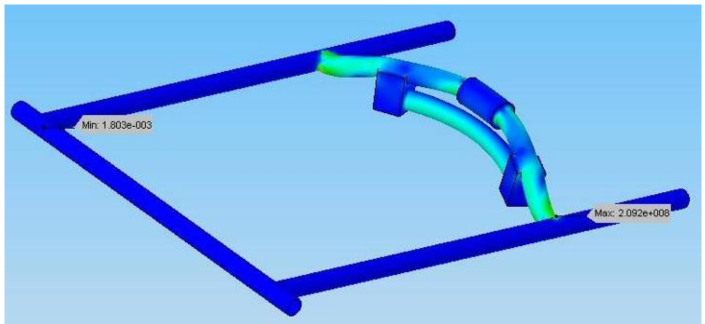



**Figure 9.** Seat frame failure

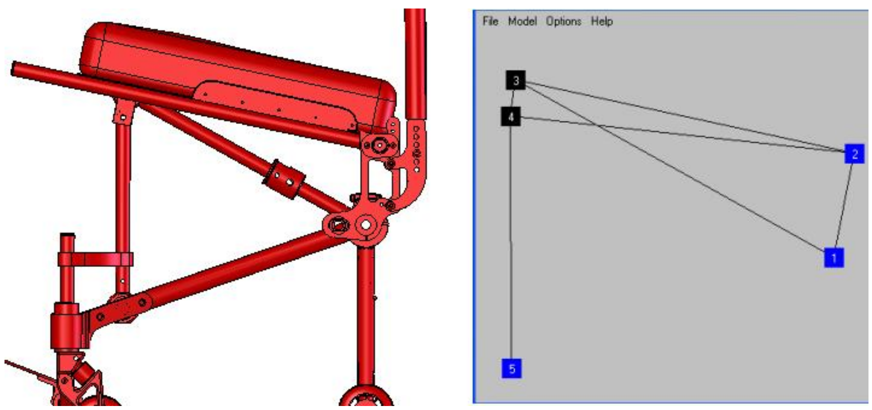



**Figure 10.** Truss

**Figure 11.** L-shaped steel bracket

This chair was tested and failed at 70,000 cycles in two places. First, the weld on the mainframe connecting the side tube to the axle tube failed. The second failure was a similar seat frame failure as experienced earlier. From this evidence it was discerned that first, the extra torque applied by the L-shaped bracket was so great that it broke the weld at the mainframe. After this, being unprotected from the force by the L-shaped bracket the seat frame failed exactly as before.

*Second attempt* There were multiple ideas of how to solve the rotating backrest problem. The first was to reinforce the seat frame with tubular gussets, widen the pivot between the middle tube and seat tube and put a suspension element in the middle tube to distribute the impulse of the impact over greater time duration. The second idea was to pop rivet a key shaped stop inside of the axle tube with an elastomer stop to help distribute the impulse. After a simple deformable solids problem, it was shown that the amount of pop rivets needed to secure the key inside of the tube made the second plan unfeasible.

After applying the first technique to the chair (Figure 12), it ran on the double drum yet again. It ran only 10,000 cycles and the air spring lost pressure and ceased to function. After replacing the spring, the chair made it only 16,000 cycles. The welds connecting the axel and side tubes failed completely (Figure 13). This was caused by the method of clamping the chair to the double drum. It did not allow the frame to articulate realistically causing a torque not seen in actual use. After redesigning the clamping it ran for 150,000 cycles before failure. This last failure occurred at the middle tube of the mainframe on the outside of where the tubes supporting the front of the seat pan pivot around this tube (node 3), it sheared (Figure 14). This type of failure is a direct result of too little area moment of inertia. This failure could not be remedied without rebuilding the main frame of the chair and inserting and larger wall thickness and maybe greater diameter tube. This was deemed economically unfeasible because it meant rebuilding all of the prefabricated aluminum frames. A decision was made to make the mainframe out of chromoly steel for strength, financial and temporal reasons.

**Figure 12.** Air spring and seat gussets

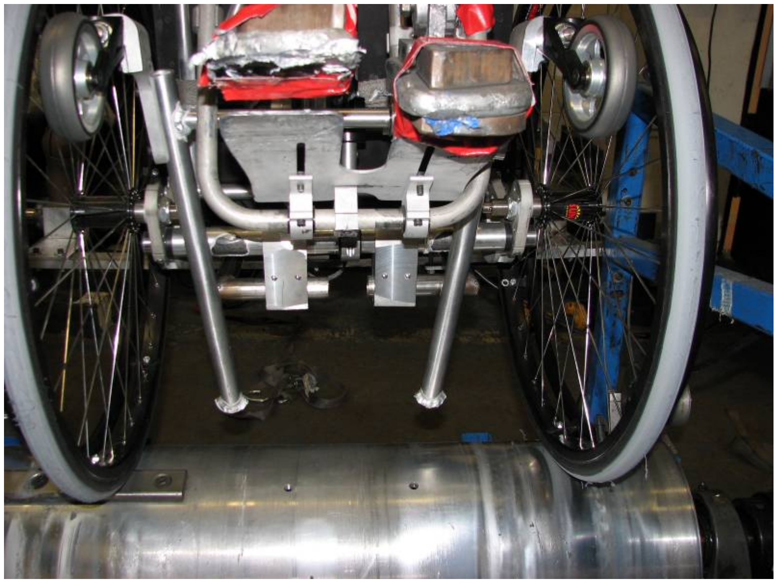


**Figure 13.** Failure as a result of improper clamping

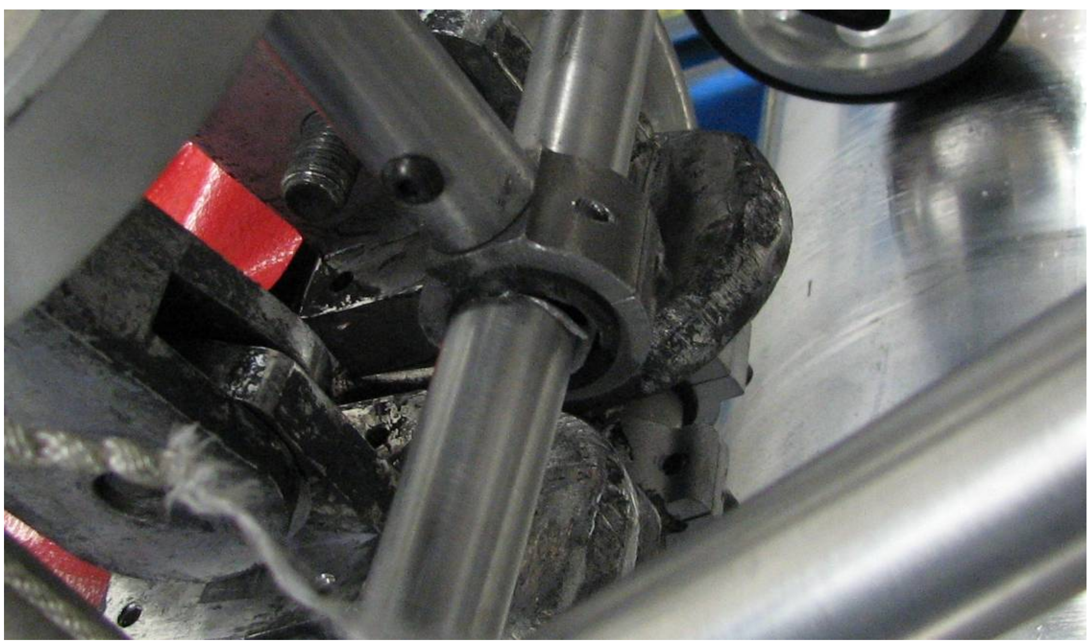


**Figure 14.** Sheared middle tube of frame

Finally the chair completed all 200,000 cycles of the double drum testing without failure.

Next came the curb drop test (Figure 15). In this test, a 100kg dummy is strapped into the wheelchair. These are then lifted 50mm and dropped 6,666 times[3]. The chair passed the first time without incident.

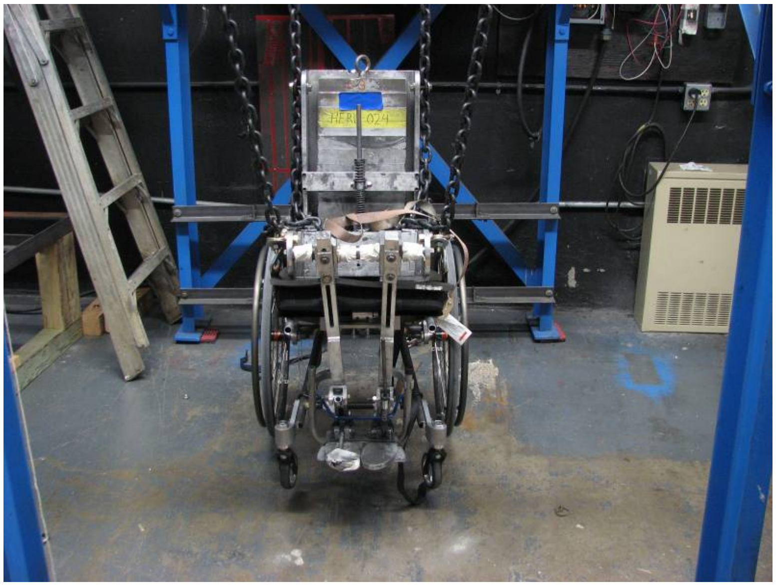


**Figure 15.** Curb drop

# 2.0 CLINICAL TESTING

## 2.1 METHODS

### 2.1.1 Recruitment

Early in February of 2008 recruitment for the study “development of a collapsible folding manual wheelchair phase II began. IRB approved mailings were sent out to persons who took part in the focus group. Other participants were recruited by word-of-mouth or their inclusion in other studies such as the wheelchair users database. In addition, persons with disability related e-mail list serves and persons with contacts in the community were asked to distribute the flyer to persons who may be eligible and interested in participating.

### 2.1.2 Demographics

There were a total of 14 participants. Two were female and the rest were male. Two participants were African-American, another was American Indian and the rest were Caucasian. Three of the participants were veterans of the armed services. The participants’ mean age was 45 years with a standard deviation of 11 years. On average they were injured for 14 years with a standard deviation of 4 1/2 years. All of the participants had spinal cord injuries. Two participants functioned at a C7 Asia level. One participant had an incomplete C6/ T11 injury the rest of the participants functioned with some level of parapeligia.

### 2.1.3 Procedure

#### 2.1.3.1 Informed consent and preliminary paperwork

First, an investigator consented the participant. During this time, the risks, benefits as well as an overview of the procedure including the take-home phase were briefly explained. The participant was also informed that they may ask questions anytime and may withdraw from the study or omit any part of the protocol for any reason. It was also stated that the investigators may withdraw the participant if they felt continuation would be unsafe. Participants were also informed that they did not need to decide if they were going to take part in the in-home phase until after completing the in-lab testing.

After filling out the main consent document, the investigator went over the inclusion exclusion criterion and determined the eligibility of the participant. The inclusion exclusion criterions were:

Inclusion

1) Use a manual wheelchair as a primary means of mobility.
2) Male and females over the age of 18.
3) The ability to adequately fit in a wheelchair with a 16" seat width.
4) A minimum of 6 months experience using a manual wheelchair as primary means of mobility.
5) Able to transfer independently.
6) Drives own vehicle from vehicle seat.

Exclusion

1) Active pressure sores as reported by participant.

2) History of traumatic upper extremity injury that would prevent you from folding, lifting and storing a manual wheelchair.

Next, they filled out the picture consent and payment sheet.

#### 2.1.3.2 Intake questionnaire, folding chair introduction and wheelchair fitting

When they had finished filling out the study forms, they were given the "intake questionnaire" (appendix A.2 page 88). This questionnaire included demographic information as well as questions pertaining to vehicle travel and air travel. In the final section information about their wheelchairs and type of motor vehicle was collected. This questionnaire was quite long so during this time, measurements of the participant personal chair were taken to speed the fitting process.

A general introduction to the folding wheelchair was done either before or after the intake questionnaire. During the introduction, the investigator instructed the participant on the folding and unfolding procedure for the Endeavor wheelchair as well as explained the use of the airplane wheels.

During this time, the investigators (a certified ATS and a certified ATP occupational therapist) fitted wheelchairs to the participants. Possible modifications included:

- moving the axle position forward or backward within the standard adjustment slot,
- changing the axle mounting position to custom location in the middle of the axle tube
- reversing the axle receivers to widen the space between the wheels,

- raising or lowering the rear of the seat using standard adjustment locations,
- lowering the front of the seat by cutting the front tubes,
- changing the backrest angle,
- raising, lowering or even cutting the backrest tubes,
- moving the seat pan backwards,
- raising or lowering the footrests,
- changing the foot plate angle,
- sliding in or out the foot plate,
- adding a seat belt,
- adding wheel locks,
- and finally, removing the handles from the front of the seat.

Participants were discouraged from removing the seat handles until after completing the indoor course because the handles were able to provide a means of keeping the participant's knees together and it was irreversible.

Depending on how extensive modifications were, the fitting might take considerable time (sometimes approximately 2 hours). If this was the case, the participant may be instructed to complete the sections of the protocol that could be done using their personal chair while modifications were being finalized.

#### 2.1.3.3 The activities for daily living course

The order in which the participants completed the different sections of the activities of daily living course was determined by convenience instead of a randomization. The investigators consulted with the participant and attempted to optimize the order to minimize the amount of time and the number of transfers. All participants were spotted through each of the activities of daily living course sections.

The first obstacle course was designed to test the stability and maneuverability of the chairs (Figure 16).

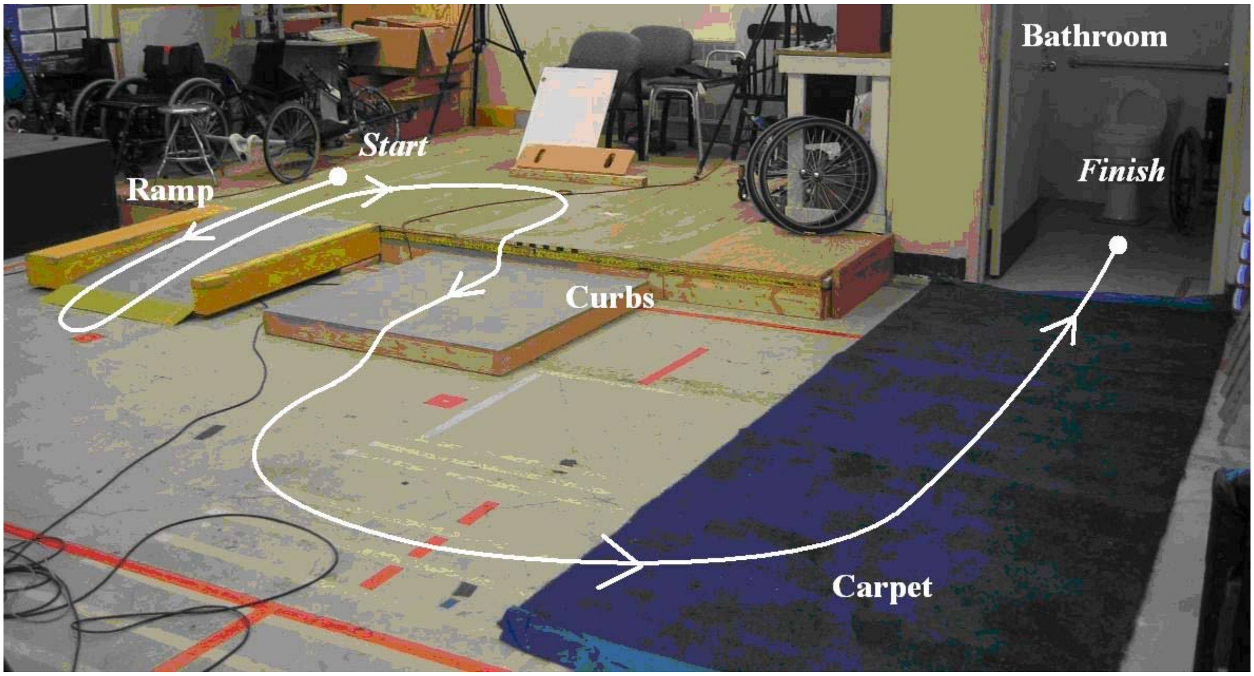



**Figure 16.** ADL Course

A participant would start at the top of platform, descend the curb cut, turnaround and go back up the curb cut, descend two shallow curbs, go across carpeting into the bathroom where they would park in front of the sink (as if they were washed their hands) and lastly park next to the toilet (as if they were going to transfer onto it). If a participant felt uncomfortable descending curbs, they were allowed omit it. Because participants were using unfamiliar chairs which in some cases could not match their personal chair set up, participants were encouraged to use the anti-tippers while completing the course.

The participant would go through the course twice to practice and on the third trial, they would be videotaped. After the recorded trial, they would check off the difficulty of completing each obstacle on the "Activities Daily Living Course Questionnaire" (appendix A.3 page 98).

The second evaluation setup was the participants own personal vehicle. The participant was instructed to transfer from the chair into their vehicle, load their chair into the vehicle, unload the chair and transfer back into the chair. Because this transfer and loading process is very familiar and possibly fatiguing, participants were only required to do this once. They were videotaped from start to finish and afterwards they rated the difficulty on the "Activities of Daily Living Course Questionnaire".

The final procedure was an airplane boarding simulation (Figure 17). This part of the protocol was only completed using the Endeavor folding wheelchair. An airline cabin was constructed using two rows of authentic airline seats. The first row was bulkhead style seats on which the armrests do not fold out of the way to ease transfers. This is because the lap tray is stored in the armrests. The second row was a standard coach airline seats with a flip aisle armrest. The seats were designed for the right hand side of the cabin. A short railing was constructed alongside the airline seats to define the edge of the aisle, simulate the armrests on the other side of the aisle and the bumper which protects the armrests from collisions with drink carts.

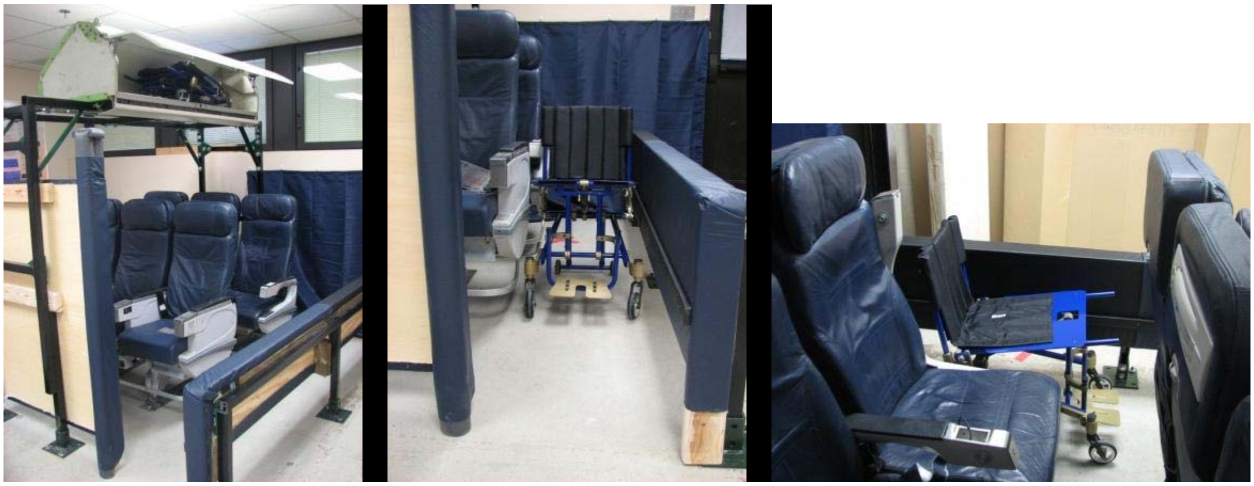


**Figure 17.** Airplane Simulation

Prior to attempting the boarding procedure, the participant was reinstructed on the use of airplane wheels. They were also informed that the armrest on the second row seats flipped backwards to help ease transfers. They were also told to think about which direction they would like to go down the aisle.

First, the participant deployed the airplane wheels and locked them into place. If they could not reach the release levers themselves, the investigators would help. The participant was given the option of removing the wheels themselves while sitting in the chair or with the help of spotters. To remove the wheels, the participant would position themselves alongside the front wall of the airplane simulation. By pulling on a bar on that wall, they could balance their chair on one large push wheel and the front caster on the same side allowing them to remove the push wheel on the opposite side. After one wheel was removed, that side was supported by the airplane wheels. By holding onto the wall, the participant was able to maneuver the chair so that the opposite side was next to the wall and remove the other push wheel. Then by pulling on the wall, armrests and small wall they maneuvered themselves down the aisle (forwards or backwards) and transferred into the airline seat. Because the chair has no breaks when rear wheels are removed, one of the investigators held the chair in position when they were transferring. Next, they transferred back into the folding wheelchair, pulled themselves back down the aisle and finally replaced the large push wheels.

Participants were only required to do it once. After completing the simulation, they filled out the final section of the "Activities Daily Living Course Questionnaire" and the "Overall Performance Ratings" questionnaire (appendices A.3 and A.4 page 101).

#### 2.1.3.4 Take home phase

Next, participants were asked if they wished to take part in the take-home phase. They were reminded of what their responsibilities consisted of. If they decided to take part in the in-home phase, it consisted of two two-week sessions. In one of the sessions, they would use the folding wheelchair as their primary wheelchair. During the other session they were advised to use their personal chair primarily. The order in which they completed the sessions was randomized. Throughout both sessions, they were instructed to keep a daily log (appendix A.5). Data loggers were installed on both wheelchairs to record the amount of usage. If the participants were to encounter any circumstance where they needed to use one or the other chair they were told it was fine but they should record the reason in their daily log. At the end of the two two-week sessions the participants filled out a survey comparing their primary chair to the Endeavor wheelchair (appendix A.6). The daily logs, comparison questionnaire and the data loggers were returned by mail. At the end of the take-home period, participants were asked if they wished to keep the chair or return it. If they decided to return the chair, they would receive $200 for their effort. If they decided to keep the chair, the investigators contacted them at 4 and 8 weeks to track the continued usage of the chair (appendix A.7 page 107).

### 2.1.4 Statistical analysis for hypotheses

All statistical analysis was completed using SPSS v14.0 software (SPSS, Inc.). Unless otherwise stated, an alpha level of .05 was chosen for the threshold of validity.

***Hypothesis #1***: The Endeavor will receive favorable *overall* performance ratings on each of the following dimensions: stability, ease of propulsion, maneuverability, and overall comfort of ride.

For this hypothesis binomial probability was used. These questions were located on the "Overall Performance Ratings Questionnaire" (see appendix A.4 page 101). The questionnaire had five checkboxes two which were negative (very poor and poor) one neutral (moderate) and two positive (good and a very good). These ratings were recoded into two groups: positive and not positive (negative and neutral scores combined). The probability of choosing one of the positive rating boxes will be assumed to be 0.4.

***Hypothesis #2***: The Endeavor will receive "ease of task" ratings that will be superior to the ratings that participant's give their own personal wheelchair for the car transfer.

The survey questions from which this data were collected contained five different ordinal levels: very difficult, difficult, moderate, easy and very easy. Because data were ordinal, nonparametric statistics were used.

***Hypothesis #3***: Participants will rate the Endeavor as superior to their own personal chair on dimensions related to compactness, folding, and stowage.

These data were gathered from three questions in the "Wheelchair Comparison" survey which was completed after the two-week trial period (page 106). These questions compared a participant's personal chair to the Endeavor. Each of these questions had five different checkboxes corresponding to: much worse, worse, equal, better and much better. The three questions which related to compactness, folding and stowage were: compactness informed position, ease of loading and ease of unloading. Because of the ordinal nature of the data, a Wilcoxon signed ranks test was also used for this hypothesis.

***Hypothesis #4***: Participants will rate the Endeavor as superior to their own personal chair on dimensions related to accessibility and maneuverability.

This data were also gathered from the "Wheelchair Comparison" survey. The three dimensions related to accessibility and maneuverability were: access to narrow doorways and confined spaces, maneuverability in confined spaces and overall maneuverability. The Wilcoxon Signed Ranks Test was used to evaluate this hypothesis.

***Hypothesis #5***: There will be *no* significant quantitative differences ($p > .05$) when comparing use of each chair during the two-week trial periods: Participants' use of the Endeavor (e.g., # of hours per day, miles per day) and their use of their own personal chair will not be significantly different.

Depending on the normalcy of the data, different analyses could be considered valid for this hypothesis. If the data was normal, a two-tailed t-test would have been used. Because the data were skewed a Wilcoxon Signed Ranks Test was used.

***Hypothesis #6***: The percent of time in the Endeavor (as a percent of total wheelchair usage) will exceed the percent of time in participants' own personal wheelchair by the end of the 8-week phone follow-up period.

Self-reported estimated percentages of time should be considered ordinal. A Wilcoxon Signed Ranks Test would have been appropriate for this analysis as well. Because the number of participants who completed this phase was so small (n=4), results were discussed but no true statistical analysis was done.

## 2.2 CLINICAL TRIAL RESULTS

### 2.2.1 Intake questionnaire

The intake questionnaire had questions on a wide variety of participants (appendix A.2 page 88). The first section contained questions about demographic information, the second on motor vehicle transportation, the third air transportation and lastly questions about their personal wheelchairs.

Table 1 is a summary of data from the first question on the Travel -- Airfare section of the intake questionnaire. The table contains average ratings given by persons who have flown post injury and those who have not. The scale was from one to 10 with one corresponding to little effect and 10 to large effect. The four highest rated factors for those who have flown and of the three highest factors for those who have not flown are highlighted. Three participants had never flown post injury while the other 11 had.

The last section of the intake questionnaire contains measurements of participants' personal chairs (Table 2). Front seat to floor height and rear seat to floor height are not present in the questionnaire but were added by the investigators and noted on this page. This measurement was more valid than the seatpan angles. Backrest angle was measured at the backrest posts for chairs with adjustable tension back rests and in the middle of the hard back rests. These measurements were done using an analog inclinometer. Axle position was measured from a relaxed shoulder position. Posture variations have a large effect on these measurements. Measurements in respect to the front of the backrest cane would have been consistent.

**Table 1.** Participants average ratings for the question "How much do these factors negatively affect your desire to fly?"

| | who have flown post injury | who have not |
|---|---|---|
| going through security | 2.00 | 5.00 |
| thick carpeting in airports | 3.45 | 5.33 |
| Airline personnel attitude | 3.82 | 5.33 |
| boarding staff | 3.82 | 3.33 |
| boarding process | 4.00 | 6.00 |
| aisle chairs | 5.27 | 5.00 |
| lack of help | 4.09 | 6.67 |
| lost luggage | 4.00 | 7.33 |
| carrying luggage | 4.09 | 7.00 |
| lost wheelchair | 5.00 | 8.33 |
| damaged wheelchair | 5.36 | 8.33 |
| missing connection | 3.91 | 7.33 |
| pressure sores | 2.18 | 6.67 |
| bowel or bladder | 5.55 | 8.00 |
| transportation to and from airport | 1.55 | 5.00 |
| plane crash | 1.91 | 6.00 |

**Table 2.** Ranges of personal chair dimensions. (Length in inches)

| | Minimum | Maximum | Mean | Std. Deviation |
|---|---|---|---|---|
| seat depth | 14 | 18 | 16.3 | 1.2 |
| backrest height | 12 | 20 | 14.4 | 2.0 |
| foot rest to seat distance | 13 | 18 | 15.0 | 1.4 |
| axle position | 0 | 3 | 0.7 | 1.0 |
| front seat to floor height | 17 | 19 | 18.4 | 0.6 |
| rear seat to floor height | 15 | 18 | 16.1 | 1.1 |
| backrest angle | 80 | 90 | 83.0 | 3.1 |

### 2.2.2 Task ratings survey.

The "Task Ratings" questionnaire was a used to evaluate the difficulty of each obstacle using the two different chairs (see appendix A.3 page 98). Each obstacle was rated as one of five different ordinal categories: very difficult, difficult, moderate, easy and very easy. Table 3 shows the results of a Wilcoxon Signed Ranks test for the "Task Ratings" questionnaire. The numbers in the first column of the table represents the numbers of participants who rated the task easier with the Endeavor than with their personal chair. The second column shows the numbers of participants who ranked tasks easier with their personal chair. The third column shows those who ranked the chairs equally. In the last column the significance using the Wilcoxon Signed Ranks Test for each task is shown. The results for the last two obstacles are used for hypothesis 2. Two participants chose not to attempt the curbs and one participant did not fill out the survey on the car tasks which accounts for the difference in tallies.

This same format was used to collect the difficulty of the airplane boarding simulation. Because there was no second chair to compare with, no statistical analysis could be done.

**Table 3.** Number of participants who prefer the Endeavor to their personal chair for the ADL course obstacles

| | Endeavor | personal | tied | statistical significance |
|---|---|---|---|---|
| down ramp | 3 | 3 | 8 | 0.74 |
| up ramp | 2 | 7 | 5 | 0.08 |
| down curbs | 2 | 5 | 5 | 0.26 |
| carpeting | 3 | 2 | 9 | 0.78 |
| sink | 2 | 0 | 12 | 0.18 |
| toilet | 3 | 0 | 11 | 0.08 |
| Transferring into car | 4 | 2 | 8 | 0.32 |
| Stowing in car | 3 | 6 | 4 | 0.07 |

### 2.2.3 Videotape data.

The final trial for each set of obstacles was video recorded. These data were used to determine the amount of time as well as the different techniques participants used when completing courses.

Table 4 shows the differences in times (in seconds) for completing the ADL course and the time to transfer into their car and stow the chair for the Endeavor and their personal chairs. This statistical significance was determined using two different tests. For data that were considered normal, the parametric paired t-test could be used. For all data that were not normal, the Wilcoxon Signed Ranks Test was used. For the ADL course two participants decided to skip the curbs part of the course. Five participants went backwards down the curbs while the remaining six participants went forwards. Because of the difference in methods of completing the course of these participants cannot be compared easily.

The car procedure had similar problems. One participant could not complete the procedure using the Endeavor because of the weight (fully assembled). Three of the participants used vans with automatic lifts or ramps. After entering the vehicle, they transferred on to a rotating seat. None of these participants folded either chair. The row labeled "car procedure (omit van)" does not include participants who used a van. Three participants never removed the large push wheels when loading their personal chairs that needed to when loading the Endeavor. The row which is labeled "car procedure (omit "don't remove wheels")" does not include participants who used vans or participants who did not remove the large push wheels when loading their chairs. Regardless of the omissions, the differences between the car procedure times were statistically significant (p-value< 0.05).

Because it is impossible for a 16 inch wide manual wheelchair to maneuver down a 17 inch wide aisleway with its wheels on, participants did not complete the airplane boarding simulation with their personal chairs. For this reason, there's nothing to compare boarding times to. Instead, the effect of different techniques on boarding times was explored. Because of the small number of participants in each group no true statistical analysis was ran. Table 5 shows the differences between boarding and deplaning times dependent on chosen row and direction participants traveled down the aisles.

**Table 4.** Statistical significance of ADL course and car procedure times from video data (seconds).

| | Endeavor | standard deviation | minimum | personal | standard deviation | minimum | significance | |
|---|---|---|---|---|---|---|---|---|
| ADL Course time | 46.7 | 18.3 | 24.0 | 40.1 | 13.5 | 25.0 | 0.05 | Wilcoxon Signed Ranks Test |
| ADL Course time (forward down curbs) | 34.7 | 9.5 | 24.0 | 33.9 | 5.9 | 25.0 | 0.78 | paired t-test |
| ADL Course time (backwards down curbs) | 65.8 | 14.6 | 47.0 | 53.8 | 12.4 | 40.0 | 0.13 | paired t-test |
| Car procedure | 181.7 | 101.5 | 37.0 | 77.0 | 58.9 | 26.0 | 0.00 | Wilcoxon Signed Ranks Test |
| Car procedure (omit van) | 219.3 | 82.7 | 82.0 | 87.5 | 63.5 | 26.0 | 0.01 | Wilcoxon Signed Ranks Test |
| Car procedure (omit "don't remove wheels") | 260.8 | 61.9 | 188.0 | 124.3 | 56.0 | 72.0 | 0.03 | Wilcoxon Signed Ranks Test |

**Table 5.** The affects of direction and row preference on airplane boarding times**.**

<table>
<tr><th colspan="3"></th><th>average time (sec)</th><th>standard deviation</th><th>number participants</th></tr>
<tr><td rowspan="5">boarding</td><td colspan="2">all</td><td>64.0</td><td>38.0</td><td>14</td></tr>
<tr><td rowspan="2">first row</td><td>forward down aisle</td><td>62.3</td><td>57.7</td><td>4</td></tr>
<tr><td>backward down aisle</td><td></td><td></td><td>0</td></tr>
<tr><td rowspan="2">second row</td><td>forward down aisle</td><td>47.0</td><td>10.1</td><td>3</td></tr>
<tr><td>backward down aisle</td><td>72.3</td><td>34.8</td><td>7</td></tr>
<tr><td rowspan="5">deplaning</td><td colspan="2">all</td><td>51.8</td><td>24.0</td><td>13</td></tr>
<tr><td rowspan="2">first row</td><td>forward down aisle</td><td>45.0</td><td>21.2</td><td>2</td></tr>
<tr><td>backward down aisle</td><td>39.0</td><td>0.0</td><td>1</td></tr>
<tr><td rowspan="2">second row</td><td>forward down aisle</td><td>53.8</td><td>27.7</td><td>9</td></tr>
<tr><td>backward down aisle</td><td>60.0</td><td></td><td>1</td></tr>
</table>

### 2.2.4 Overall Ratings survey data.

One participant did not complete the overall ratings survey for the Endeavor (page 101. Because of this, only 13 pairs were recorded. Table 7 shows the number of positive ratings for the "overall ratings" survey and the binomial probability of having that many positive ratings. With an alpha level of 0.05 and a 0.4 probability of receiving a positive score, four dimensions are statistically significant: feel of a ride, support, ease of propelling and maneuverability with p-values of .01, .04, .00 and .01 respectively. This table was used for the first hypothesis.

The results from Table 8 through 11 show the categorized responses from the last section of the "Overall Ratings" survey. These were two essay style questions asking what participants liked best and least about the Endeavor and their personal chairs. No question was mandatory and many participants left at least one of the questions blank. Other participants wrote down multiple answers. For this reason, the numbers of responses are highly variable between questions. On Table 11 which displays what persons liked least about their personal chairs three participants actually wrote "nothing".

**Table 6. N**umber of participants who positively rated the Endeavor on the "Overall Ratings" survey.

| | positive | total | probability |
|---|---|---|---|
| comfort | 7 | 13 | 0.13 |
| feel of a ride | 10 | 13 | 0.01 |
| support | 8 | 12 | 0.04 |
| stability | 5 | 13 | 0.22 |
| ease of propelling | 11 | 13 | 0.00 |
| maneuverability | 10 | 13 | 0.01 |
| transferring | 7 | 13 | 0.13 |

**Table 7.** Number of participants who prefer the Endeavor to their personal chair on the "Overall Ratings" survey.

| | Endeavor | personal | neutral | statistical significance |
|---|---|---|---|---|
| comfort | 2 | 6 | 4 | 0.25 |
| feel of a ride | 4 | 3 | 5 | 0.49 |
| support | 4 | 4 | 3 | 0.77 |
| stability | 1 | 8 | 3 | 0.02 |
| ease of propelling | 1 | 2 | 9 | 0.41 |
| maneuverability | 1 | 3 | 8 | 0.26 |
| transferring | 1 | 5 | 6 | 0.10 |

**Table 8.** Comments on what users most liked about Endeavor chair from "Overall Ratings" survey and number of times mentioned.

| Endeavor liked best | |
|---|---|
| small folded | 4 |
| maneuverable/ good ride | 6 |
| airplane wheels | 2 |

**Table 9.** Comments on what users like least about Endeavor chair from "Overall Ratings" survey and number of times mentioned.

| Endeavor liked least | |
|---|---|
| unstable | 3 |
| sharp edges | 2 |
| fit | 2 |
| propulsion | 1 |
| folding | 2 |
| weight | 3 |
| handles interference | 2 |
| side guards | 1 |
| metal seat | 2 |
| suspension descending | 1 |
| restraint | 1 |

**Table 10.** Comments on what users most liked about their personal chair from "Overall Ratings" survey and number of times mentioned.

| personal liked best | |
|---|---|
| support/fit | 1 |
| comfort | 1 |
| stability | 3 |
| weight | 1 |
| front casters | 1 |
| suspension | 1 |

**Table 11.** Comments on what users like least about their personal chair from "Overall Ratings" survey and number of times mentioned.

| personal liked least | |
|---|---|
| width | 2 |
| weight | 3 |
| uncomfortable | 1 |
| nothing | 3 |

## 2.3 THE TAKE-HOME PHASE.

### 2.3.1 Data logger based results.

The data logger results were based on 10 participants three of which have only partial data and another participant's data was suspect. One participant experienced a massive stroke at the very end of the Endeavor phase. For two other participants, one of their two data loggers did not collect data. The one participant whose data was suspect returned one heavily used data logger on which the battery was no longer working. He stated in his daily logs that one day he took the chair on the ocean. The data which could be retrieved from the data logger were analyzed but a large chunk corresponding to the time after this event was missing. When comparing the two data loggers, there were some days where no distance was recorded for either chair even though it appears as a normal day on the daily log. It was not possible to tell if there was a failure with the data logger or the participant took liberties with the daily log.

Table 12 shows the mean times and distances for the participants over the four-week testing period. Table 13 shows the results of the statistical analysis between the two groups. Using an alpha value of .05, it shows that when comparing total time per day, total driving time per day and total distance per day for the chairs in their respective two-week periods, participants used their own chair significantly more with P- values of .03, .04 and .04 respectively. Using the same alpha value, the difference in total distance between the two two-week phases and the distance participants traveled in their personal chairs during the two two-week phases were not statistically significant.

**Table 12.** Mean times and distances for Endeavor and personal chairs during the take-home phase.

| | Mean | Std. Deviation |
|---|---|---|
| total time per day for personal chair during two-week period (minutes) | 1008 | 215 |
| total traveling time for personal chair during two-week period (minutes) | 78 | 37 |
| total distance per day for personal chair during two-week period (meters) | 1726 | 716 |
| total time per day for personal chair during Endeavor period (minutes) | 722 | 436 |
| total traveling time for personal chair during Endeavor period (minutes) | 53 | 35 |
| total distance per day for personal chair during Endeavor period (meters) | 1354 | 1143 |
| total time per day for Endeavor chair during two-week period (minutes) | 637 | 319 |
| total traveling time for Endeavor chair during two-week period (minutes) | 36 | 26 |
| total distance per day for Endeavor chair during two-week period (meters) | 593 | 410 |
| total time per day during Endeavor period (minutes) | 923 | 484 |
| total traveling time during Endeavor period (minutes) | 78 | 27 |
| total distance per day during Endeavor period (meters) | 1688 | 822 |

**Table 13.** Statistical significance of specific chair use on time and distance.

| Wilcoxon Signed Ranks Test | Significance |
|---|---|
| total time per day (minutes) | 0.03 |
| total driving time per day(minutes) | 0.04 |
| total distance per day (meters) | 0.04 |
| total distance between weeks (meters) | 0.87 |
| personal chair distance between weeks | 0.31 |

### 2.3.2 Wheelchair comparison survey results.

Table 14 shows the results of the "Wheelchair Comparison" survey (page 106). These data were used for hypotheses three and four. Statistical significance was found using the Wilcoxon Signed Ranks Test. When using an alpha value of .05 the three dimensions which the Endeavor statistically ranked better than their personal chairs were: compactness in folded position, improving access to narrow doorways in confined spaces and maneuverability in confined spaces with P. values of .02, .01 and .02 respectively.

**Table 14.** Number of participants who rated the Endeavor better than their personal chair on the "Wheelchair Comparison" survey.

| | better | worse | equal | statistical significance |
|---|---|---|---|---|
| compactness in folded position | 8 | 1 | 0 | 0.02 |
| ease of loading | 0 | 4 | 5 | 0.06 |
| ease of unloading | 2 | 3 | 4 | 0.48 |
| ease of traveling | 5 | 3 | 1 | 0.66 |
| overall maneuverability | 2 | 3 | 4 | 0.65 |
| access to narrow doorways and confined spaces | 8 | 0 | 1 | 0.01 |
| maneuverability in confined places | 7 | 0 | 2 | 0.02 |
| ascending and descending stairs | 0 | 4 | 5 | 0.07 |

### 2.3.3 Other take-home phase results.

Table 15 shows a categorized list of issues and the number of times each issue was mentioned. The columns show the phase, the means of obtaining and severity of each issue. An incident indicates a cut, bruise, tip or fall. These issues will be used to develop design modifications.

Table 16 shows the list of participants, the percent of time each participant used the Endeavor during the Endeavor phase of the in-home trial, the number of days the participant said they used the Endeavor chair during that phase and their decision to keep the chair. It shows that based on these two dimensions it was not possible to predict if a participant would keep their chair.

**Table 15.** Number of times an issue occurred by phase

| | | in lab | | take-home | | | |
|---|---|---|---|---|---|---|---|
| | issue | in lab issue | in lab incident | daily log issue | phone call issue | made unusable | take home incident |
| safety | sharp edges | 2 | 1 | 1 | 1 | | 1 |
| | footrest problems | | | 3 | | | 2 |
| | caster size | | | 3 | | | 1 |
| | forward stability | | 2 | | | | |
| | rearward stability | 1 | 2 | 1 | 1 | 2 | |
| | uncomfortable (seatpan) | | | 1 | 2 | 1 | |
| | uncomfortable (backrest) | | | 2 | | | |
| | fit | | | 1 | | 1 | |
| hardware | splash guards/cushion sliding | 1 | | | 1 | | |
| | rear wheels falling off | | | 1 | 2 | | |
| | no armrests | | | 1 | 1 | 1 | |
| | no push handles | | | 1 | 1 | | |
| | handle | 2 | | 2 | | | |
| folding | middle tube discnnect | | | 1 | 3 | | |
| | strap | | | | 1 | | |
| | sliding joints | 3 | | | 2 | | |

**Table 16.** How percent of time and logged days effects desire to keep chair.

| participant id | percent Endeavor used during Endeavor trial(distance) | days on log | keep chair |
|---|---|---|---|
| 2 | 0.710562 | 2 | 0 |
| 3 | 97.23628 | | 1 |
| 4 | 50.34976 | 9 | 1 |
| 5 | missing | 7 | 0 |
| 7 | missing | 14 | 1 |
| 9 | 28.40632 | 6 | 1 |
| 10 | 13.33069 | 4 | 0 |
| 11 | 46.41411 | 11 | 0 |
| 12 | 100 | 14 | 0 |
| 13 | 20.92652 | 9 | 1 |

### 2.3.4 Anecdotal results from take-home phase

***Chair usage***. Though these results were difficult to quantify numerically they were interesting nonetheless. Two other users have used the chair on airplanes. The first user said that his chair was too wide to fit down the aisle through the first-class section on one of his flights. He was upgraded to first-class and successfully used the chair for boarding. He said that the chair had no problems folding small enough to fit into overhead bin. The other user has said that he has used the chair for airplane boarding twice. On one leg of the trip, he used the chair as a boarding chair without incident. On the way back, the chair was too wide. The same user also has used the chair on a boat. One user who decided to keep the chair has used it when he was traveling to places that he knew where narrow. He keeps the chair as a special-purpose chair in case he needs to access narrow places again. A second participant uses the chair frequently to access an inaccessible bathroom and the inside of his camper.

***Wheelchair modifications done by users.*** Two of our users have modified the chair themselves. One has replaced the hard plastic handles with soft rubber handles decreasing pressure to combat bruising, installed his own sling seating system and added a strap to the back of the chair to make it easier to load into his vehicle. Another user has lowered the front of the chair, removed the handles at the front of the seat, made new detachable handles and readjusted the foot plates. Following is a drawing of the removable front handle designed by this user (Figure 18).

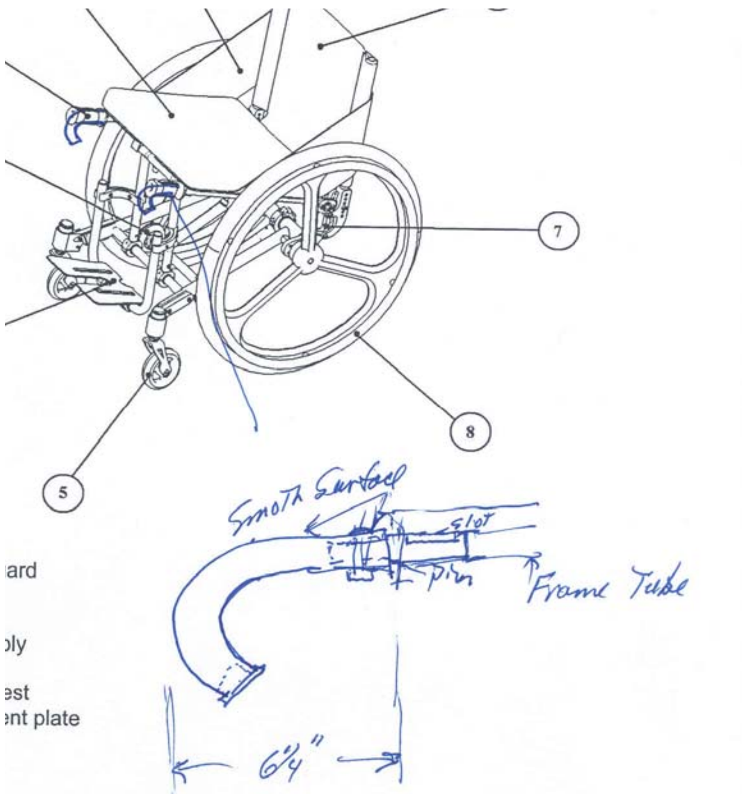



**Figure 18.** Curved detachable handle

These users have also suggested adding a bar across the backrest to help with loading and rigidity and adding detent removable casters with an auxiliary housing to store them located on the chair and finally a strapping system to keep the chair secured when folded.

# 3.0 DISCUSSION

## 3.1 HYPOTHESES EVALUATIONS

***Hypothesis #1***: The Endeavor will receive favorable *overall* performance ratings (page 101) on each of the following dimensions: stability, ease of propulsion, maneuverability, and overall comfort of ride.

The five questions which related to the dimensions were "how would you rate the: comfort, feel of ride, stability, ease of propelling and maneuverability of the Endeavor chair (Table 6). For these questions three were considered statistically significant using an alpha value of .05 and binomial probability. These three were feel of ride, ease of propelling and maneuverability with p-values of .01, .00 and .01 respectively. Comfort and stability had p-values of .13 and .22 respectively.

***Hypothesis #2***: The Endeavor will receive "ease of task" ratings (page 98) that will be superior to the ratings that participant's give their own personal wheelchair for the car transfer.

Similarly to hypothesis 1, the ease of task ratings for transferring and stowing the personal chair are not statistically significant when compared to the ratings for the Endeavor chair with p-values of .32 and .07 respectively. The fact that stowing approaches significance may also be attributed to being unfamiliar with the stowing process (Table 3).

***Hypothesis #3***: Participants will rate the Endeavor as superior to their own personal chair on dimensions related to compactness, folding, and stowage (page 106).

The three dimensions which relate to compactness, folding and stowage were: compactness in folded position, ease of loading and ease of unloading. Of the three dimensions, the only one which was statistically significant was compactness in folded position with a p-value of .02 with seven of eight persons ranking the Endeavor better. Four persons ranked the ease of loading worse than the Endeavor. This was very concerning because of those persons who ranked the chair equal, three of those used wheelchair accessible vans where folding was unnecessary. Increasing the ease of folding or at least ease of preparation for vehicle stowage should be considered in future models (Table 14).

***Hypothesis #4***: Participants will rate the Endeavor as superior to their own personal chair on dimensions related to accessibility and maneuverability.

For two of the three dimensions related to accessibility and maneuverability the Endeavor preformed statistically better. “Access to narrow doorways and confined spaces" was statistically significant with a p-value of .01 and "maneuverability in confined spaces" was significant with a p-value of .02. Interestingly, overall maneuverability was not significant (p-value of .65). This may be due to participants' difficulties accessing familiar places with a new wheelchair setup (Table 7).

***Hypothesis #5***: There will be *no* significant quantitative differences ($p > .05$) when comparing use of each chair during the two-week trial periods: Participants’ use of the Endeavor (e.g., # of hours per day, miles per day) and their use of their own personal chair will not be significantly different.

For "total time per day," "total driving time per day," and "total distance per day" the difference between the two samples was statistically significant with p-values of .03, .04 and .04 respectively. This shows that persons did not use the Endeavor chair as much as their personal chair during their respective two-week phases. Also, the difference in the total driving distance between the two weeks was not statistically significant (p=.87). This shows that the differences cannot be accounted for by just having a "slow week" during the Endeavor phase. These results are very similar to those found in a similar style trial studying push rim activated power assist wheelchairs[6]. Disuse of the intervention was even more emphasized in the current study. The usage between persons personal chairs during the first phase and second phase did not differ significantly (p=.31). This lack of difference may show that the actual percentage of time the person actually used the Endeavor during its respective phase was on average minimal.. Implying many participants may have not used the Endeavor as their primary chair but only used it when not inconvenient. This evidence points to the possibility that the current form of the Endeavor wheelchair is only a special-purpose chair for most users. To make this an everyday chair, changes in the design or delivery must be made (Table 13).

***Hypothesis #6***: The percent of time in the Endeavor (as a percent of total wheelchair usage) will exceed the percent of time in participants' own personal wheelchair by the end of the 8-week phone follow-up period.

Only four people opted to participate in the follow-up phase. Of these four persons, when asked at the eight week follow-up two reported using the chair 0 percent of their total time in a chair. The remaining participants reported using the chair 25 and 40 percent of time. Of the two who did not use the chair, one said it was not as convenient as his personal chair to use while the second only uses the chair when the need arises such as for accessing narrow places. The participant who used the chair 25 percent of the time used his chair at his friend's house because of the narrow bathroom doors. The participant who used the chair most, modified his chair to suit his needs and preferences.

## 3.2 GENERAL DISCUSSION

### 3.2.1 Intake Questionnaire

Besides the hypotheses, much interesting data were collected. In the intake survey, one section gauged the contribution of certain factors as dislike of flying (Table 1). Of the 13 participants, three had never flown post injury. Because these participants may have been less informed on the actual experience, in the chart they were separated from those who have flown. These participants were also interesting because possibly with the peace of mind of having a device which can help alleviate some of their worries they may feel comfortable flying. For the non-flyers, the three most highly rated factors were: "damaged wheelchair", "bowel or bladder issues," and lost wheelchair. All three of these factors were in the top four factors rated by flying participants. The additional factor was the use of aisle chairs. That this was not a major factor for non-flyers was unsurprising. There was no reason to dislike something that you had no experience with. A product like the Endeavor wheelchair was potentially very useful. It can fold small enough to fit in the overhead bin of an airplane greatly reducing the risk of damaging the wheelchair and eliminating the possibility of losing it. Also, if properly designed it may serve as a tool to help access the onboard bathroom.

Also included at the end of intake questionnaire was an area in which the wheelchair dimensions were recorded (Table 2). This table gives a very good look at the possible ranges of dimensions possible for a user with a 16 inch wide chair. The two dimensions which may be difficult to reach with one product are the variations in seat depth and rear seat to floor height. As can be seen later it would have been useful to collect casters size even though there were no caster size options on the Endeavor.

### 3.2.2 Video data

The video data, can be used to help understand the abilities of our users and the properties of testing procedures. In the first table describing the video taped results (Table 4), the significance of chair on time to complete the obstacle course and the car procedure is shown. For the obstacle course, participants can be easily grouped into two different groups: those who went forwards down the curbs and those who went backwards. After dividing the participants into these two groups the data was no longer skewed and parametric statistics can be used. For both sets of users using an alpha value of .05, time difference was not significant with a p-value of .78 for those who went forward down curbs and .13 for those who went backwards.

For the car procedure the effect of the chair on time to complete was statistically significant with a p-value of .00 (Table 4). Persons who use an accessible van have the highest likelihood of similar times because they're not required to fold the chair. Another useful grouping is persons who do not remove their wheels on their personal chair when stowing. These persons will likely have much higher times for stowing the Endeavor when in comparison to their personal chair. Even when omitting either of these groups the time difference is still statistically significant (.01 when omitting van, .03 when omitting "don't remove wheels"). The data from loading and unloading the chairs was not normal so the Wilcoxson signed ranks task needed to be used.

When doing the airplane simulation there was a large variety of different methods chosen by the particular participants (Table 5). Because the method chosen has a large effect on the time it takes to complete the course these are divided into groups. For both boarding deplaneing there are four possible options: first row of seats traveling forwards, first row of seats traveling backwards, the second row of seats traveling forwards and second row of seats traveling backwards. Many participants chose to propel themselves to the second row of seats because the armrest would move out of the way for transfers. From the time data, it shows that it is easier to move forward down the aisle and for shorter distances. This is directly related to the axle sleeves getting caught on barriers. Because of the differing amounts of external help, wheel removal and installation data were not analyzed.

### 3.2.3 Overall questionnaire

Beside stability (p=.02) there were no statistically significant results in the overall performance ratings questionnaire using an alpha value of .05 (Table 7). So for all other dimensions, the null hypothesis could not be rejected. This means that even though some people ranked their chairs higher or lower on particular dimensions at least with this sample size you difference cannot be claimed. This means that people were rating the Endeavor, a chair which they have never used before similarly to their personal chair, which they are intimately familiar with.

It is encouraging to see that stability turned out to be statistically significant as a mark of the validity of the test. Throughout the study, there were issues with the wheelchair being too "tippy". For example, when ascending the ramp, the casters of the chair would leave the ground. Also, there was one tip and one fall which can be related to stability during the in-lab testing phase. Neither incident happened during completion of the courses. These will be explained further on page 56.

At the end of the overall questionnaires, there was a section where participants were asked what they liked least and most about their own chairs and the Endeavor chair (Table 8-11). The most common positive responses for the Endeavor pertained to its small folded size, it's maneuverability or good ride and finally on its airplane wheels. Even with the large push wheels installed this chair is much narrower than most persons every day chairs. It also had a more forward axle position and high-pressure tires. For these reasons it was more maneuverable and had lower rolling resistance than most personal chairs. There were a number of different things about the Endeavor users thought could be improved. The most common comments addressed the stability and weight.

Possibly in response to the perceived instability of the Endeavor, stability was the most commonly appreciated feature on persons' personal chairs. Interestingly, the same number of users that rated weight as a negative on the Endeavor said the same about their personal chairs (these are not necessarily the same users). Two persons also commented that they did not like the width of their personal chair probably prompted by the extreme narrowness of the Endeavor. Three persons instead of leaving the question blank stated that there was nothing that they did not like about their personal chair. This shows a very high level of satisfaction for these users.

These comments show a few different things. First, most users like a smaller, more maneuverable chair. Second, everyone wanted the chair as light as possible. And lastly for this group of participants, the Endeavor had stability issues. In future chairs it would be useful to include all factors that make the chair maneuverable while fixing stability issues and including more axle adjustment.

### 3.2.4 In lab phase adverse events

During the course of the in lab phase of the study, there were two adverse events which needed to be submitted to the IRB. After their review, the IRB did not consider the event's serious. The first was a wheelchair tip. While filling out a survey, a user stopped himself from rolling underneath the desk by pushing against the front of it. As he did this, his chair continued to roll under the desk and the front edge which flipped him backwards. Later after returning the chair it was found that the gas spring had lost compression allowing the backrest to move backwards and change the center of gravity. The second adverse event was a fall. This user fell when the front of the chair tipped forward during a transfer. This type of incident is common among ultralight manual wheelchair users. It is possible that the participant moved further forward in the chair than normal to avoid getting caught on the carrying handles at the front of the seat plate. For proposed modifications to the Endeavor to address these issues refer to appendix E (page 145).

## 3.3 TAKE-HOME PHASE ADVERSE EVENTS AND SAFETY ISSUES.

The last adverse event took place during the take-home phase. One of the users needed to transfer into the chair from position that was oriented 180 degrees from the chair. During the transfer, his foot was caught in the footrest assembly. The torque applied to his foot during the transfer caused severe bruising. It was never x-rayed. One other user reported falling from the chair. Because this happened after the protocol modifications so it did not need to be reported. He stated that he failed to negotiate an uneven place in the sidewalk and his casters stopped causing him to fall forward out of the chair.

There were a few other important safety issues (Table 14). First, as a result of the machining processes many sharp edges were left on places which frequently come in contact with parts of a person's body. The front of the seat pan and edges of the footrest were left unfinished and sharp. Users with a spinal cord injury in general have little to no sensation in their legs, these sharp edges may cut a user without them knowing. Also, these narrow areas greatly increase local pressure areas possibly leading to pressure sores[7]. At least three participants reported being cut or bruised by these edges. These edges were so sharp in fact that it would not be recommended to use the current model using open toe shoes.

Second, the metal seat pan was frequently reported as being very uncomfortable. Most manual wheelchairs used either strap or sling seating. This type of system helps a cushion conform to the natural curves of the body more equally distributing pressure. The lower peak pressures allow for persons to use thinner seat cushions. Because participants were instructed to use their own seat cushions, many felt that the hard seat pan was unforgiving. This caused the chair to be unusable for one user and was commented on by at least three other users.

Third, the handles at the front of the seat pan intimidated users during transfers. During the in lab phase two persons felt more comfortable with the handles removed. During this first phase, there were no incidents of users actually being caught on the handles during transfers. In real-life they may interfere more especially when transferring in the chair from the front or from a lower seat height without spotters. They may possibly also interfere if a user is trying to get into the chair from the ground.

Lastly, the seat pan depth did not properly fit persons with long or short legs. Because of the bar at the front of the seat frame there was only a finite distance the seat pan can be moved backwards. If the seat pan is moved further forward, it does not leave enough room for a person's feet to sit securely on the foot plates. The seat depth was not one of the inclusion/exclusion criteria. Relying on self-reported cushion measurements were not accurate either. Many persons did not actually know the true size of their cushion and many others did not have a depth that matched their leg length. Proper seat depth may have kept users legs from splaying outwards without the front carrying handles.

## 3.4 DIFFERENT TYPES OF WHEELCHAIR USERS

It may be possible to fit the participants into certain empirically derived categories which can help to describe their feelings towards a new mobility device. Because of the limited number of participants, there are probably other major categories that were missed and it's quite possible to transition between categories.

**Group 1.** *Users who are highly dissatisfied with their current wheelchair.* In most cases these users have only used chairs as a means of transportation for four to six years. In most cases they are still using their first chair or have recently recived a second chair that did not meet expectations. This group of users is easily pleased with any new chair especially if the process of selection and fitting is highly personal. They are open to new ideas and their lifestyle isn't so fixed that a new chair with different form or functionality would be an intrusion.

**Group 2**. *Users whose current chair is worn out*. These users have had their personal chair for a long time and use it very heavily. Throughout their experience as a wheelchair user, they have used similar chairs to the one they have now. Their chair is in such a state of disrepair that they feel they may need a new chair in the very near future. Initially these participants are open-minded to new technology. However, after the in-home trials if they find the chair does not allow them to function as well in their everyday environment they will abandon it. For these users, form is negotiable but functionality definitely is not.

**Group 3**. *Users who use multiple chairs*. These users are also longtime manual wheelchair users. Throughout their lives they have accumulated many different mobility devices. They have found that certain chairs or devices are appropriate for particular situations. Because of their extensive experience with multiple devices their feedback on a device is very relevant and valuable. However, they may see the device they are evaluating only as a special-purpose tool.

**Group 4.** *The satisfied long-time single chair users.* This type of user also has used a manual wheelchair for a long period of time. Throughout their history, they mostly used a primary chair and did not use any sort of secondary means regularly. In most cases their current wheelchair is very similar in form and function to their previous primary chairs. This group of users is very difficult to please. If the chair they are evaluating does not nearly perfectly match their current chair in all options they will dislike it.

**Table 17.** The effect of grouping on study completion

| participant id | user type | start study | finish study | keep chair |
|---|---|---|---|---|
| 1 | 4 | 0 | 0 | 0 |
| 2 | 4 | 1 | 0 | 0 |
| 3 | 1 | 1 | 1 | 1 |
| 4 | undetermined | 1 | 1 | 1 |
| 5 | 2 | 1 | 1 | 0 |
| 6 | 2 | 1 | 0 | 0 |
| 7 | 3 | 1 | 1 | 1 |
| 8 | 4 | 0 | 0 | 0 |
| 9 | 3 | 1 | 1 | 1 |
| 10 | 2 | 1 | 1 | 0 |
| 11 | 2 | 1 | 1 | 0 |
| 12 | transitioning | 1 | 1 | 0 |
| 13 | 3 | 1 | 1 | 1 |
| 14 | 4 | 0 | 0 | 0 |

After the author empirically categorized the participants into each of these four groups retroactively, the results are unsurprising. No user categorized as a "4" kept the chair. Only one of these users started the take-home phase of the study. All the group two users started the study, and all but one finished the study. None of these users decided to keep the chair. All of the group 3 users also started and finished the study. Each of these decided to keep the chair and to use it in special circumstances where a narrow chair was necessary. Two out of the three modified their own chairs to better suit their needs. All of the group 1 users started the study. One of the group 1 users transitioned to group 4. During the take-home phase he received a new wheelchair which he was greatly satisfied with. He decided not to keep the chair. It should be noted that these groups may not be the perfect predictor that they seem to be for this study. Recall bias and already knowing the results may have influenced the author's participant categorization.

### 3.5 WERE OUR USERS APPROPRIATE FOR THIS CHAIR?

The current version of the folding chair is in a prototype stage. For this reason, there are only a few different options which are available on the chair. The current chair was set up to be most similar to a highly skilled wheelchair user's chair. Two common traits of this user group's chairs are often a more forward rear axle position and small caster wheels. A more forward axle position creates less rolling resistance because it centers most of the weight over the rear axle and very little is distributed on the smaller caster wheels. It also makes it easy for a user to wheelie over obstacles. For persons who do not have this axle position set up, a high-performance chair would feel unstable. If a user does not have enough practice with this set up the chair may be uncomfortable. Many high-performance chairs have relatively small caster diameters to lower rolling resistance on hard indoor surfaces. Using a smaller caster size also allows the caster barrels to be located closer to the footrest without interfering. This makes for a tighter, more nimble chair configuration. The smaller caster also decreases weight. Unfortunately, smaller front wheels do not fair very well over obstacles. The smaller width allows them to sink deeper into soft surfaces. The smaller diameter makes them more likely to be stopped by cracks or bumps possibly throwing a rider from the chair. Because most highly skilled users prefer to wheelie over obstacles these problems are minimized. For a less skilled rider who cannot adequately compensate for the smaller caster size a chair with this option could also be hazardous.

This study had an interesting mixture of users. Of our participants who decided to take part in the take-home phase, three have used wheelchairs for more than 30 years, two of which had larger casters. Two of our other participants used older Quickie 2 style wheelchairs with large front casters and very rearward axle positions. This was a very common type and set up for wheelchairs years ago [8]. Because of our participants extensive amount of experience they should not be thought of as unskilled users. Even so, these users have learned to function in their environment with a particular type of chair. They have not adapted to newer more efficient devices and propulsion methods. Possibly, some of these users may not have been appropriate for this chair. This chair also did not fit two of these users properly because of their long leg length.

Caster size and relative axle position would have been useful criteria for choosing participants to complete the in-home phase of the study. Even so, there were difficulties recruiting with the current criteria. By further limiting the possible users, testing would have taken much more time. Also, the feedback from these users was not without merit. Many of the comments and issues faced throughout the take-home phase were not necessarily related to axle position or caster size. And finally, because this type of user showed up so frequently in recruitment, axle position and the option of different caster diameters may be more important to make a more universally usable chair than originally thought. This need would not have been so emphasized with a more homogenous group of participants.

## 3.6 THE BUILDING OF THE "HOUSE OF QUALITY" MATRIX FOR THE ENDEAVOR FOLDING WHEELCHAIR.

### 3.6.1 Development of the customer requirements table.

Traditionally, customer requirements would come from the "customers own mouth". There are several points where participants were able to respond in a free format. One area was the end of the "overall results" questionnaire where they commented on what they like most in least about their personal and the Endeavor wheelchairs. There are some drawbacks from this format. This phrasing of the question especially after ranking their personal chair and the Endeavor chair on identical dimensions leads to responses which highlight the differences between their personal chair and the Endeavor. Participants also had the opportunity to comment on the chair during the daily logs and in the follow-up phone interviews. The mindset during these open response periods also focused the conversations on the benefits and drawbacks of the current product not on the general picture. The recorded responses from these feedback sessions, at least give us a place to start from (these issues and responses can be seen in the results section). More time and a different protocol would be needed to create a better focused customer requirements section from customer responses alone. Because of the lack of a broader focus categories were refined to create a customer requirements section based both on actual responses and redefined to fit in the framework of the general idea. The general idea is an everyday wheelchair which can be used as an airline boarding chair and can fold small enough to fit into the overhead bin of an airplane.

### 3.6.2 Development of the planning matrix.

***Creating a customer importance weighting.*** Each category was weighted on a scale from 1 to 5 with 5 being the most important. As you can see, it's outdoor use and vehicle storage was emphasized over its usability in the air travel setting. This is because the chair is first of all an everyday chair and as an added function it can be used as a boarding chair. For our current group of participants outdoor use was highly emphasized. Most users travel much more frequently in their own vehicle than in an airplane. It is also not quite so important to be as efficient in the airplane operations as they are when storing in their own vehicle (it is never raining inside the plane). As long as the chair meets the folding requirements to fit in the designated space, more compactness is of little use. Ideally these weightings would come from questionnaire surveys and be rating customer requirements based on earlier open conversation with actual customers.

***Selecting competitors.*** Appendix (page 127) shows potential competitors with the Endeavor wheelchair as everyday chairs which could fold small enough to fit in the overhead bin of an airplane. So as not to only focus on chairs which fold in the sagittal plane, two other chairs are added (Kuschall Champion, and the Quickie GTX).

***Planned satisfaction rating.*** These would normally be determined by the entire design team but in this instance they were developed solely by the author. Those categories which were deemed most important in the customer importance weighting as well as those the chair already performs well in where most emphasized.

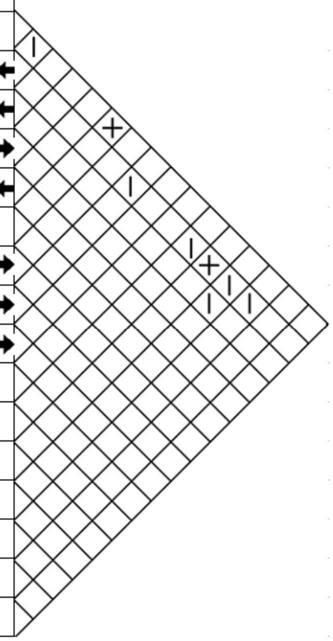
***Sales point emphasis.*** Because the overall size and its special features as an aisle chair set it apart from other chairs these can be used as marketing points.

***Developing technical requirements.*** Technical requirements need to be measurable. The requirements were divided into three different categories. The first included measurable performance criteria pertaining to durability, maneuverability and folded size. The second category encompassed factors that would determine the number of different types of products that would be sold. The last section focused on possible options.

***A little bit about benchmarking.*** Most of the data about the technical requirements of the commercially available chairs are not included. This is because much of this data is not published and when it is. the validity is questionable.

# Table 18. The Endeavor wheelchair House of Quality matrix

| Technical Requirements \ User Requirements | Able to fit down airplane aisle | Easy to handle when collapsed | easy to fold | Folds small | Easy to store in overhead bin | Easy to store in car | Lightweight | Easy to transfer in and out of | Fits well | Comfortable | Maneuverable in small areas | Stable | Safe for outdoor use | | direction of improvement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | traveling usability | | | | | | general usability | | | | | | | | |
| customer importance | 3 | 3 | 3 | 3 | 2 | 4 | 4 | 4 | 4 | 5 | 3 | 4 | 4 | | |
| passes durability standards | | | | | | | 6 | | | | | | 9 | performance | |
| chair weight | | 6 | | | 6 | 6 | 9 | | | | | 3 | | performance | ← |
| turning radius | 9 | | | | | | | | | | 9 | | 3 | performance | ← |
| tipping angle | | | | | | | | | | 3 | 3 | 9 | 6 | performance | → |
| folded dimensions without wheels | | 3 | | 9 | 6 | 6 | | | | | | | | performance | ← |
| hardware quality | | | | | | | 3 | | | | | | 9 | performance | |
| adjustability | | | | | | | 6 | | 9 | 9 | | 6 | 3 | range | → |
| number of different sizes | | | | 3 | | | 6 | | 9 | 6 | | | | range | → |
| color options | | | | | | | | | | | | | | range | → |
| hard splash guards | | 3 | 6 | 3 | | 6 | | | 6 | | | | 6 | options | |
| armrests | | | | 6 | | | | | 9 | | | | | options | |
| sling seating | | | | | | | 6 | | | 9 | | | | options | |
| caster size options | | 6 | | 9 | | | | | | | 9 | 6 | 9 | options | |
| rear push handles | | | | 6 | 9 | 6 | | | | | | | | options | |
| camber options | | 6 | | | | | | | | | 6 | 9 | | options | |
| third party backrest compatibility | | | | 6 | | | | | | 9 | | | | options | |



| Technical Requirement | Technical Requirements | Percentage of Total | Endeavor | Quickie Revolution | OttoBock Switch | Click New Reality | Reha Technik pro active Jet | Da Vinci Wheelchairs- Leggera Supra Compatta | Mobility Vision Activator | Da Vinci Wheelchairs-Leggera Compact | Kuschall Champion | Quickie GTX | Design Targets |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Technical Benchmarking | | | | | | | | | | |
| passes durability standards | 99.1 | 5.26 | y | y | y | y | y | y | y | y | y | y | y |
| chair weight | 169 | 8.98 | 19.5 | 23 | 10.6 | 16.8 | | | | | 14.7 | 16.3 | 16 |
| turning radius | 93 | 4.94 | | | | | | | | | | | |
| tipping angle | 122 | 6.49 | 5 | | | | | | | | | | 5-10 |
| folded dimensions without wheels | 111 | 5.88 | 6x22 | | | | | | | | | | |
| hardware quality | 77.3 | 4.1 | high | | | | | | | | | | high |
| adjustability | 218 | 11.6 | yes | yes | yes | | | | | | yes | yes | |
| number of different sizes | 155 | 8.21 | 2 | | | | | | | | | | 2 |
| color options | 0 | 0 | 1 | ~20 | | | | | | | | ~20 | 2 |
| hard splash guards | 170 | 9.03 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| armrests | 75.6 | 4.01 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| sling seating | 116 | 6.14 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| caster size options | 187 | 9.93 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| rear push handles | 93.6 | 4.97 | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 |
| camber options | 99.7 | 5.3 | 1 | 3 | 0-15 | 1 | 1 | 1 | 1 | 1 | 1 | ~19 | 3 |
| third party backrest compatibility | 97.2 | 5.16 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 |

| | Able to fit down airplane aisle | Easy to handle when collapsed | easy to fold | Folds small | Easy to store in overhead bin | Easy to store in car | Lightweight | Easy to transfer in and out of | Fits well | Comfortable | Maneuverable in small areas | Stable | Safe for outdoor use |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Endeavor | 4 | 2 | 2 | 4 | 2 | 2 | 2 | 3 | 2 | 2 | 5 | 2 | 2 |
| Quickie Revolution | 2 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 4 | 5 | 3 | 4 | 4 |
| OttoBock Switch | 2 | 4 | 3 | 4 | 3 | 4 | 4 | 4 | 4 | 5 | 3 | 4 | 4 |
| Click New Reality | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 3 | 5 | 3 | 4 | 4 |
| Reha Technik pro active Jet | 2 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 3 | 4 | 3 | 4 | 3 |
| Da Vinci Wheelchairs- Leggera Supra Compatta | 2 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 5 | 5 | 3 | 4 | 4 |
| Mobility Vision Activator | 2 | 4 | 5 | 4 | 3 | 4 | 5 | 4 | 3 | 5 | 4 | 4 | 3 |
| Da Vinci Wheelchairs-Leggera Compact | 2 | 4 | 3 | 4 | 3 | 4 | 5 | 4 | 5 | 5 | 4 | 4 | 3 |
| Kuschall Champion | 3 | 4 | 4 | 4 | 3 | 4 | 5 | 4 | 4 | 5 | 4 | 4 | 3 |
| Quickie GTX | 3 | 4 | 5 | 4 | 3 | 5 | 5 | 4 | 5 | 5 | 4 | 4 | 4 |
| Planned Rating | 5 | 4 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 4 | 4 |
| improvement factor | 1.2 | 1.4 | 1.4 | 1 | 1.2 | 1.4 | 1.4 | 1.2 | 1.4 | 1.6 | 1 | 1.4 | 1.4 |
| Sales Point | 1.3 | 1.1 | 1.3 | 1.4 | 1.3 | 1.2 | 1.3 | 1 | 1 | 1 | 1.2 | 1 | 1.1 |
| Overall Rating | 4.68 | 4.62 | 5.46 | 4.2 | 3.12 | 6.72 | 7.28 | 4.8 | 5.6 | 8 | 3.6 | 5.6 | 6.16 |
| Percentage of Total | 6.7 | 6.6 | 7.8 | 6 | 4.5 | 9.6 | 10 | 6.9 | 8 | 11 | 5.2 | 8 | 8.8 |

# 4.0 CONCLUSIONS AND FUTURE WORK

Currently, the 16 inch wide Endeavor is a hit or miss airplane boarding tool. The chair can function as a boarding chair on planes where the aisle is wide enough. Also, given an open cabin configuration it could possibly be used as an in-flight mobility tool to reach an airplane bathroom. Sadly, there are no guarantees by the airlines to maintain at least a 17 inch aisle width (refer back to the introduction). Aisle ways are frequently even narrower in smaller planes and through the first-class section. As aisles get smaller, the 16 inch width wheelchair frame will lose its usefulness as a boarding method. Luckily, overhead bins are not shrinking. A user will probably be able to fit their folding wheelchair in the overhead bin for the foreseeable future. There is also the much neglected designated wheelchair storage closet. Being able to travel without entrusting the safety of a person's wheelchair to a third party would greatly increase peace of mind.

To be a true airline boarding chair the Endeavor would need to be able to support a wide range of function levels including persons with total paralysis of all four limbs and partial paralysis of the neck (page 114). The Endeavor will never be able to do this. The 16 inch chair is also too wide to fit down some airplane aisles already. It would be inappropriate to use as an in-terminal chair if it was wide enough to accommodate most chair users. This could be accomplished by adding a quick release wheel spacing system.

The compact size in its collapsed position is helpful for those who, with assistance, store the chair in a small automobile trunk.  For independent car stowage, the chair requires some redesign to make it more effective.  Removing the rear wheels, disconnecting the two links and properly folding the chair require more time and effort than most chairs.  Because users travel much more frequently by car than by plane, future redesigns must take vehicle loading and storage into consideration.

To allow for more useful critical analysis, the airplane wheels and the Endeavor folding wheelchair from now on will be considered separately.  As we have demonstrated on several chairs, there's no reason why the airplane wheels could not be installed on any chair with a cylindrical axle tube.

## 4.1 THE ENDEAVOR FOLDING WHEELCHAIR

Using the current definition of the forward folding wheelchair based on historical designs, the concept itself has drawbacks.  There will always be two disconnection points and the rear tires must be removed.  This makes for 3 more steps than the traditional cross brace style folding wheelchair.  Even though a traditional depot style wheelchair could never fit in an overhead bin, a few ultralightweight alternative laterally folding manual wheelchairs with a folding backrest and quick release rear axles such as the Kuschall Champion can.  When the two joints are disengaged, there will always be at least five unconstrained links (the current iteration has six). By mounting the casters on the bottom frame, the caster height will always be the determining factor on the height of the folded wheelchair. Adding disconnecting casters would be able to lower the overall height of the folded Endeavor wheelchair at the expense of another step. There will always be 5 separate links which makes it very difficult to make the chair's weight competitive with less involved folding designs.

Wheelchair users travel much more frequently in their personal vehicles than they do by air. The folding requirements for most motor vehicles are much less stringent than those for air travel. This gives rise to another option for our chair. A collective decision could be made by the design team to make the folding a more auxiliary feature. This was the course that was taken with the OttoBock Switch. By adding a folding backrest to the chair the Endeavor would function exactly as a rigid manual wheelchair for everyday use. This may increase the acceptance of the chair for many manual wheelchair users. They would have all the benefits of a rigid manual wheelchair with the added function of folding to fit in an airplane overhead bin if necessary. If the chair only needed to be completely collapsed occasionally, inefficiencies in the folding system may not be quite so disagreeable for a user. Detent removable casters would work perfectly for such usage. The drawback of going this route would be that the chair would lose focus on the compact car or sports car driver market niche. For frequent total collapse of the chair, the folding system will need to be streamlined or even rethought.

Throughout the study, the three missing wheelchair options users most frequently cited were: lack of sling seating, the inability to move the axle receivers far enough backwards, and lack of caster diameter options. Our next chair must address these needs. In descending level of importance the other options which should be added are: hard splash guards, armrests, and then folding push handles.

One of the benefits of this chair is the theory behind the adjustability design. It is possible to intuitively adjust the seat dump independent of backrest or caster angle. While new users are still getting used to their wheelchairs, optimal chair configuration may vary greatly. Many users have their chairs adjusted similarly to how their chairs were originally set up[8]. By making adjustments independent and intuitive it may encourage users to adjust their chair to an optimal position. The Endeavor may be a good choice for new wheelchair users when perfecting their personal wheelchair configuration. These measurements and options can then be used when purchasing future customizable yet less adjustable chairs. If the chair is to be used in this method, it must be designed to accommodate all wheelchair options and option adjustability for example: armrest height. The actual measurement could be written near the adjustment point. Spontaneous configuration experimentation might be encouraged through tool-less adjustability [9]. It should be noted that independent adjustment of seat dump is not novel. Both Invacare and Sunrise Medical have patents for designs with this in mind [10, 11] (see page 135).

## 4.2 AIRPLANE WHEELS

The airplane wheels may be much closer to being a marketable product. Five of our take-home phase users stated that they would like their own chair better if they had airplane wheels. This is as the product currently is. This group of users did not include new wheelchair users. New wheelchair users as well as frequent fliers should be the focus of this product. A new user most likely will be returning to an environment which is not architecturally accessible. Bathroom and bedroom doorways especially in small and older houses are rarely wide enough to accommodate a wheelchair. These access wheels would make it possible to function at least until home modifications can be made. They may also make it possible to visit their friends and go to places that they previously frequented with less fear of possible architectural barriers. To increase accessibility outside air travel the requirements are much less. There are very few doorways which are less than 18 inches wide. This means that the airplane wheels could be appropriate for persons with wheelchairs wider than 16 inches.

Longtime manual wheelchair users in most cases already have figured out how to function in their world. They have adapted their lifestyle as well as their environment. They mostly avoid places that they feel are too inaccessible, unknown situations that they feel may be difficult and rarely visit friends whose houses they cannot easily get in to.

Another use of the airplane wheels that users (somewhat surprisingly) appreciated was the anti-tipper configuration. When in the anti-tipper position the rollerblade wheels were higher off the ground than traditional anti-tippers. Users felt an increased sense of security when they were attempting obstacles on which there was a greater chance of tipping rearwards while still being able to traverse them.

The three most common negative comments were the added weight, getting stuck on thresholds and the difficulties extending the airplane wheels to the anti-tipper position. The weight issue could be addressed by choosing lighter materials or making them removable or partially removable. Larger wheels would ease crossing thresholds. Extension still needs to be rethought.

## 4.3 FUTURE WORK

### 4.3.1 Retrospective improvements to the current study

Possible improvements to the current study would have been the inclusion of an airline boarding simulation with an actual boarding chair. This would have given participants the ability to compare the Endeavor against the current method. Comparing the Endeavor chair to their personal chair for car loading was unfair. Two possible methods could have been used to deal with this. First, participants could have loaded and unloaded a dissimilar chair to their own. Second, participants could have came back to the lab after the two week Endeavor section of the take-home phase and the process could have been recorded a second time.

Some improved inclusion/exclusion criteria would have been caster size, seat depth, injury level or diagnosis and a self reported level of rearward stability. This could have been captured using the bedside test of stability test as developed by Kirby[12]. Using the standardized wheelchair skills test with both chairs may have been a more valid method of classifying the skill level of participants. Because the users who had most difficulties with the chair were in most cases had the most advanced skills, the wheelchair skills test would probably only be valid after applying the caster size, rearward stability and seat depth exclusion criteria. It would have also been interesting to add a questionnaire to determine the subject's motivation for participation. Wheelchair standards testing of competing chairs could accentuate the differences.

### 4.3.2 Proposed alternate study design

Almost all of the feedback received from the study focused on the difference between a participant's personal chair and the Endeavor. It may have been more effective to make customized chairs for each subject. Because the parts were based on a computer model, customization would have been relatively easy. In this way it would have been possible to ensure proper fit and the presence of similar options while decreasing weight. Another drawback with the responses was the emphasis on the same difficulties (such as difficulty with the middle tube disconnect). If the protocol allowed for cycles of design iteration and reevaluation these and other problems may have been solved. Since redesign would be a primary focus of such a protocol, subjects could be tested in series instead of parallel allowing each trial to benefit from those previous.

Another possible drawback to the design process up to this point has been the focus on highly developed prototypes and linear development. Instead of evaluating scores of prototypes and design ideas and picking and choosing the best of each, there have been seven relatively similar incremental iterations in the last eight years. Also, knowledge gained through earlier prototyping has been lost because of the extended breaks between iterations.

A possibly more effective method of collecting relevant data would have been to design the study as the combination of many observation sessions first in simulated and later in real-life environments. It should focus first on folding and later on real world usability in everyday and travel situations.

#### 4.3.2.1 Protocol to improve folding and storing in car:

Recruit a small sample (n~4 to 6) of self-reported highly skilled manual wheelchair users selected for greatest variety in wheelchair set up, diagnosis, time post diagnosis and personal vehicle set up.

*First visit:* have subject attempt to fold, load, unload and unfold multiple prototype chairs using user's personal vehicle. Discuss methods of improving experience.

*Second visit:* repeat protocol with multiple new prototype chairs modified to reflect different discussed methods. Discuss methods of further improving performance -- iterate until satisfied.

#### 4.3.2.2 Protocol to improve usability as an everyday wheelchair and as an airplane boarding device:

Recruit a small sample (n~4 to 6) of self-reported highly skilled manual wheelchair users selected for greatest variety in wheelchair set up, diagnosis, time post diagnosis and personal vehicle set up.

*First visit:* collect wheelchair measurements, have subject complete the wheelchair skills test with their personal wheelchair.

*Second visit:* verify fit and suitability of a custom-built wheelchair based on their everyday wheelchair measurements using the wheelchair skills test, loading and unloading from personal vehicle and the airplane simulation. Discuss problems, iterate if necessary until user is comfortable.

*Take-home phase:* first day, investigators will accompany participant through out daily routine confirming suitability and fit as well as access. If any problems are found the chair will be redesigned -- iterate until user is satisfied. Once design is perfected, user will use chair as primary chair for one week. Data loggers and daily logs will be used to collect feedback. At the end of the week, investigators will accompany user throughout routine a final time. At the end of the observation period, a discussion would be held about the experience.

*Real life air travel experience:* user would be accompanied by investigators on a flight to on unfamiliar location with multiple connections and layovers of different time periods and different sized planes. They would then use the chair on public transportation, taxis and rental vehicles while visiting sites of varying accessibility. The experience will be evaluated throughout. This could be repeated (in a different location) with a redesigned chair based on observed needs and user suggestions.

*Final focus group:* At the end of all testing and redesign, the design team and participants should all meet to discuss results.

No doubt this type of protocol would be more time-consuming and expensive but the end product may be superior. Data collected from this protocol could also be used as pilot data for wheeled mobility design and transportation related future work.

### 4.3.3 Product development based study

Prior to the clinical trial it would have been useful to follow a more formal approach to the product development. The focus group was a good tool to gain information but it would have gained much from presenting users with a variety of wheelchairs. After presenting all of the options, the users could have comparatively evaluated the different options and this information could have been used to make more market conscious decisions about features. Even though the background information is not as a sound as it could have been and the prototype may have not met the needs of some of the recruited users properly, considerable amounts of usability information for future prototypes has been gained.

**Figure 19.** Highly modified folding wheelchair accounting for some proposed modifications.

It is not too late to try again. First, the needs of the users should be obtained through casual conversation with users about the general idea; a manual wheelchair for everyday use which can be folded small enough to fit in to the overhead bin of an airplane. The initial conception of the product was very narrow and it may be beneficial to step back from the current solution and evaluate the problem more globally. Second, the needs should be comparatively ranked and weighted based on surveys. Next, an upgraded chair which has addressed all of the issues that could increase safety, comfort, fitting, usability and folding as outlined in this document would be produced (Figure 19). This next generation product can be evaluated in accordance to the user needs obtained in the first part of the study after seeing all of the competitors. All of the chairs presented earlier in the House of Quality matrix should be comparatively evaluated with systematically developed conjoint questionnaires. In the course of acquiring and examining these chairs, much will be learned about the available options, dimensions and ranges of adjustability necessary to complete the benchmarking section of the House of Quality. After this formal evaluation, this information can be used to develop a set of goals for a new chair while in evaluating possible market heterogeneity [13]. This new chair could then be either subjected to another round of clinical testing or just marketed as is.

### 4.3.4 Patents

There is no reason why either the folding wheelchair or the airplane wheels could not be patented. To save money it may be beneficial to make one multipart patent covering both potential products. Hundreds of folding wheelchair patents were reviewed as background material for this thesis. None of these previously patented wheelchairs folded similarly to the Endeavor. And even though the idea of an auxiliary set of wheels to make a chair narrower is not novel, the design and operation are. There was one previous attempt to patent this system. There were no problems pertaining to the novelty of the invention but the execution of the patent application was flawed. In a letter from the patent office, they stated that the application should not have used photographs but black and white line drawings describing the preferred embodiment. These line drawings should have used numbers to refer to points of interest and properly referenced by the text. The patent attorney suggested trying again with a properly constructed document and a product that was closer to its commercial version. Black and white drawings from our solid modeling programs would work fine for a patent application. After review by the patent attorney he may feel that the product is far enough along for it to be worthwhile to patent.

### 4.3.5 Non-Endeavor related future studies.

***Manual wheelchair and wheelchair user dimension database.*** Designing wheelchairs which fit users without having a database of measurements, as has been seen in this project, has major drawbacks. Right now there is no list of measurements of manual wheelchairs and the users chosen adjustments. The proposed database would include both user based measurements and chair based measurements. Relying solely on either type of measurement leads to flaws in interpretation. By having this information readily available, chairs can be designed with the proper dimensions and adjustability for a particular set of users.

***Prospective wheelchair user grouping study.*** Another interesting study would be to attempt describing and grouping wheelchair users for the purpose of determining outcomes for wheeled mobility products. Through the help of clinicians and perspective surveys a more scientifically derived set of groups can be developed. Finally after the groups have been defined a prospective study could be done on user choices and mobility AT abandonment.

# APPENDIX A

# PHASE II STUDY MATERIALS

## A.1 PROTOCOL

Title: Development of Collapsible Folding Manual Wheelchair Phase II

Principle Investigator: Rory A. Cooper, Ph.D.
Co-Investigator(s): Michael Boninger, MD; Annmarie Kelleher, OTR/L; Jeremy Puhlman, BS; Rosemarie Cooper, MPT; Emily Teodorski, BS; Ana Souza, PT; Joseph Olson, BS; Eun-Kyoung Hong, BS; Jon Pearlman, PhD

Date: March 31, 2008

**Objective and Specific Aims**

The purpose of this research project is to evaluate the effectiveness of the Endeavor, which is a compact, forward-folding, ultralight manual wheelchair with an innovative design that incorporates "swing-down" access wheels for navigation in confined areas. This facilitates access to narrow environs such as those encountered in compact dwellings, offices, restrooms, and transportation settings. When using the access wheels, the wheelchair also fits down the aisle of airplanes and collapses to be stowed in the overhead compartment. It is anticipated that the Endeavor will maximize mobility; increase access to confined areas; and ease the demands of travel for people with disabilities. The overall objects and hypothesis are listed below:

1) Verify full functionality of the Endeavor and all its features through human participants testing and evaluation with the use an Activities of Daily Living Course.

***Hypothesis #1***: The Endeavor will receive favorable *overall* performance ratings on each of the following dimensions: stability, ease of propulsion, maneuverability, and overall comfort of ride.

***Hypothesis #2***: The Endeavor will receive "ease of task" ratings that will be superior to the ratings that subject's give their own personal wheelchair for the car transfer.

2) Conduct take-home trials to examine the performance of the Endeavor in the natural environment of the end-user**.**

***Hypothesis #3***: Subjects will rate the Endeavor as superior to their own personal chair on dimensions related to compactness, folding, and stowage.

***Hypothesis #4***: Subjects will rate the Endeavor as superior to their own personal chair on dimensions related to accessibility and maneuverability.

***Hypothesis #5***: There will be *no* significant quantitative differences ($p > .05$) when comparing use of each chair during the two-week trial periods: Subjects' use of the Endeavor (e.g., # of hours per day, miles per day) and their use of their own personal chair will not be significantly different.

***Hypothesis #6***: The percent of time in the Endeavor (as a percent of total wheelchair usage) will exceed the percent of time in subjects' own personal wheelchair by the end of the 8-week phone follow-up period.

## 2.0 Background and Significance

### 2.1 Background

In the U.S. alone, 54 million people have disabilities, and of this population, more than 16 million people have mobility disabilities (US Census Bureau, 1997). This population faces an array of challenges when they travel outside of their home. In a recent survey (National Organization on Disability/Harris Survey of Americans with Disabilities, 2000), 30% of people with disabilities reported that inadequate transportation was a problem in their daily lives. This percentage was almost three times greater than the percentage of people without disabilities who reported that inadequate transportation was a problem. Similarly, the Wall Street Journal reported (May 13, 2001) that in the two years prior to their article, complaints from people with disabilities regarding air-travel discrimination had increased by 81%! The dramatic increase in complaints likely stems from the fact that people with disabilities are traveling more while accommodations in these environments (e.g., on airplanes) remain inadequate. When traveling by plane, wheelchair users typically "gate-check" their wheelchair and transfer to an "aisle-chair". In some cases, the aisle-chairs are little more than dollies (typically used to transport goods) that have been modified to accommodate the transport of people.

The same survey cited above (National Organization on Disability/Harris Survey of Americans with Disabilities, 2000) also found that people with disabilities were far less likely to be employed (only 32% were employed full-time or part-time) than people without disabilities (81% were employed). Yet, the survey found that the vast majority of this unemployed population of people with disabilities would prefer to be working. People with disabilities were also more likely to come from low-income households. One important source of these economic disadvantages is the difficulty that people with disabilities face when they travel outside their home. Importantly, people with limited finances are especially likely to turn to more economically affordable compact cars – yet it is precisely the compact nature of these cars that causes difficulty for the manual wheelchair user. In contrast, larger vans that are significantly more wheelchair-friendly are expensive and often economically unfeasible.

### 2.2 Significance

Wheelchairs have not been adequately designed to meet the demands of the confined areas that are a necessary reality in transportation settings. For example, manual wheelchairs (including more expensive lightweight designs) do not fit down the aisle of full-size commercial aircraft and they do not fold down into a size that fits in the overhead compartment of these airplanes. A more compact, easily collapsible wheelchair would, for instance, make it easier for airlines to stow wheelchairs in the passenger compartment of the airplane. A compact collapsible chair would also ease car travel by making wheelchair handling (the placing in and removal from the trunk) a less demanding task. A wheelchair that has the capability to convert to a narrower set-up (e.g., through the use of swing down wheels) would also allow access to bathrooms, offices, and other places that otherwise may not be wheelchair accessible. Clearly, there is a need for a wheelchair design that maximizes mobility, increases access to confined areas, and eases the demands of travel for people with disabilities.

## 3.0 Research Design and Methods

### 3.1 Device Information

In Phase I of this research, two prototypes of a fully adjustable, compact, forward-folding, ultralight manual wheelchair with an innovative design that incorporates swing-down access wheels for navigation in confined areas were built. The prototypes have an adjustable axle, adjustable backrest and seat angle, and a rigid frame. Testing of the first prototype confirmed that it met or exceeded American National Standard Institute/ Rehabilitation Engineering & Assistive Technology Society of North America (ANSI/RESNA) standards, and it performed similar to other comparable ultralight manual wheelchairs on those standards.

To further advance the development of the Endeavor, a second prototype was built. The second prototype improved on the first in three important ways. First, whereas the first prototype was constructed in an “in-house” machine shop, the second prototype was constructed in a professional machine shop with extensive experience in wheelchair manufacturing. Second, to reduce the weight, the second prototype used lightweight aluminum (6061) for the construction of the frame *and* all the component parts. The weight of the second prototype, including the standard rear wheels and the swing-down access wheels, was reduced from 28.1 lbs to 24.3 lbs. Third, the swing-down access wheels were more fully integrated into the frame of the chair and deploy (swing-down) and stow-away (swing-up) functions were easily achieved.

Refer to Figures 1-6 in Appendix A for pictures of the Endeavor prototypes.

have requested that the University of Pittsburgh’s Institutional Review Board designate the Endeavor as a non-significant risk device. Manual wheelchairs are a 510(k) Class I device through the FDA and compliance with ANSI/RESNA standards is the basis for FDA approval. The Endeavor prototype has met currently approved ANSI/RESNA standards.

### 3.2 Research Design and Methods

<u>Activities of Daily Living Course (ADLC)</u>

The ADLC simulates simple barriers encountered by manual wheelchair users during daily community living such as going up and down ramps, curbs, a simulated bathroom, curb cuts, and traversing over carpet. For the purposes of this study, additional tasks will be added that simulate boarding an airplane and performing a car transfer. The car transfer portion will use the subject's own vehicle.

Measurements will be taken of the subject’s own personal wheelchair, and the Endeavor prototype will be adjusted to match the settings on their personal wheelchair as close as possible. This will include matching settings for seat angle (i.e., seat dump), backrest angles, axle position, footrest length, etc. While the Endeavor is being adjusted, the subject will complete an intake questionnaire. This survey will include questions related to standard demographics and travel routine details. The subject will be given the choice of dictating or writing out the responses to the questions for all questionnaires. Dictated responses will be recorded using a tape recorder.

Subjects will receive an introduction to the Endeavor. They will be given detailed descriptions and hands-on demonstrations of 1) how the Endeavor folds and unfolds, 2) how the swing-down access wheels work (e.g., deploying the swing-down access wheels and then removing the standard rear wheels), and 3) how the adjustable features of the Endeavor are executed. It will be emphasized to subjects that navigation of the ADLC and completion of the additional tasks will involve these features and so they should take advantage of this orientation to get comfortable with using these features on their own. expect the fitting and the introduction to take approximately 30-45 minutes.

After the Endeavor has been fitted for the subject and they report they are comfortable with use of the Endeavor after the orientation, subjects will be introduced to the ADLC to ensure that they understand the tasks that they are going to be asked to complete. Subjects will then be asked to complete ADLC three times with the Endeavor and three times with their own personal wheelchair. When using the Endeavor subjects will use their own personal seat cushion. Each task within a trial should take less than 2 minutes to complete. Between trials, subjects will be allowed to rest as needed and between each three-trial set, subjects will have a required 10-minute rest period. A spotter will follow subjects throughout the course and additional tasks as a safety precaution. After completing each task during the last set of three trials for each chair, subjects will be asked to give "ease of task" ratings for that task. Refer to Appendix B (Task Ratings) for the questionnaires.

**Car Transfer.** Subjects will be asked to transfer into their own vehicle and load the chair. This will be completed once for both chairs (personal w/c and the Endeavor). After completing the transfer with each chair, subjects will be asked to give overall performance ratings and "ease of task" ratings for the car transfer.

**Airplane Boarding Simulation.** This simulation will be completed once using only the Endeavor. Subjects will be asked to give "ease of task" ratings for the airplane boarding simulation.

Finally, the subjects will complete a questionnaire which will focus on overall performance ratings for both chairs and visiting possibly inaccessible places. Appendix B (Overall Performance) for the questionnaires.

Subjects will be instructed to complete the course at a comfortable pace (i.e. freely chosen speed). They will be instructed that in any instance where they feel that a task is inaccessible or they are unable to complete it, they should simply move on to the next task. At all times and for all tasks, the experimenter will be available if a subject reaches an impasse or is unable to complete a task.

Subjects will be videotaped throughout the trials to monitor data collection. The videotapes will be kept indefinitely. Videotapes will be kept in locked file cabinets within the Human Engineering Research Laboratories. Only the Principal Investigators and the associated research staff will have access to the videotapes. The videotapes will not be provided to secondary investigators. A case number will indicate identity on these records. The information linking these code numbers to the corresponding subjects' name will be kept in a separate secure location. If subjects withdraw from the study, their videotape will continue be stored with linkage code to the subject's name. The same procedure will be used with any possible audio recordings. Total testing time for the Activities of Daily Living course testing will be a maximum of 2 ½ hours.

1.0 <u>In Home Trial</u>

At the end of the ADLC testing the subject may choose to participate in the in-home trial. The subject will be given the Endeavor which they used during testing. In this phase, will use a cross-over design in which subjects serve as their own controls. The order in which the wheelchairs will be tested (personal wheelchair versus the Endeavor) will be randomized for each subject. Recall that the Endeavor was already fitted to subjects in the lab component of this research. The subject will be instructed which chair to use as their primary means of mobility for the first two weeks in accordance with the randomization. All subjects will have data recorded for both wheelchairs for the entire four-week in-home trial.

Both wheelchairs will be equipped with a datalogger, which will give information about distance traveled, average speed, and time used. This device is portable, battery-powered, weather-proof, and attaches to the spokes of a wheelchair. This device will not interfere with the subject's daily activities.

In addition to the datalogger, subjects will also be asked to keep a brief, daily, written log of the activities they performed while in the chair (e.g., school/work activities, shopping, exercise, leisure activities, and various in-home activities). Whereas the data-logger will provide purely quantitative data, the written logs will provide more qualitative data. Midway through each two-week time period, subjects will be contacted by phone to ensure that they are keeping their daily logs and to provide an opportunity for subjects to ask questions if any should arise. At the end of each two-week time period, the written logs will be collected and the data from the data-loggers will be downloaded.

Also, at the end of the Endeavor trial-use period, subjects will complete an evaluation questionnaire in which they will have the opportunity to compare the Endeavor to their own personal wheelchair on dimensions related to compactness and maneuverability or "creating access". Refer to Appendix C for the questionnaire.

*Phone Follow-Ups*

After the completion of both two-week trials and the questionnaire, subjects will be allowed to permanently keep the Endeavor. This will allow them to use it as much or as little as they choose in the ensuing weeks. For an additional 8 weeks, will continue to track use of the Endeavor through follow-up phone calls at approximately 4 and 8 weeks. The phone follow-ups will be short structured interviews (less than 10 minutes) in which subjects will be probed about their usage of the Endeavor over the ensuring time period. Refer to the appendix for the follow-up phone questionnaire.

### 3.3 Data Collection and Statistical Considerations

Distributions of all data will be examined, and values that are clearly in error (e.g., out of a scale range) will either be corrected (if the correct response can be discerned) or deleted and treated as missing data. Means, medians, and standard deviations will be calculated on all variables. Hypothesis #1 (favorable overall performance ratings for the Endeavor) will be tested via an examination of the responses to the evaluation questionnaire in Appendix B. Non-parametric analyses (e.g., chi-square analyses) will be used to demonstrate that the distribution of favorable versus unfavorable responses is not what would be expected by chance (i.e., significantly different from a chance distribution). Hypotheses #2 will be examined by comparing "ease of task" ratings for the Endeavor and for subjects' own personal wheelchair on the car transfer. These comparisons will be made using pair t-tests. Hypotheses #3 and #4 (direct comparisons between the Endeavor and subjects' personal wheelchair) will be tested via an examination of the responses to the comparative questionnaire in Appendix C. As was the case for Hypothesis #1, here too will use non-parametric analyses (e.g., chi-square analyses) to examine the whether or not the distribution of "Endeavor preferred over personal chair" responses is what would be expected by chance. In other words, the chi-square analyses will enable us to test for skewed distributions (e.g., toward the favorable side). In each case, a significant chi-square in which the distribution is skewed in the predicted direction will provide evidence in support of these hypotheses.

Hypothesis #5 (no difference in use time during the 2-week trial period) will be examined through paired t-tests comparing the information (i.e., amount of usage) provided by the data-logger for each wheelchair. Finally, Hypothesis #6 (increased use of the Endeavor during the 8-week follow-up period) will be examined using information provided by the phone follow-ups. If the percent-time in the Endeavor exceeds 50% at the end of the 8-week period for the majority of subjects (again a chi-square will be used to demonstrate that this majority would be more than what would be expected by chance), this would support Hypothesis #6. In addition, will also examine trend analyses to explore the possibility of significant linear trends of either increasing or decreasing usage.

There is no prior research testing the Endeavor Wheelchair or comparing it to alternative chairs. As a result, there is little information (e.g., regarding effect sizes) on which to base power analyses. Nevertheless, related work using the Activities of Daily Living Course (e.g., Cooper et al., 2001) and using the data-logger methodology (Arva et al., 2001; Cooper at al., 2002; Spaeth et al., 2000) strongly suggest that will have sufficient statistical power to examine the hypotheses have put forth. This prior research has detected significant differences with samples sizes as low as 10 subjects. To account for possible attrition and to be conservative in our approach, will recruit up to 25 subjects to participate in the present research.

## 4.0 Human Subjects

### 4.1 General Characteristics- Minority Inclusion and Non-Discriminatory Statements

Up to 25 males and females over the age of 18 will be recruited to participate in this research study. All subjects will use manual wheelchairs as their primary means of mobility and have used a manual wheelchair for a minimum of six months prior to participating in the study. The investigators may remove you from this study if you exhibit a poor, injury-prone propulsion style and fail to respond to clinical guidance to correct this. Listed below are the inclusion/exclusion criteria for the study:

<u>Inclusion</u>

1) Use a manual wheelchair as a primary means of mobility.
2) Male and females over the age of 18.
3) The ability to adequately fit in a wheelchair with a 16" seat width.
4) A minimum of 6 months experience using a manual wheelchair as primary means of mobility.
5) Able to transfer independently.
6) Drives own vehicle from vehicle seat.

<u>Exclusion</u>

1) Active pressure sores as reported by subject.
2) History of traumatic upper extremity injury that would prevent you from folding, lifting and storing a manual wheelchair.

The racial, gender, and ethnic characteristics of the proposed subject population reflects the demographics of Pittsburgh and the surrounding area. shall attempt to recruit subjects in respective proportion to these demographics. No exclusion criteria shall be based on race, ethnicity, gender, or HIV status.

**4.2 Recruitment Procedures**

Up to 25 manual wheelchair users will be recruited to participate in the Activities of Daily Living Course portion of this research study. will then ask those participants who complete the ADLC testing, to participate in the In-home phase portion of the study. will recruit subjects through registries developed by the Human Engineering Research Laboratories (HERL) (VA IRB #01185) and the Center for Assistive Technology (CAT) (Pitt IRB #020354). Both of these registries have been approved by their designated institution, the VA IRB and the Pitt IRB, respectively. All subjects in the registries have signed informed consent documents to be contacted for future research studies. A flyer will be provided to registry investigators to send to potential participants according to protocol. In response to the flyer, potential subjects will directly contact the research team if interested in participating.

In addition, participants may be recruited via flyers and advertisements in print media (magazines, newspapers, newsletters) and web-based postings. Flyers may be posted in local rehabilitation facilities, outpatient facilities, and disability organizations. The advertisement will be posted on the Human Engineering Research Laboratories website (www.herlpitt.org). Refer to the appendix for the advertisement/flyer to be used for all recruitment materials listed. No recruitment materials will be used without prior IRB approval. The advertisement instructs potential subjects to contact a Clinical Coordinator at HERL for additional information.

Subjects who contact HERL and express an interest in the study will be read the inclusion/exclusion criteria. Subjects will be informed that they should not answer whether or not they meet any specific criteria or whether they are eligible. Refer to the screening script in the Appendix. Only contact information will be collected from the subject at the time of the call. If the subject is still interested in participating in the study, the subject will be scheduled to obtain informed consent and possible testing. If it found that the subject is not eligible to participate in the study, contact information will be destroyed immediately. After informed consent is obtained, it will be verified and documented whether or not the subject meets inclusion/exclusion criteria for the study.

The principal investigator or one of the co-investigators of this study will administer informed consent. Signed, written informed consent will be obtained prior to the initiation of any study procedures. After the informed consent process, it will be verified and documented whether or not subjects meet the inclusion/exclusion criteria for the study.

**4.3 Risk/Benefit Ratio**

The risks involved in this study include minor muscle fatigue and inconvenience of time. Subjects will be informed that they may take a break and/or discontinue the study at any time. Subjects will not be asked to participate in any tasks that they may not encounter during every day activities at home or in the community. Subjects will have the option to decline to complete a task if they are unable or choose not to.

During the transfers in and out of the subject's wheelchair, there may be a risk for a fall. However, there will be knowledgeable staff spotting the subject during their transfers. Also, as with the use of any wheelchair, there is a risk of tips and falls. To help minimize these risks, research investigators will adjust the Endeavor wheelchair as close as possible to the subject's current wheelchair configuration, the subjects will be encouraged to utilize the anti-tippers provided with the Endeavor wheelchair, subjects will receive an orientation/training on use of the Endeavor, and will be spotted during the ADLC. There is also a risk for subject's skin to be pinched or scraped while folding and unfolding the chair.

Participants may not directly benefit from the testing, but will have the satisfaction of contributing to research, which may lead to an improved mobility device that improves wheelchair accessibility at home, work, and in the community.

**Data and Safety Management Plan**

Any information obtained from this study will be treated as confidential and will be safeguarded in accordance with the HIPAA privacy and security regulations. Research records may be released or disclosed if required by federal law. Records will be coded by assigning a case number and the information linking the case number to the subject's identity will be stored electronically on the Human Engineering Research Laboratories server. Only the principal investigator and lead research staff on the project will have access to this information.

The datalogger records only date and time stamps along with distance traveled information. No identifiable information will be collected on the dataloggers. This information can only be downloaded by personnel at HERL. The information linking the case number to the subject's identity will be stored in a separate location on the secure Human Engineering Research Laboratories server.

Any protected health information (PHI) stored electronically is in compliance with the HIPAA security rule. will collect the participant's name, address, phone number, social security number and e-mail address. Study participants will not be specifically identified in any publication of research results. Paper source documents of the coded research records will be kept in file cabinets within a locked file room within the Human Engineering Research Laboratories. Any records, such as consent forms, that contain direct subject identifiers (e.g., name, social security number) will be stored separately, with a different identification code, in a locked file cabinet within a locked file room within the Human Engineering Research Laboratories. Electronic data will be stored on the HERL server. Access to both the electronic and paper-based files is restricted to the Principal Investigator and the associated research staff working on the project. Each user account for the Human Engineering Research Laboratories network is password protected. Records will be kept for at least 5 years after completion of this study, at which time they may be destroyed.

**Data Safety Monitoring**

A data and safety monitoring plan will be implemented to insure that no changes in the benefit/risk ratio occur during the study and that confidentiality of research data is maintained. Investigators, study personnel, and the clinical coordinators involved in the study will meet quarterly to discuss the study (e.g. study goals, progress, modifications, documentation, recruitment, retention, data analysis, and confidentiality) and addressing any issues or concerns at this time. These meetings are overseen by the Directors of HERL or their designees. Minutes are kept for these meetings and will be on file. Any instances of adverse effects will be reported immediately using the standard forms and/or procedures set forth by the Institutional Review

Board. In addition, clinical coordinators from HERL may periodically review study documentation and/or consent forms to ensure that subject's confidentiality is maintained. Reporting of adverse events will be done as outlined by the VAPHS IRB. A data safety and monitoring report will be sent to the IRB at the time of renewal.

**5.0 Costs and Payments**

**5.1 Research Study Costs**

Subject will incur no direct costs as a result of their participation in this research study.

**5.2 Research Study Payments**

Subjects will be reimbursed $100 for their participation in the research conducted in the Activities of Daily Living Course (ADLC).

In return for their participation in the in-home trial-use period, subjects will be given a choice between either keeping the Endeavor or receiving $200 for their time and effort in completing the study.

The payment (if applicable) will be processed after the activities of daily living testing and the in-home trial and subjects can expect to receive a check within 4-6 weeks through the mail. If the subject is a veteran and has a direct deposit account arranged through the Department of Veterans Affairs, payment will be deposited directly into their account.

**6.0 Appendices**

6.1 Qualifications of Investigators

**Rory Cooper, PhD** received the B.S. and M.Eng. degrees in electrical engineering from California Polytechnic State University, San Luis Obispo in 1985 and 1986, respectively. He received a PhD degree in electrical and computer engineering with a concentration in bioengineering from the University of California at Santa Barbara in 1989. He is chairman and distinguished professor of the Department of Rehabilitation Science and Technology, and professor of Bioengineering and Mechanical Engineering at the University of Pittsburgh. He is also a professor in the Department of Physical Medicine and Rehabilitation within the Department of Orthopedic Surgery at the University of Pittsburgh Medical Center Health System. Dr. Cooper is director of the Pittsburgh VA Rehabilitation Research & Development Center. Dr. Cooper will serve as the principal investigator of this project. Also, Dr. Rory Cooper is a co-inventor of the Endeavor wheelchair and may have a financial interest in this study.

**Michael Boninger, MD** graduated from the Ohio State University with both a medical doctorate and a degree in Mechanical Engineering. He specialized in Physical Medicine and Rehabilitation at the University of Michigan Medical Center, where he served as Chief Resident. After his residency program, he completed an NIDRR Fellowship in Assistive Technology at the University of Pittsburgh. Dr. Boninger is Professor and Research Director in the Department of Physical Medicine and Rehabilitation and University of Pittsburgh. He also holds appointments in the Department of Rehabilitation Science and Technology and the Department of Bioengineering. He is also the Executive Director of the UPMC Health System's Center for Assistive Technology. Dr. Boninger will serve as a co-investigator of this project.

**Annmarie Kelleher, MS, OTR/L** received her BA degree in Occupational Therapy from the University of Pittsburgh in June 2001 and her MS degree in Rehabilitation Science and Technology in 2004. Ms. Kelleher is currently working as a Clinical Coordinator at the Human Engineering Research Laboratories and as a Wheelchair Seating Clinician at the UPMC Center for Assistive Technology. Knowledgeable in the proper administration of clinical studies involving human subjects, she is experienced in coordinating complex research projects.

**Rosemarie Cooper, MPT** received the BA degree with concentration in International Business from California State University, Sacramento in 1994. She received the MPT degree in Physical Therapy from University of Pittsburgh in 1998. She is currently working as a Clinical Coordinator at the Human Engineering Research Laboratories and as a Wheelchair Seating Clinician at the UPMC Center for Assistive Technology. Also, Rosemarie Cooper, is the wife of the principal investigator and may have a financial interest in this study.

**Jeremy Puhlman, BSE** received his Bachelor of Science degree in Biomedical Engineering from the University of Pittsburgh in April 2003. Mr. Puhlman is currently working as a Research Engineer at the Human Engineering Research Laboratories. His main duty is to assist graduate students and faculty with the technical aspects of their projects. When he is not assisting graduate students, you will find him designing and building prototypes for projects of his own. Knowledgeable in machining technology such as: EDM, Stereo Lithography, CNC mill, and CNC lathe.

**Emily Teodorski, BS** is a Clinical Coordinator at the Human Engineering Research Laboratories. She received her BS in Psychology from the University of Pittsburgh in 2003 and is currently pursuing a Master of Social Work degree. Previous research experience at the University of Pittsburgh has included work on studies of cardiovascular issues. At HERL, she is responsible for assisting in the development of clinical protocols, monitoring and participating in study implementation, subject recruitment, and data management.

**Ana Souza, MS, PT** is a research assistant at the Human Engineering Research Laboratories, Department of Rehabilitation Science and Technology, University of Pittsburgh. She received her Bachelor degree in Physical Therapy from the Federal University of Pernambuco-UFPE-Brazil, in August 1999. She received her master degree at the Rehabilitation Science and Technology department from University of Pittsburgh, PA in April 2007 and is currently working in the research project Mobility Aids for Persons with Multiple Sclerosis at the Human Engineering Research Laboratories.

**Joseph Olson, BS** received his Bachelors of Science in mechanical Engineering at Michigan State University with a Bio-Medical option in 2004. He is a Masters student at the University of Pittsburgh in the department of Rehabilitation Science and Technology. He has experience with engineering design and will be the lead student on this project.

**Eun-Kyoung Hong, BS,** received her BS (2006) degree in rehabilitation technology from Korea Nazarene University, Cheon-an, South Korea. Ms. Hong is certificated a special education teacher with a background in rehabilitation technology. Ms. Hong is currently working in the Human Engineering Research Laboratories as a Research Associate and a full-time graduate student in the department of Rehabilitation Science and Technology at the University of Pittsburgh.

**Jon Pearlman, PhD** received his BS in Mechanical Engineering from the University of California at Berkeley, his M.Sc. in Mechanical Engineering from Cornell University with a focus in Biomechanics, and his PhD in Rehabilitation Science and Technology from the University of Pittsburgh School of Health and Rehabilitation Science. He currently works as a faculty researcher at the Human Engineering Research Laboratories. His research focus is on understanding and improving assistive technology transfer to developing nations.

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## A.2 INTAKE QUESTIONNAIRE

**Date:** ____/____/____

| **Demographics** |
| --- |

Age:________

**Gender**: · Male · Female

**Veteran**: · Yes · No

**Ethnic Origin**: · African American/Black
· Asian American
· Caucasian/White
· Hispanic
· Other (please specify): ______________________

**Injury Level or Diagnosis: ______________________**

**Date of Injury or Date of Diagnosis**: ____/____/____

**Travel - Ground Transportation**

**1. What kind of vehicle(s) do you primarily transport your wheelchair in?**
- Car
- Sports Utility Vehicle (SUV)
- Mini van
- Full size van
- Pickup truck
- Other (please specify): ______________________

**2. How do you transport your wheelchair in your vehicle?**
- Independently lift into vehicle
- Require assistance of others to lift into vehicle
- Use power ramp or lift
- Other (please specify): ______________________

**Note: If your wheelchair is not physically loaded into a vehicle, please skip to Page 4; Travel-Airfare section.**

**3. When loading your wheelchair into your vehicle, which parts of your wheelchair do you remove or fold? Please use the following code below:**

**F** for **Fold**

**DF** if it is **Foldable** but you **Do Not Fold** it

**R** for **Remove**

**DR** if it is **<u>Removable</u>** but you **<u>D</u>o Not <u>R</u>emove** it

**DT** if you **<u>D</u>o Not <u>T</u>ravel** with it

**N/A** if your chair **<u>does not have</u>** that component

**X** if your chair **<u>has</u>** the component and you **<u>can not</u>** remove or fold it

a. Frame ____ b. Cushion ____ c. Wheels ____ d. Side Guards ____

e. Leg Rests ____ f. Footplates ____ g. Armrests ____ h. Backrest ____

i. Backpacks or Wheelchair Bags ____

Additional Comments:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________

____________________________________________________________________

**4. List where in your vehicle you store your chair and chair parts.**
Use the lower case letters (a, b, c … i) that corresponds to component from above (question 3)

Trunk or other rear storage area: ____ ____ ____ ____ ____ ____ ____ ____ ____

Front passenger seat: ____ ____ ____ ____ ____ ____ ____ ____ ____

Back seat: ____ ____ ____ ____ ____ ____ ____ ____ ____

Other (specify): ____ ____ ____ ____ ____ ____ ____ ____ ____

Additional Comments:

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________________________

________________________________________________________

**5. On average, how many times <u>per day</u> do you load your w/c in and out of your vehicle?**
**Note: Please count each way as one.**

- 2 times or less
- 3-6 times
- 7-10 times
- 11 times or more

**6. Do you sit on your wheelchair cushion while in a vehicle?**

- Yes
- No
- Sometimes (please explain): __________________________________________

**7. Explain how it affects your routine if:**

You **have** a passenger with you: ______________________________________________

_______________________________________________________________________

_________________________________________________________________

You **are** a passenger: _____________________________________________________

_______________________________________________________________________

_________________________________________________________________

You are driving an unfamiliar vehicle (e.g. rental car, etc.) ____________________________

_______________________________________________________________________

_________________________________________________________________

You are transporting something large: ___________________________________________

_______________________________________________________________________

_________________________________________________________________

You are going on a long trip: ________________________________________________

_______________________________________________________________________

_________________________________________________________________

Additional Comments/Description:_____________________________________________

_______________________________________________________________________

_______________________________________________________________________

_______________________________________________________________________

_______________________________________________________________________

_______________________________________________________________________

___________________________________________________

## Travel- Airfare

**1. How much do the following things NEGATIVELY affect your desire to fly?**

| | No effect | | | | | | | | | Large effect |
|---|---|---|---|---|---|---|---|---|---|---|
| Going through security | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Thick carpeting in airports | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Airline personnel attitude | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Boarding staff | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Boarding process | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Using aisle chairs | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Lack of help | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Possibility of lost luggage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Carrying your luggage | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Possibility of lost wheelchair | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Possibly damaging Wheelchair | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Possibility of missing your connection | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Risk of pressure sores | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Risk of bowel or bladder issues while traveling | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Transportation to and from airport | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Possibility of plane crash | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Other (explain) ____________________ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

**2. How many times did you travel by airplane in the last year? __________**

If you **do not** travel by air, you have completed this questionnaire. Thank you!

---

**3. How do you currently get to your seat inside the airplane?**
- In your personal wheelchair
- In an aisle chair
- Other (explain)______________________________________________________________

______________________________________________________________________________

**4. Where do you typically sit? (Check all that apply)**
- First-class
- Coach
- Bulkhead
- Not bulkhead
- Along aisle
- Chair with flip up armrest
- Window or middle seat

Why? _________________________________________________________________________

______________________________________________________________________________

**5. Do you transfer independently into the airplane seat?**
- Yes
- No
- Sometimes (explain)__________________________________________________________

______________________________________________________________________________

**~Please continue to next page~**

**6. When preparing your wheelchair to be stowed in an airplane, which parts of your wheelchair do you remove or fold? Answer:**

**F** for **Fold**

**DF** if it is **Foldable** but you **Do Not Fold** it

**R** for **Remove**

**DR** if it is **Removable** but you **Do Not Remove** it

**DT** if you **Do Not Travel** with it

**N/A** if your chair **does not have** that component

**X** if your chair **has** the component and you **can not** remove or fold it

a. Frame ____ b. Cushion ____ c. Wheels ____ d. Side Guards ____

e. Leg Rests ____ f. Footplates ____ g. Armrests ____ h. Backrest ____

i. Backpacks or Wheelchair Bags ____

Additional Comments: ________________________________________________________________

________________________________________________________________________________

________________________________________________________________________________

______________________________________________________________________

**7. List where in the airplane you store your chair and chair parts.**
Use the lower case letter that corresponds to component from question 6 (a,b,c ..k).
And the additional components:
j. Luggage
k. Carry-on luggage

Gate check: ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Sent through to destination: ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Overhead bin: ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Designated wheelchair closet: ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Other airplane cabin closet: ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Under or behind airplane seat: ____ ____ ____ ____ ____ ____ ____ ____ ____ ___

Other location (specify): ______________________ Components stored there: ____ ____ ____

______________________ Components stored there: ____ ____ ____

Additional Comments:

________________________________________________________________________________

________________________________________________________________________________

**8. How do you protect your chair from being damaged or losing parts?**

**9. Do you gate check your chair?**

- Yes
- No

**10. Do you sit on your cushion during the flight?**

- Yes
- No

**11. During the flight, how do you move around the cabin?**

**12. Can you use the airplane's bathroom?**

- Yes
- No

**13. How do you transport your other luggage?**

**14. Explain how it affects your flying routine if:**

You are flying straight through:

You have a long layover:

You have a short layover:

You are flying on a small plane:

You are flying with a companion: ______________________________________________________
______________________________________________________________________________
____________________________________________________________________

Additional Comments/Description: ________________________________________________
______________________________________________________________________________
______________________________________________________________________________
_________________________________________________________________

☺ **Thank you for completing the questionnaire!**

## Wheelchair

**1. What is the make and model of your PRIMARY manual wheelchair?**

Make: ______________________________ Model: ____________________________

**2. What is the make and model of your BACK-UP manual wheelchair?** ☐ **Not Applicable**

Make: ______________________________ Model: ____________________________

**3. Primary Wheelchair Dimensions and Set up**

**Seat depth (in): _____ Seat width (in): _____**

**Cushion type:**
**Make: ______________________________ Model: ____________________________**

**Backrest type:**
**Make: ______________________________ Model: ____________________________**

**Backrest height (in): _____ Seat to back angle (degrees): _____**

**Seat plane angle (degrees): _____ Footrest to seat distance (in): _____**

**Axle position (cm) (horizontal distance from acromion to axle): _____**

**Seat height (cm) (vertical distance from acromion to axle): _____**

## Vehicle

**1. What is the make and model of your vehicle?**

Make: ______________________________ Model: ____________________________

Year: ____________________________

## A.3 TASK RATINGS QUESTIONNAIRE

### *Activities of Daily Living Course*

**Endeavor**

***For each statement below please check the response that best indicates your opinion.***

**Ramp**

1) How would you rate the level of difficulty in going down the ramp?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in going up the ramp?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Curb**

1) How would you rate the level of difficulty in descending the curb?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Carpet**

1) How would you rate the level of difficulty propelling across the carpet?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Bathroom**

1) How would you rate the level of difficulty in maneuvering up to the sink?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in maneuvering up to the toilet?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Comments:**

## *Activities of Daily Living Course*

**Personal wheelchair**

***For each statement below please check the response that best indicates your opinion.***

**Ramp**

1) How would you rate the level of difficulty in going down the ramp?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in going up the ramp?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Curb**

1) How would you rate the level of difficulty in descending the curb?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Carpet**

1) How would you rate the level of difficulty propelling across the carpet?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Bathroom**

1) How would you rate the level of difficulty in maneuvering up to the sink?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in maneuvering up to the toilet?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Comments:**

## *Car Transfer*

**Endeavor**

***For each statement below please check the response that best indicates your opinion***

1) How would you rate the level of difficulty in transferring into the car seat?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in stowing the wheelchair in the car?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Comments:**

**Personal wheelchair**

1) How would you rate the level of difficulty in transferring into the car seat?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in stowing the wheelchair in the car?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Comments:**

### *Airplane Boarding*

1) How would you rate the level of difficulty deploying the airplane wheels?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in removing the large wheels?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in propelling yourself down the aisle?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

2) How would you rate the level of difficulty in transferring to the airline seat?

Very Difficult ☐ Difficult ☐ Moderate ☐ Easy ☐ Very Easy ☐

**Comments:**

## A.4 OVERALL QUESTIONAIRE

# Appendix B: Final Questionnaire

## *Overall Performance Ratings*

### Endeavor

1) How would you rate the overall ***comfort*** of the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

2) How would you rate the overall ***feel of the ride*** of the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

3) How would you rate the ***support*** provided by the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

4) How would you rate the ***stability*** provided by the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

5) How would you rate the ***ease of propelling*** the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

6) How would you rate the ***ease of maneuvering*** with the Endeavor?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

7) How would you rate the ***ease of transferring*** with your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

Based on your experience with the Endeavor on the course you just completed, what were the things you ***liked most*** about the Endeavor? Please explain your answer.

Based on your experience with the Endeavor on the course you just completed, what were the things you liked ***least*** about the Endeavor? Please explain your answer.

**Personal Wheelchair**

1) How would you rate the overall ***comfort*** of your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

2) How would you rate the overall ***feel of the ride*** of your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

3) How would you rate the ***support*** provided by your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

4) How would you rate the ***stability*** provided by your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

5) How would you rate the ***ease of propelling*** your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

6) How would you rate the ***ease of maneuvering*** with your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

7) How would you rate the ***ease of transferring*** with your personal wheelchair?

Very Poor ☐ Poor ☐ Moderate ☐ Good ☐ Very Good ☐

Based on your experience with your personal wheelchair on the course you just completed, what were the things you ***liked most*** about your personal wheelchair? Please explain your answer.

Based on your experience with your personal wheelchair on the course you just completed, what were the things you liked ***least*** about your personal wheelchair? Please explain your answer.

**Thank you very much for your time!!**

## A.5 DAILY LOG

**Daily Log- Please complete one form for each day.**

**Date:** ____/____/____ ____ Personal Wheelchair ____ Endeavor

Number of Times you used transportation ________

Amount of Time away from home: ______hours ______minutes

----------------------------------

**Transportation Utilized** (write number of times utilized, count separately both directions)

____ ACCESS ____ Plane

____ Public Bus ____ Other: (please specify)

____ Own vehicle (modified van/vehicle)

____ Car

____ loaded wheelchair independently ____ loaded wheelchair with assistance

**Places Visited** (check all that apply)

____ Grocery store ____ Movie Theatre

____ Mall/Department store ____ Family/Friends' Residence

____ Restaurant ____ Church

____ Work (Paid or Volunteer) ____ School

____ Doctor's office

____ Other: (specify) ______________________ ______________________

______________________ ______________________

**Obstacles encountered** First column, check all that apply. Other three columns, write number of times you had difficulties with an obstacle in the corresponding space. If you easily traversed a particular type of obstacle you do not need to record it in the last three columns.

| Type of Obstacle Obstacle | | Traversed Independently But With Difficulty | Required Assistance | Avoided |
|---|---|---|---|---|
| ____ | Up ramp | _______ | ________ | ________ |
| ____ | Down ramp | _______ | ________ | ________ |
| ____ | Grass | _______ | ________ | ________ |
| ____ | Gravel | _______ | ________ | ________ |
| ____ | Curb cuts | _______ | ________ | ________ |
| ____ | Small curb | _______ | ________ | ________ |
| ____ | Door threshold | _______ | ________ | ________ |
| ____ | Carpet | _______ | ________ | ________ |
| ____ | Other | _______ | ________ | ________ |

1. Was today a typical day?
   _____ Yes
   _____ No -----→ _____ more active than usual
   _____ less active than usual

2. Were there any reasons that prevented you from traveling outside the home today?
   ____ No
   ____ Yes ----→ Please check all that apply:
   _____ weather (raining, snowing, heat)
   _____ was not feeling well
   _____ problems with transportation (automobile problems, etc)
   _____ problems with wheelchair

3. Did you have any technical problems with the chair you were using?
   ____ No
   ____ Yes --→
   ____ Not Applicable

Please explain: ________________________________________

________________________________________

________________________________________

________________________________________

*Endeavor users only*

4. Did you fold your chair today?
_____ No
_____ Yes --→

| Describe Situation: |
|---|
| ________________________________________ |
| ________________________________________ |
| ________________________________________ |

5. Did you use the airplane wheels?
_____ No
_____ Yes --→

| Describe Situation: |
|---|
| ________________________________________ |
| ________________________________________ |
| ________________________________________ |

**Thank you for completing the Daily Logs!**

## A.6 WHEELCHAIR COMPARISON AFTER TWO-WEEK TRIAL-USE PERIOD

***For each statement below please check the response that best indicates your opinion.***

**Compactness**
1) In comparison to your own personal wheelchair, how would you rate the **overall compactness** of the Endeavor when it is in its **folded position**?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

2) In comparison to your own personal wheelchair, how would you rate the **ease of loading** the Endeavor in your vehicle?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

3) In comparison to your own personal wheelchair, how would you rate the **ease of unloading** the Endeavor from your vehicle?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

4) In comparison to your own personal wheelchair, how would you rate the **ease of traveling** with the Endeavor?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

**Creating Access and Maneuverability**

5) In comparison to your own personal wheelchair, how would you rate the **overall maneuverability** of the Endeavor?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

6) In comparison to your own personal wheelchair, how would you rate the ability of the Endeavor to enable you to **access narrow doorways and confined spaces**?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

7) In comparison to your own personal wheelchair, how would you rate the **maneuverability** of the Endeavor in **confined spaces**?

Much Worse ☐ Worse ☐ Equal ☐ Better ☐ Much Better ☐

8) In comparison to your own personal wheelchair, how would you rate the Endeavor in ease of **ascending or descending stairs**?

Much Worse ☐ Worse ☐ The Same ☐ Better ☐ Much Better ☐

9) Would your own personal wheelchair be better or worse than it is now if it had "swing-down access wheels" like the Endeavor?

Much Worse ☐ Worse ☐ The Same ☐ Better ☐ Much Better ☐

**Thank you very much for your time!!**

## A.7 FOLLOW-UP PHONE QUESTIONNAIRE

____4 weeks; specify date: ___________
____8 weeks; specify date: ___________

1) Of your total time using a wheelchair in the last four weeks, what is your best estimate of the percent of time you were using the Endeavor? _____.   Your own personal chair? _____.
Other_____  (Please Explain Your Answer)

2) If you are using the Endeavor *more* than you used to at the beginning of the trial period, please explain why you think this is the case.  Be specific in your answer.

3) If you are using the Endeavor *less* than you used to at the beginning of the trial period, please explain why you think this is the case.  Be specific in your answer.

# APPENDIX B

# REFERENCE MATERIAL

## B.1 THE AIR CARIERS ACCESS ACT

This section describes the legislation governing the interaction between air carriers and persons with mobility impairments. These documents describe the environment in which the Endeavor must function. These laws also can tell us in what situations the chair may have difficulties.

The Air Carrier Access Act (ACAA) of 1986 is the piece of legislation which regulates every aspect of how persons with disabilities and air carriers interact[14]. This means that the requirements for policy as well as the accessibility of the physical environment can be found here. It states that: In providing air transportation, an air carrier, including any foreign air carrier, may not discriminate against an otherwise qualified individual on the following grounds:

- The individual has a physical or mental impairment that substantially limits one or more major life activities.
- The individual has a record of such an impairment.
- The individual is regarded as having such an impairment.

An otherwise qualified individual is someone: "who is willing to comply with reasonable requests of airline personnel, or, if not, is accompanied by a responsible adult passenger who can ensure that requests are complied with." This law was patterned off of civil rights legislation. To understand the necessity of such a law and its method of enforcement it is helpful to look at the legislation leading up to this act.

In the federal aviation act passed in 1958 there were two passages that were used to uphold the rights of disabled people and the accessibility of facilities [15].

- 404(a) (1), air carriers must "provide safe and adequate service, equipment, and facilities
- 404(b) air carriers must not "subject any particular person.., to any unjust discrimination or any undue or unreasonable prejudice or disadvantage in any respect whatsoever."

First the Civil Aeronautics Board (CAB) and later the Department of Transportation (DOT) enforced under 404a.

Section 504 of the Rehabilitation Act of 1973 states: "No otherwise qualified individual with handicaps in the United States, as defined in Section 706(8) of this Title, shall, solely by reason of her or his handicap, be excluded from the participation in, be denied the benefits, or be subjected to discrimination under any program or activity receiving federal financial assistance." This act has been used to enforce the rights of persons with disabilities and improve accessibility of all government buildings and hiring processes [16]. It also is applicable to anything that directly receives federal funding such as universities. The CAB only used this act to regulate air services which were directly subsidized by the government such as mail services and passenger flights to small communities.

In 1978 as a way of decreasing costs and improving services the airline deregulation act was passed. In its passing, section 404b of the Federal Aviation Act was repealed. This meant that now there was no method of privately suing air carriers for discrimination.

In 1986 the Paralyzed Veterans of America sued the Department of Transportation [17]. They felt that because all airlines received federal aid in the form of facilities and air traffic control services the CAB should use the rehabilitation act to regulate all air carriers. The case went to the Supreme Court which ruled against the PVA because even though the air carriers received indirect benefits from government funds they were not directly accepting funds from the government. This ruling showed the pressing need of civil rights legislation addressing air travel for persons with disabilities. That same year Congress passed the Air Carrier Access Act[1].

This act was drafted to address three other issues along with guaranteeing rights for disabled passengers. The first was to prevent potential undue financial burdens to airlines; second to provide consistency for travelers with disabilities and third to address struggle between nondiscrimination and safety concerns passengers. The effects of these goals can be seen both in the enforcement as well as the "undue financial or administrative burden" to the airlines provision in the document. When persons have tried to sue privately for violations of this law no punitive damages have ever been won and no attorney's fees are covered. This greatly deters private lawsuits under this law.

The Department of Transportation is solely responsible for enforcing the ACAA. It penalizes an air carrier $10,000 for each infraction (this is up from $1100). After investigation, almost all infractions are ultimately dismissed without any fines being levied. When airline is found to be at fault, many times the fine can be lowered by purchasing wheelchairs or improving infrastructure.

The complaint process works like this: as described in the ACAA each airline has its own complaint resolution officer (CRO) who must be available at the airport or able to be contacted toll-free at anytime a day. If the CRO feels that a violation has been committed they will contact the Department of Transportation. Next, the DOT will investigate the possible infraction. If the infraction is verified then the airline will be fined [18].

In 2006 air carriers submitted data on 13,766 complaints from disabled passengers to the Department of Transportation. Because of the lack of investigative resources the DOT was not able to verify if these complaints were actual infractions of the ACAA [19]. Lack of funding has made enforcement of the law as outlined in the document (assessing for each infraction) impossible[18].

Besides detailing enforcement, the ACAA also defines what is required of the air carriers for architectural accessibility and boarding processes. This gives us the ability to start to define the needs of an aircraft boarding system.

### B.1.1 What the ACCA says about aircraft accessibility

- Aircraft with 30 or more passenger seats shall have movable aisle armrests on at least one-half of the aisle seats.
- Aircraft with 100 or more passenger seats shall have priority space in the cabin designated for storage of at least one of folding wheelchair.
- Aircraft with more than one aisle with bathrooms shall have one bathroom that is accessible with the use of the aircraft's onboard wheelchair.

- The onboard wheelchair will be supplied if there is advanced notice.
- Aircraft's shall comply with the requirements to the extent not inconsistent with structural, weight and balance, operational and interior configuration limitations.
- Any replacement or refurbishing shall not reduce existing accessibility to level below that specified.

In practice, this usually means that all aisle armrests in coach besides the bulkhead seats are movable. First-class seats rarely ever have movable armrests. It also means that a cabin can be refurbished in a way that it is less accessible than it was before so long as it still meets the level of accessibility outlined in this document. This is why it is possible for aisles, seats and legroom to continue to get smaller.

### B.1.2 What the ACCA says about boarding policies

- Carriers will provide assistance enplaning and deplaning as well as be responsible for assistance in making flight connections and transportation between gates.
- Assistance will include the use of services personnel, ground wheelchairs, boarding wheelchairs, onboard wheelchairs and ramps or mechanical lifts.
- When available, boarding will be by level entry loading bridges or accessible passenger lounges. In no case will carrier personnel directly carry a person when helping board or deplane.
- The carrier will provide assistance in loading and retrieving carry-on items and mobility aids stored onboard.

- Access to passenger planes with less than 19 seats may be provided by any means that the passenger consents to besides directly carrying a person.
- Accessible boarding (level entry) for large aircraft shall be provided.
- Assistive devices including wheelchairs will not count toward a limit on carry on items.
- The carrier shall permit storage of wheelchairs or components of wheelchairs in overhead compartments and under seats.
- To be allowed to use the reserved space for a wheelchair of the passenger must pre-board.
- Compensation for a lost, damaged or destroyed wheelchair will be the purchase price of the wheelchair.

There are a number of rules ensuring that appropriate seating is provided allowing even the reassigning of seats of other passengers. To take advantage of this the passenger must arrive at least one hour prior to departure.

## B.2 AIRPLANE BOARDING CHAIRS

Airline boarding chairs are the traditional means of enplaning for persons with mobility related impairments. The following look at the guidelines fills in details about the current process as well as gives requirements for these boarding chairs. By comparing the Endeavor to the guidelines it can be evaluated on its ability to function as a universal airline boarding chair.

The Architectural and Transportation Barriers Compliance Board started the process of writing guidelines for airplane boarding chairs in 1984. The first draft was distributed in May of

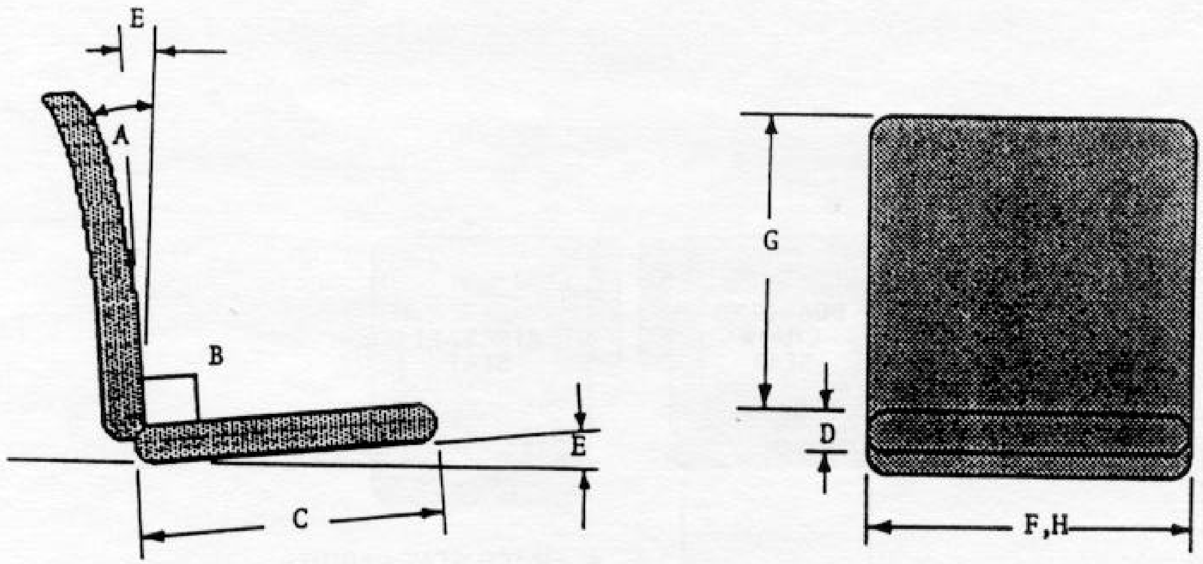
1986. It provides recommendations to manufacturers of airplane boarding chairs on proper design requirements. None of the requirements were made to be legally enforceable and seem to have been in some cases ignored by manufacturers. The following passage reflects the goals of this document[20].

"It should be the goal of boarding chair designers and manufacturers to develop boarding chairs that minimize the potential for injury and increase overall comfort without sacrificing ease of use and low-cost." Section 5 paragraph 1

This is a list of some of the important requirements.

### B.2.1 Boarding chair characteristics as outlined by the Aircraft Boarding Guidelines

- The boarding chair should be able to accommodate the physical body dimensions from a 5 percentile female to 95 percentile male. When practical, it should be adjustable providing it does not sacrifice chair and passenger stability.




| | DIMENSION | VALUE |
|---|---|---|
| A | Backrest, Optimum Angle (degrees) | 8-10 |
| B | Backrest to Seat Angle (degrees) | 90 |
| C | Seat depth (inches) | 16 |
| D | Seat Thickness (inches) | 2 (min) |
| E | Seat Angle (degrees) | 5 |
| F | Backrest width (inches) | 15 |
| G | Backrest height (inches) | 25 |
| H | Seat width (inches) | 15 |

**Figure 20.** Seat dimensions from *Guidelines for Aircraft Boarding Chairs*

- The maximum body weight to chair should be able to accommodate the weight of a 99 percentile male (241 pounds) with a safety factor of 3 (723 pounds).
- Boarding chairs should be designed for passengers with maximum disability (person with quadriplegia involving complete loss of control in all four appendages and weakened head control). They should also consider the needs of persons with

- The restraints on the chair must be able to support the torso, hips, knees, and feet. They should prevent a passenger from falling out of the boarding chair under all circumstances.
- The chair should also be designed with consideration of the attendant's strength and size characteristics. As with the passenger, the fifth percentile female and 95th percentile male should be considered as the ranges. Because of the strength requirements of transporting and transferring a passenger from the boarding chair (with a lifting transfer) are greater than that of a fifth percentile female, multiple attendants or relatively strong attendants are necessary.
- The chair must be able to withstand all impact and static strength tests defined in the ANSI/RESNA wheelchair standards.

### B.2.2 Physical environment as outlined by the Aircraft Boarding Guidelines

The terminal, being a federally funded facility, should be up to federal guidelines as to wheelchair accessibility. This being true, wheelchair access in this area should be of limited concern. If the boarding chair is designed to be used inside of the terminal, it should allow for independent mobility for those who have the means.

The sky bridge may be narrower than hallways within the terminal but should easily still provide wheelchair access. The overall incline of a movable sky bridge can be up to 7 1/2 degrees while the connecting ramps between sections may be up to 13 degrees. The wheel locks should be able to keep the chair stationery on these inclines faced either uphill or down with a 100kg ISO dummy.

Wheelchair users usually travel down the sky bridge in a regular size wheelchair and are transferred into the boarding chair at its base. There is a threshold gap between the end of the sky bridge and airplane. The attendants must be able to negotiate the threshold with the boarding chair safely.

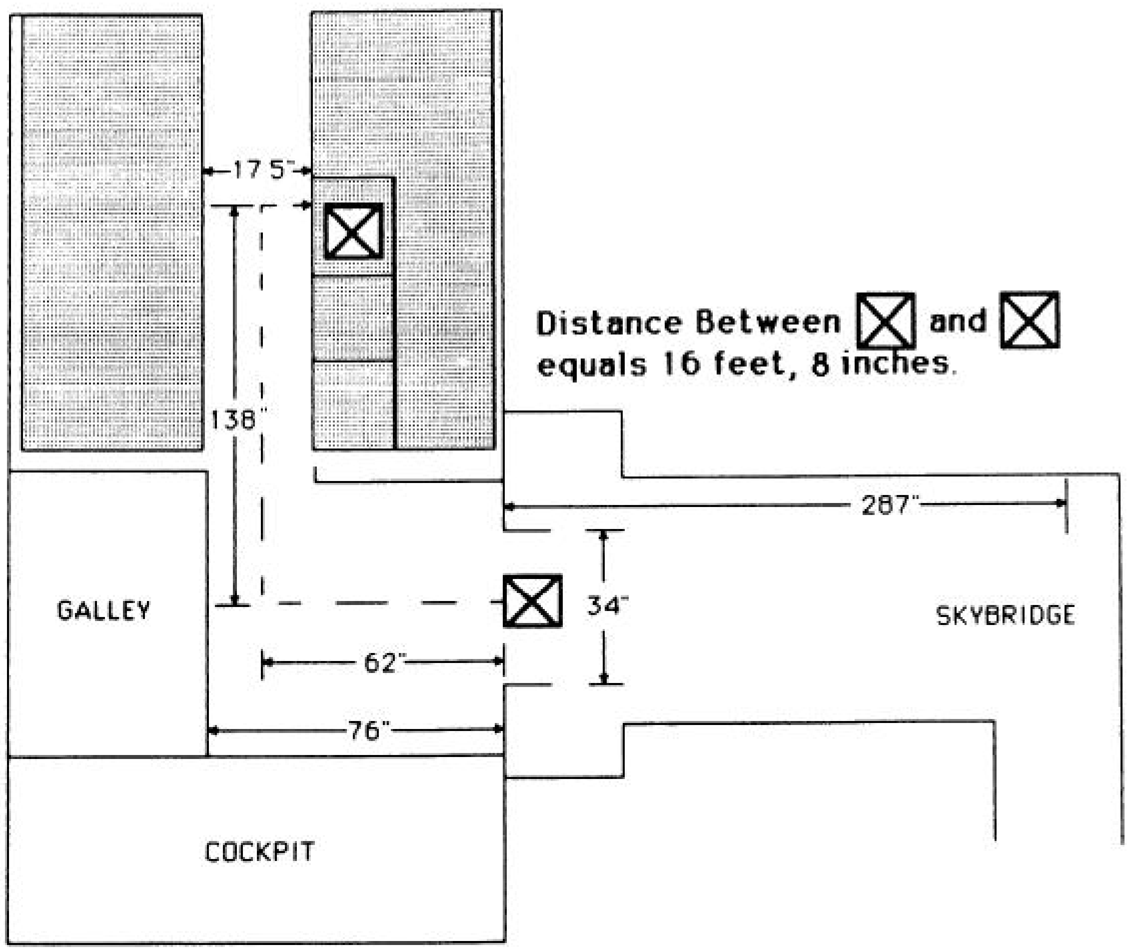



**Figure 21.** Typical layout of a jet aircraft from *Guidelines for Aircraft Boarding Chairs*

Access within an airplane is dependent on cabin configuration. On small aircraft this is particularly apparent. The doorway and entranceway are usually wide enough the permit boarding chair access but the narrow aisle way may pose a problem. In general, boarding chairs are designed to be operated and maneuvered in the environment shown in Figure 21. In 1991, a group from Ohio State University found that aisles very between 16.5 and 19 inches wide [21]. Attendants must be able to safely transfer a passenger to their seat in this confined area. The chair should also be designed with rounded edges to protect the passenger, attendant and physical environment.

Smaller regional airports and commuter aircraft may use stairs as a method of boarding the plane. This is also true for larger aircraft at high traffic times. The boarding chair must be safe to use on stairways.

# APPENDIX C

# THE STATE OF AIRPLANE BOARDING TECHNOLOGIES, ALTERNATIVE FOLDING WHEELCHAIRS AND AXLE ADJUSTABILITY

This appendix will focus on the most common designs and most innovative designs in the areas of mobility equipment that are directly related to the Endeavor folding wheelchair (aisle chair and airplane boarding technologies, folding wheelchair design and adjustability).

## C.1 AISLE CHAIRS AND AIRPLANE BOARDING TECHNOLOGIES

### C.1.1 Aircraft boarding chairs

An aircraft boarding chair is simply a wheeled chair narrow enough to fit down the aisle of a particular aircraft. Figure 22 shows the typical geometry of an airplane boarding chair. It is simple, durable, uncomfortable, ill fitting and impossible to propel independently. Disappointingly, the patent for this particular device was filed in 2005 more than 17 years after the access boards guidelines were published[22].

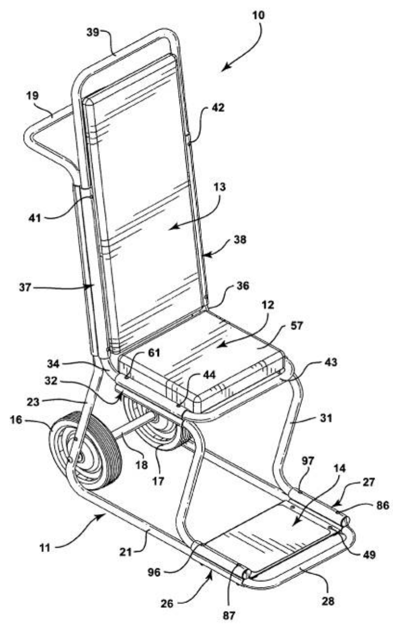



**Figure 22** A typical boarding wheelchair design

In the early to mid-1980s, two of the major US manufacturers of airplanes patented aircraft boarding chairs (Figure 23 and Figure 24). These chairs were able to be folded for easy storage. The patent granted to Boeing was also able to be configured as an in-flight seat for airline attendants. Even though these chairs were developed prior to the guidelines, they (especially the Boeing chair) are examples of the best designed boarding chairs to date[23, 24].

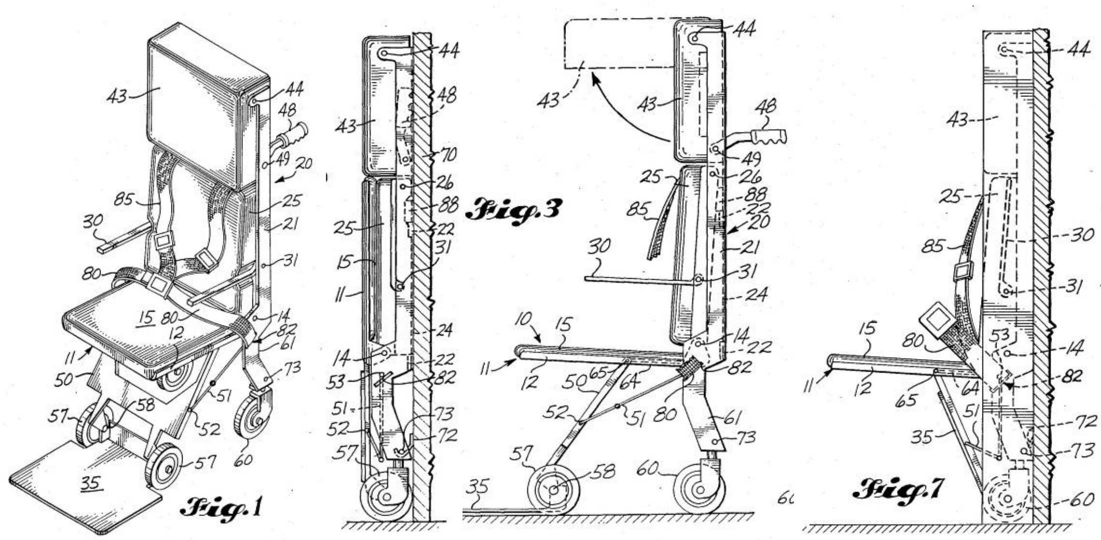



**Figure 23** The Boeing folding aisle chair

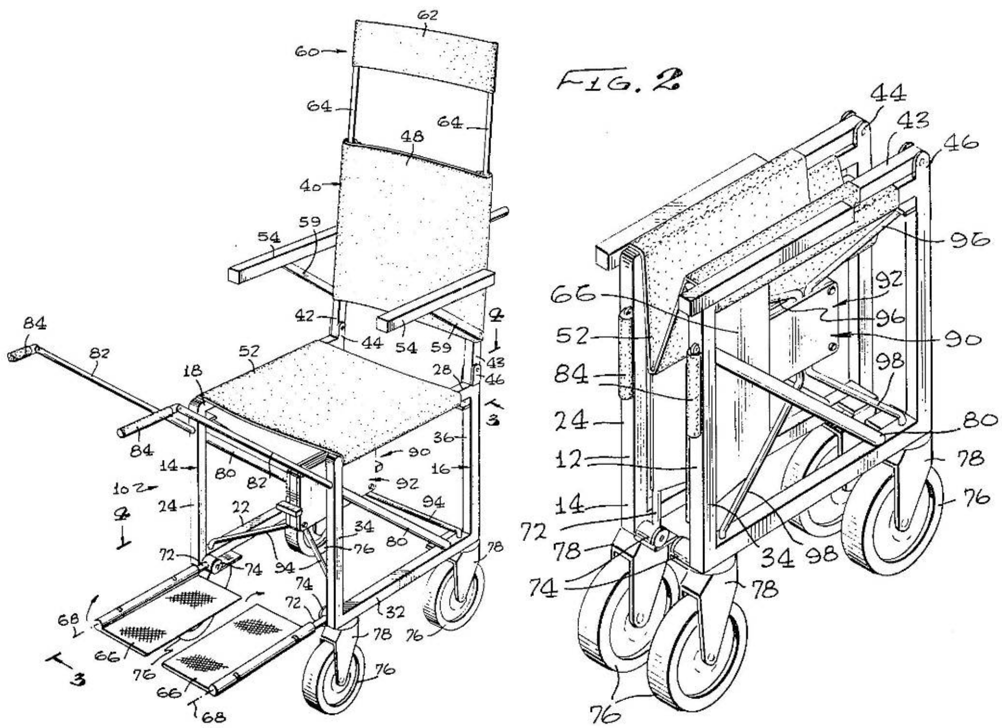



**Figure 24** The Lockheed folding aisle chair

### C.1.2 Airplane wheels

The idea of removing the large push wheels from a manual wheelchair to decrease the width has existed for a long time. Two different patents were filed in 1984 which were essentially systems such as this. One of them was an adapted E&J style folding wheelchair (Figure 26) [25]while the other was a cantilever style frame on which the rear axle tube was removed (Figure 25) [26]. Ironically, both used highly complicated release assemblies for the rear wheels even though a quick release system similar to modern ones was designed in 1982 (Figure 27) [25].

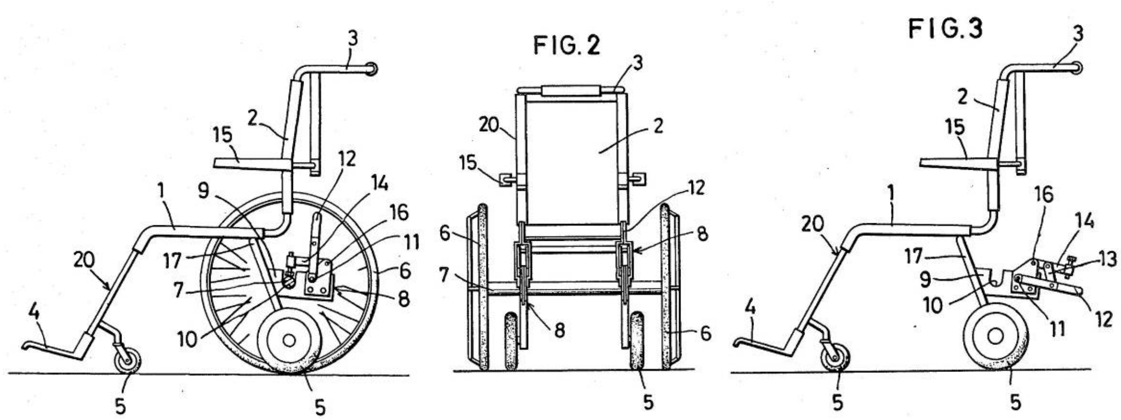



**Figure 25.** Ichikawa removable axle tube transport chair

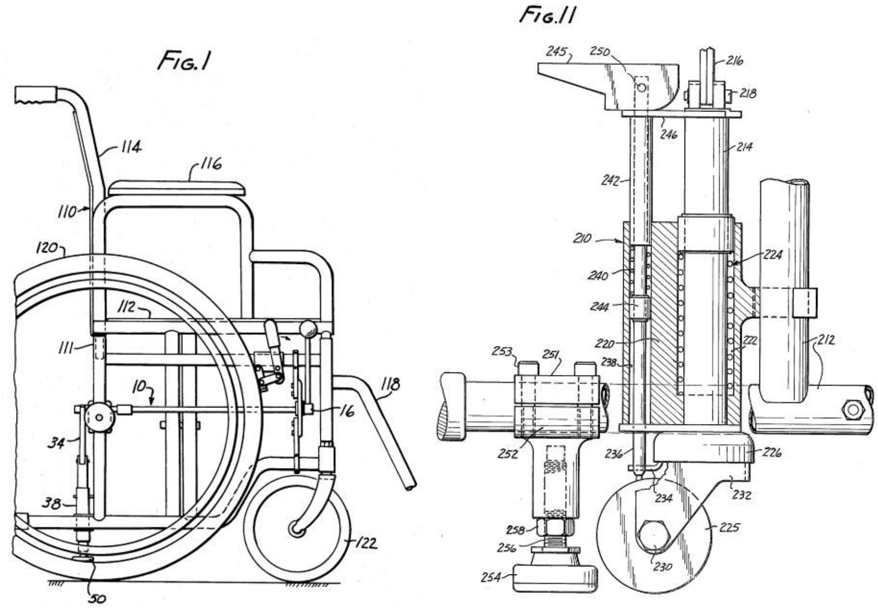



**Figure 26.** Castello removable wheel apparatus

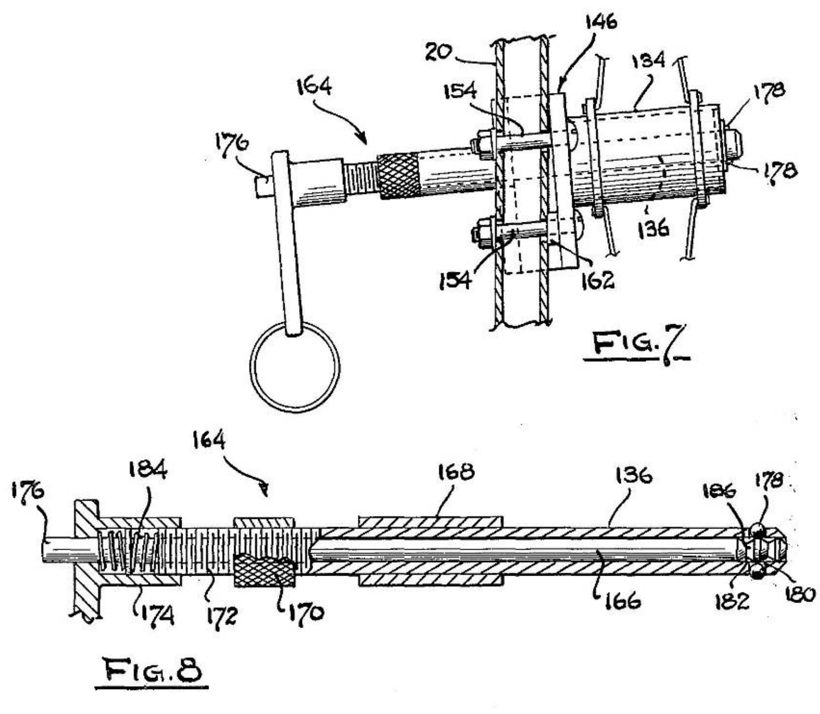



**Figure 27.** Quick release as designed by Minnebraker

The wheelchair guidelines may have accidentally killed the self-propelled boarding chair. Even though in section 3.1(k) it says "Boarding chairs designed to be used in the airport terminal should provide manual independent mobility for passengers who have manual independent mobility in their own wheelchairs."; it also repeatedly states that the chairs should be designed to be compatible with the needs of the most disabled user defined as a person with complete paralysis of all four limbs and partial paralysis of the neck. It seems that in an effort to provide adequate and consistent service to the most disabled user, independent mobility has been neglected[20]. Whatever the true reason, the result has been almost no development of chairs capable of independent mobility. Instead, passengers use depot style wheelchairs within the airport and transfer into a boarding chair just prior to getting on the plane.

### C.1.3 Non aisle chair boarding technologies

There've been a few attempts at creating boarding systems which do not use a traditional boarding chair. One of these is a removable airplane seat on wheels (Figure 28). A passenger would transfer onto the seat in the jetway they would be then rolled into place and secured. This solution would most likely be more dignified, comfortable and safe than the current method. The patent was not awarded to any airplane or airplane seating manufacturer. Unsurprisingly, there are no examples of the system in use today. Implementing this would require cooperation with the airlines, plane manufacturers and seating manufacturers specifically, the removable airline seat must be narrow enough to fit down the aisle [27].

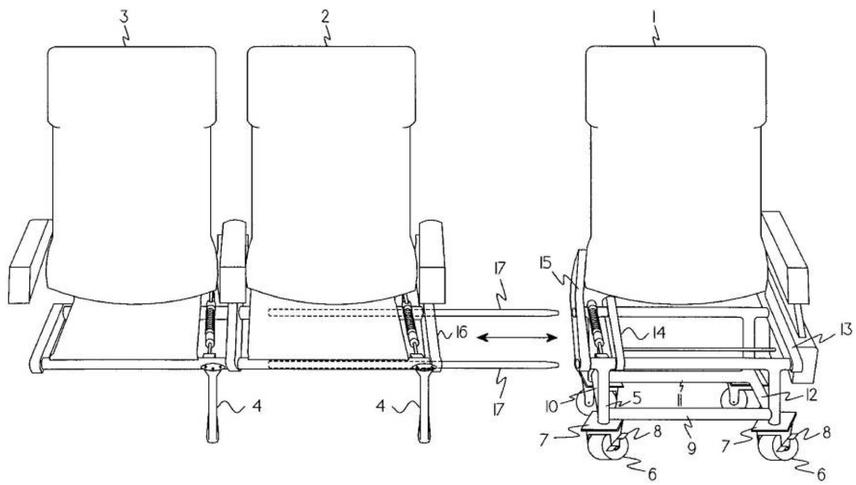


**Figure 28.** The Krebs Easy Transport Seat

Another solution is a wheeled gantry (Figure 29). It uses a sling system similar to a Hoyer lift. This type of system would make it easier for airline attendants to help transfer. Wider passengers than those who can currently use boarding chairs could use the system because it could raise them above the height of the armrests. Likely it would be more expensive than a traditional boarding chair. This patent also was never issued to an airline. It will probably never be seen[28].

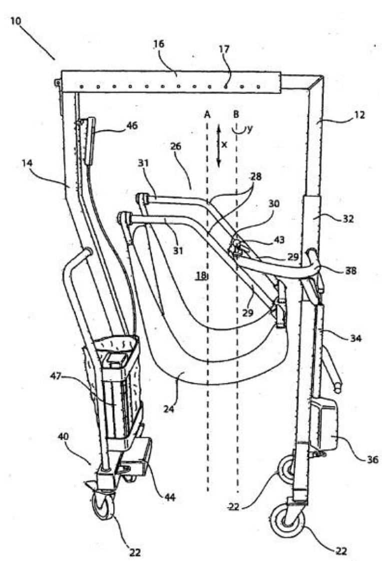


**Figure 29.** The Hay Apparatus for Transferring a Person from a Wheelchair to a Fixed Seat

## C.2 FOLDING CHAIRS TECHNOLOGIES

The most common type of folding wheelchair was originally designed by Herbert Everest and Harry Jennings and was patented in 1937 (Figure 30). This chair folded by the means an X-shaped cross brace. The casters are located at the back of the chair instead of the front. None of the wheels were tall enough for independent propulsion using a push rim so the patent also included a chain based drive system to power the front wheels. They also mentioned that the frame was very flexible which allowed all four wheels to maintain contact with the ground. This was probably due to the flexibility of the cross brace design. To properly support the top of the folding cross brace two tubes supporting the seat sling were made to slide up the parallel vertical armrest tubes. If you look at the Everest and Jennings "Tracer Transport Wheelchair" you will see a living dinosaur. Overlooking the swing away a leg rests and the reversed caster location this chair could have came directly from 1937[29]. There have been many improvements in cross brace designs to increase durability, allow for greater seat width and increase rigidity.

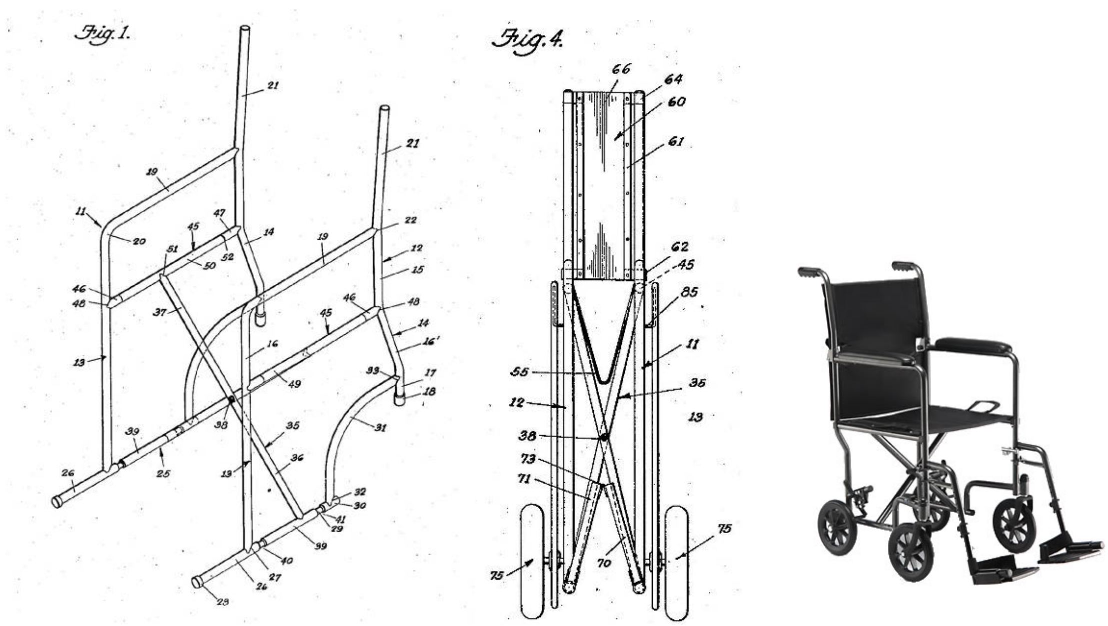



**Figure 30.** The Everest and Jennings 1937 patent drawings and the Tracer Transport Wheelchair

There are many other possible methods of folding chairs besides the cross brace. To decrease the storage demands resulting from the large push wheels most of these chairs are attendant propelled. Some of these are based on a pair of locking pivoted assemblies forming the two sides of the chair which are connected by either folding or unfolding cross members[30]. There are also a surprising number of chairs that are based on folding canvas lawn chairs.

From now on the focus will only be on current or past commercially available every day wheelchairs designed for self propulsion which do not use a lateral folding cross brace.

### C.2.1 Box frame style folding wheelchairs

#### Quickie revolution

The most successful nontraditional folding wheelchair to date is the Quickie "Revolution". All of the folding takes place in the lateral plane (Figure 31). The frame is a four bar linkage. When in the unfolded position two of the four links are nearly collinear- locking the linkage. It is further secured with a spring pin. This linkage is unlocked when the chair is unweighted by pulling on a string releasing the spring pins. It also uses a folding back rest in which splash guards perform an important role in the rearwards rigidity. Because of limitations in the geometry, if the back rest did not fold, it would not allow the linkage to completely fold and the back rest would the would not fold flat against the seat pan Mounting places for armrests are also included [31]. After extended use, joints tend to bind. Some common complaints about this chair are weight and pinch points.

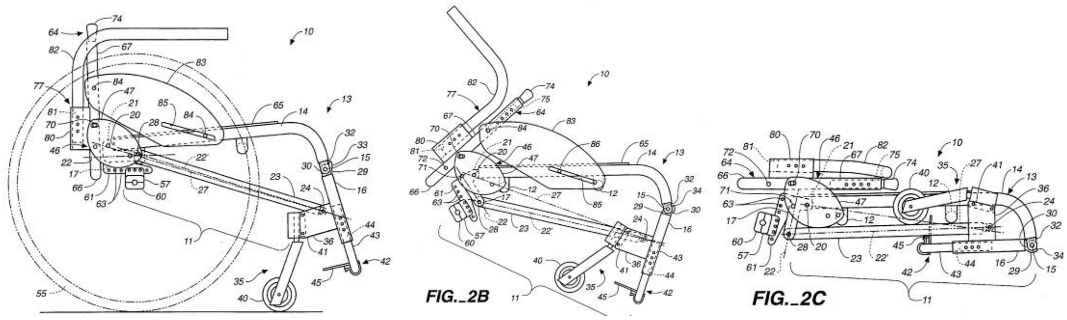



**Figure 31.** Williamson's Vertical Folding Wheelchair Frame -- the *Quickie Revolution*

**Otto Bock switch**

This is a discontinued German folding wheelchair (Figure 32). It was only intended to be collapsed to it's minimum size infrequently. First a user would fold down the back rest and remove the front casters. Then they could release the spring pins connecting the rear section of the box frame and fold it even tighter by crossing the frame linkage.

**Figure 32.** The OttoBock *Switch*

### Click New Reality

This chair was developed in the Netherlands and is currently available in Europe. It does have an American patent. The frame is based on a four bar linkage which is nearly a parallelogram (Figure 33). Unfolded it looks very similar to a traditional box frame chair. The first link is the origin of the back rest and contains the axle adjustment slots. The second link forms the seat. The third link makes up the front bars and is the origin of the footrest and casters. The fourth link connects the first and third links and is nearly parallel to the seat. In the patent, mechanical stops prevent the chair from over opening and locks into the open position with a spring-loaded pin. The patent also includes small wheels that could be used with the large wheels removed and a method of increasing the rearward adjustability of the axle[32]. These options are not present in the commercial product [33].

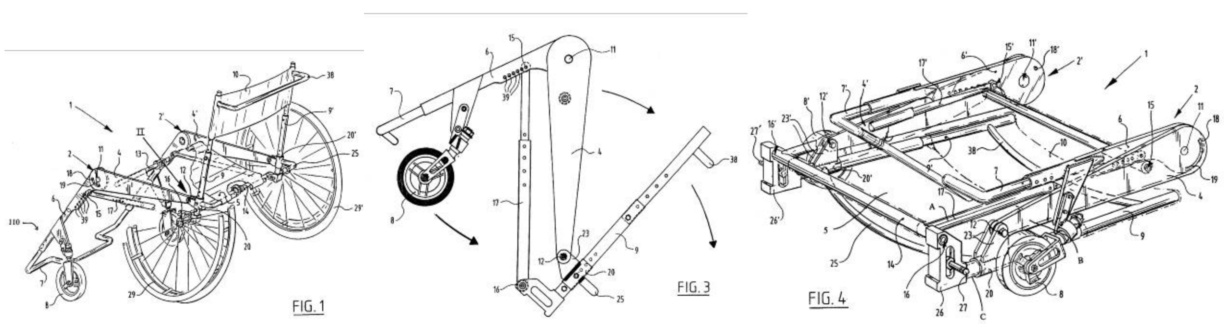



**Figure 33.** The Ordelman Collapsible Wheelchair -- *Click New Reality*

**Figure 34.** The commercial version of the *Click New Reality*

## Reha-Technik Pro-Activ Jet

This German chair folds similarly to the click new reality (Figure 35). The joint on the front link which includes the footrests and casters has a single pivot point behind the center post footrest. It also has a folding footrest [34].

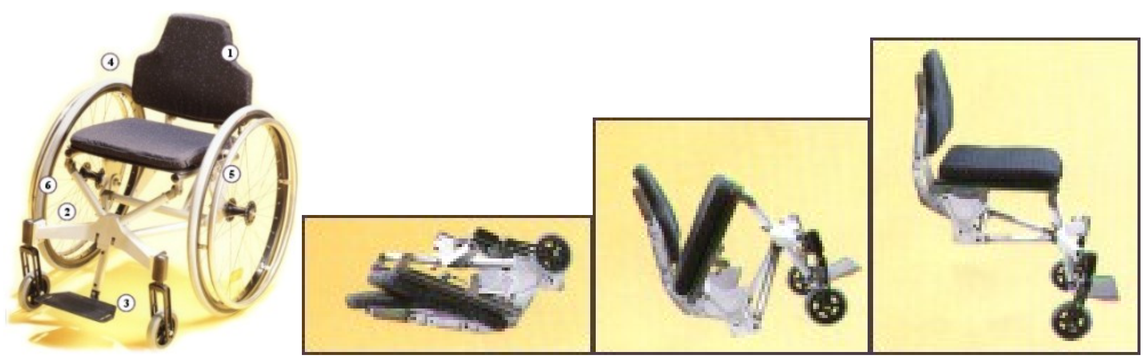


**Figure 35.** Reha-Technik *Pro-Activ Jet*

### Da Vinci wheelchairs – Leggera Super Compatta

This chair also folds almost identically to the click new reality (Figure 36). The only difference is that this chair uses a solid axle tube stead of an axle plate. The locking mechanism is not immediately obvious from the pictures. The axle is not connected to the same link that the backrest is[35].

**Figure 36.** Da Vinci wheelchairs – *Leggera Super Compatta*

## C.2.2 Cantilever style folding chairs

### Mobility Vision Activator

This Irish chair unfolded looks identical to a cantilever manual wheelchair (Figure 37). Beneath the bend between the sling seat and footrest the frame is able to fold backwards such that the front of the frame is parallel to the seat. This joint is locked with the use of two spring pins. To further minimize the package, a folding back rest is used [36].

**Figure 37.** The Mobility Vision *Activator*

## Da Vinci wheelchairs – Leggera Compact

This British chair also looks identical to a cantilever manual wheelchair (Figure 38). Instead of folding, above the bend at the "knee" of the chair the leg rests disconnect from the seat. The back rest also folds[37].

**Figure 38.** Da Vinci wheelchairs – *Leggera Compact*

## C.3 ADVANCEMENTS IN AXLE POSITION ADJUSTABILITY

Until the advent of wheelchair sports in the late 1970s, axle position was not adjustable on manual wheelchairs [38]. Most chairs had either a non adjustable front or rear push wheel design. The axle position of rear wheel designs were located near the backrest cane making them very rearward stable but difficult to push. In 1980 Minnebraker filed the patent for his famous rigid wheelchair with adjustable axle position [39]. The axle slot method of adjustment was filed by Invacare in 1982 (Figure 39) [40].

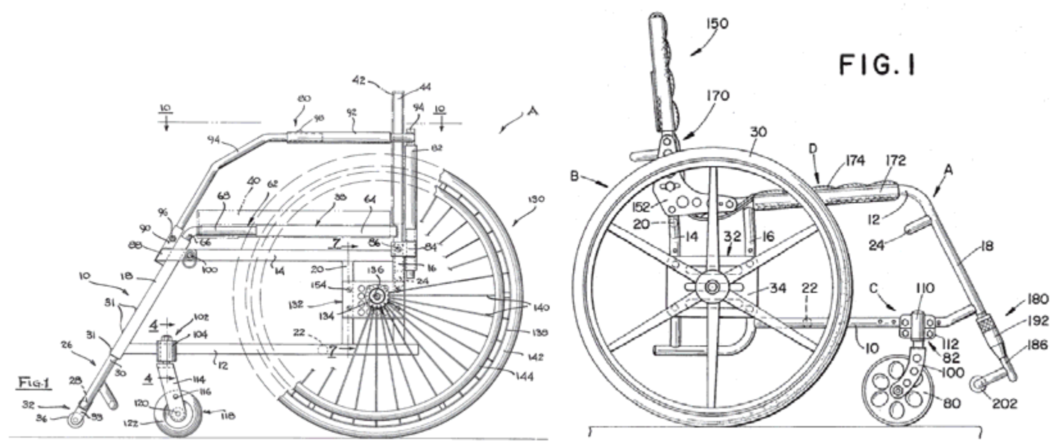



**Figure 39.** The 1980 Minnebraker and 1982 Invacare adjustable axle position wheelchairs

The major drawback of these wheelchair designs were that when a user would adjust the vertical axle position, they would also need to readjust the caster orientation to normal. This would also be necessary when adding or subtracting camber. This problem was mostly alleviated by the development of chairs with pivot points at the front of the seat pan allowing a user to adjust the rear seat height independently from the push wheel and caster orientation (Figure 40) [41].

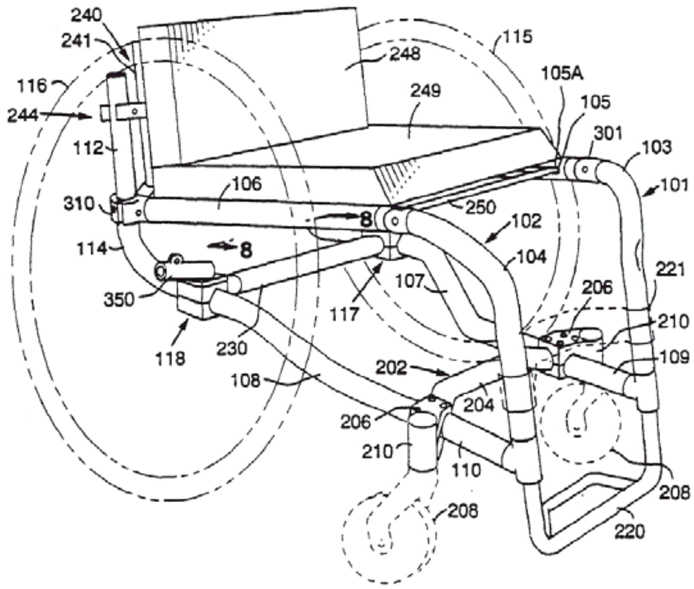



**Figure 40.** The 1991 Medical Composites adjustable wheelchair

Adjusting seat dump was still inconvenient because the backrest angle was at least partially dependent on the angle of the seat pan. So, when a user would attempt to increase their seat dump, they would also need to decrease the angle between the backrest and seat to maintain the same global backrest angle. Sunrise medical was the first to solve this problem. In 1997 they filed a patent in which the backrest was still attached to the seat but the backrest angle was dependent on two attachment points to a vertical bar behind the backrest (Figure 41) [10]. In 2000 Invacare solved this problem in a slightly different method. They attached the backrest angle adjustment assembly to a telescoping tube protruding from the rear vertical frame member [11].

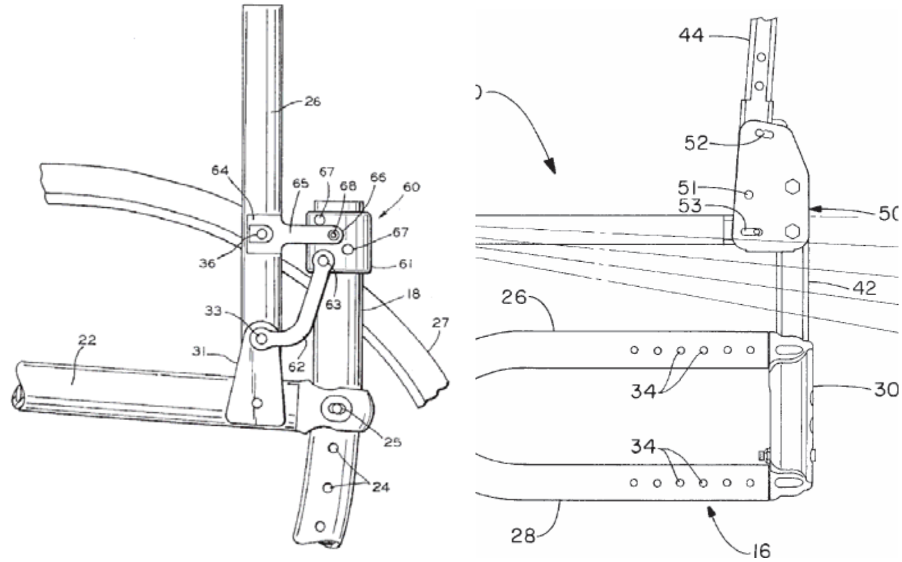



**Figure 41.** The Sunrise Medical and Invacare independent backrest adjustment designs

## APPENDIX D

## THE EVOLUTION OF THE ENDEAVOR FOLDING WHEELCHAIR

This section will describe the history of the folding wheelchair up until this point. It is divided into two sections. The first section describes the evolution of the chair from the initial conceptual drawing through the testing of the Endeavor folding wheelchair produced by Three Rivers. Much of this was covered more thoroughly in Cory Blauch's Masters thesis [5]. This may be the first time that all of this information has appeared in the same place especially the documentation of the early development.

### D.1 THE ORIGINAL SKETCH, JANUARY 30, 2000

The original wheelchair was designed as a diamond shaped truss formed by two triangles. The link E. contained a suspension element similar to those found on mountain bikes (Figure 42). The footplate was to be made to flip up to minimize size when folding.

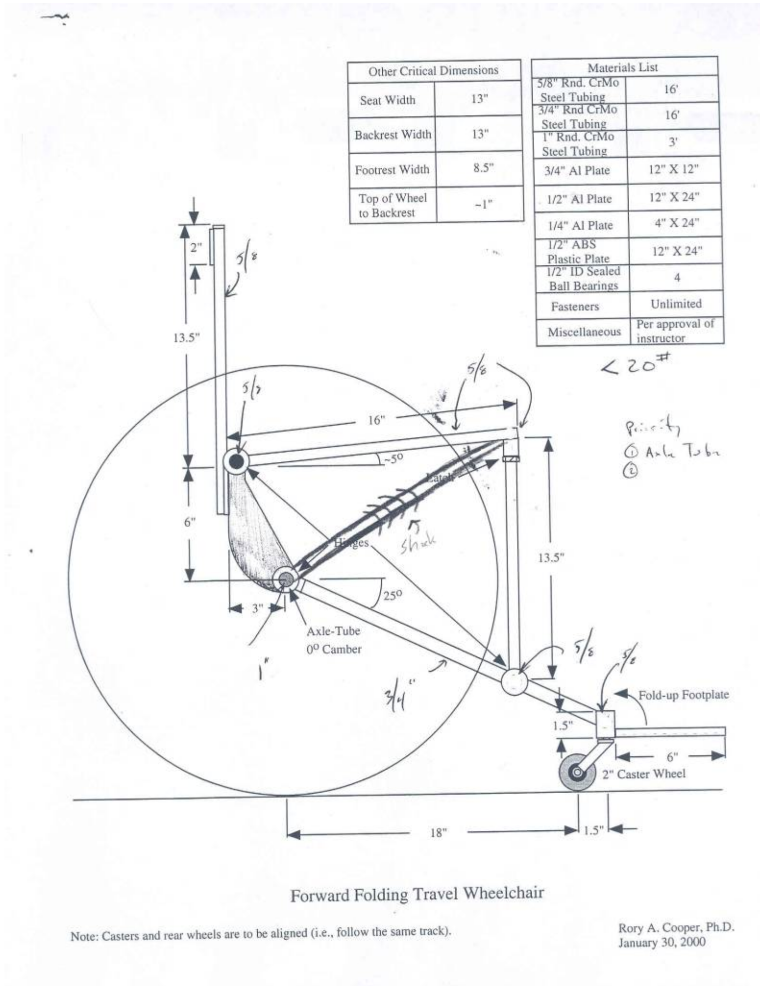



**Figure 42.** The first sketch

## D.2 FIRST PROTOTYPE

April 21, 2000. In the first prototype the carrying handles at the front of the seat pan appear (Figure 43). These were added as a means for keeping Dr. Cooper's knees from splaying outwards. Another departure from the original sketch is the change in location of node 3. In the original drawing, this was located part way down the tubes which supported the casters and footrest on link C. On the prototype, node 3 is located on the horizontal bar between the front casters. To accommodate the 19 1/2 inch rear axle to front caster barrel length while maintaining a 90° angle at node 2, the disconnects for link B were moved forward down the carrying handles. This prototype included what at first look seems to be nonfunctional suspension element (because the connection between link one and link two contains no degrees of freedom, link one and link two should be considered as one link -- after this combination, there are three links and 3 degrees of freedom making a structure -- adding a suspension element to an already fully defined structure should have no effect). After talking with Dr. Cooper, he said that the suspension element was actually too soft. The real world functionality of the suspension element could be contributed to frame flexibility and possibly slop in the front disconnects. It was never fatigue tested.


**Figure 43.** First prototype

## D.3 SECOND NON-ADJUSTABLE PROTOTYPE

This prototype was built by Dr. Cooper and the students of his SHRS 1709 class (Figure 44). Dr. Cooper actually traveled with this chair around the world. It is no longer suspended. This was because the suspension element was too heavy and soft. The vertical requirement for the link B. tubes has been dispensed with. Link B extends from the front edge of the seat pan down to the horizontal bars connecting the caster barrels on link C. To accommodate the proper leg length, the bar which connected the two front casters has been cut and rejoined with a U-shaped extension. The disconnect for link E. at node 2 is still a welded joint. It features folding hard splash guards and a folding footplate. It also marks the first appearance of the "airplane wheels" and the "pinch disconnect" at the node 2 connection of link B. Instead of traditional caster forks the newly developed "oblique angle suspension castor fork" was used. An OEM luggage rack was installed on the front down tubes[5, 42].

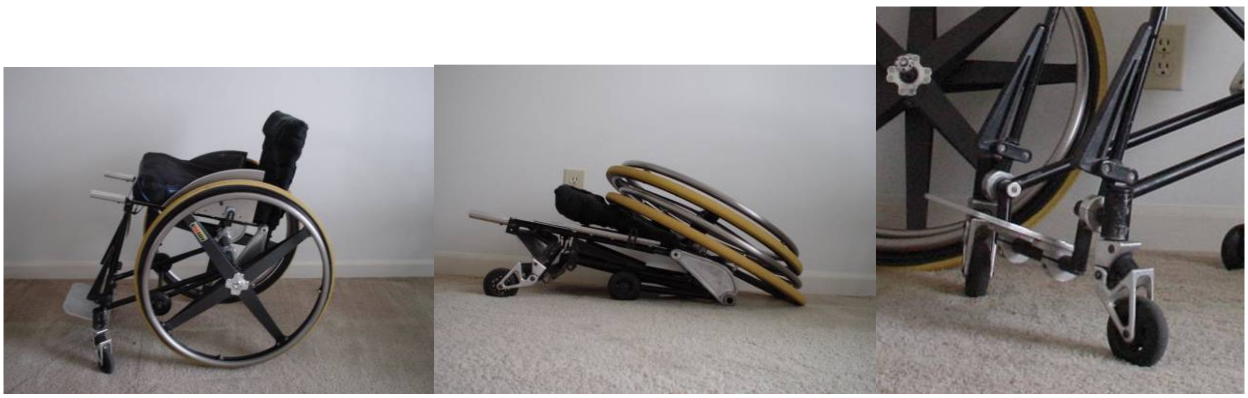


**Figure 44.** First functional prototype

## D.4 THE ADJUSTABLE PROTOTYPE

This is the second functional prototype (Figure 46). It was only tested by a wheelchair user for a short period of time. It is a 16 inch wide chair made to be adjustable to a range of axle positions and floor to seat heights. This chair went through all standards testing. It also used the "oblique angle caster fork". This is very important to note because the suspension would have helped increase the durability of the chair during double drum and curb drop testing. Because the angle between Link E (the middle tube) and Link A (the seat pan) changes with varying lengths of a link D (changing rear floor to seat height) the node 2 connection of Link E can no longer be welded. For this reason the welded connection was turned into a pivot joint. Originally, link C. (the bottom frame) was similar to the rigid prototype. The side frame tube was directly connected to a perpendicular tube which was mounted to the caster housing tube. Between 5550 and 7600 (of 200,000) cycles into the double drum testing, the torsional moment on the perpendicular tube caused by the caster wheels hitting the double drum slats twisted the caster housing [43]. The welds did not fail but the perpendicular tube was permanently deformed to a point that the chair was no longer operable. To increase the rigidity of the frame at this point, the frame geometry was changed so that the side frame tube connected directly to the back of the caster housing and the footrest support tube was attached to the front inside edge of the caster housing tube. This frame geometry change eliminated the original location of node 3. This joint was moved to the bar supporting the footplate. To allow for the tube bends to get the footplate low enough, while maintaining the same attachment points of link B. at node 2, the distance between the two caster housing tubes needed to be increased (Figure 45) [5].

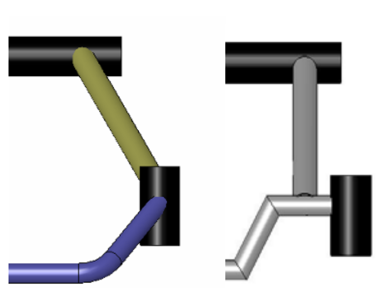


**Figure 45.** redesigned vs. original frame geometry

**Figure 46.** Adjustable chair

One of the somewhat unique features of this version is the concept behind its adjustability. It was designed such that, fore and aft axle position, seat dump and backrest angle could all be adjusted independently in a global coordinate system. This is a departure from most chairs in the independence of the global backrest angle from seat dump. In all future versions, this adjustability concept was used.

# APPENDIX E

## PROPOSED MODIFICATIONS AND SPECIFICATIONS FOR FUTURE CHAIRS BASED ON OBSERVATIONS AND CLINICALLY ENCOUNTERED ISSUES.

The following sections will describe issues, options and probable design improvements for future models. The format will be similar to that of the take-home phase issue section. First, safety issues will be discussed along with fitting and comfort. These are the most important parts of making a safe and usable everyday chair. The next part will describe usability issues especially focusing on important options for future models. The last section will describe things that should be done to increase the ease of folding.

### E.1 SAFETY

***Sharp edges.*** One of the most serious complaints about this generation of the Endeavor folding wheelchair was the multiple sharp edges. During the in lab phase one user cut their foot on the foot plate. In the take-home phase two users commented about the sharp edges on the foot plate and one of these documented being cut multiple times during the two week trial. Also, during the mock trial our able-bodied test pilot received multiple bruises on the back of her calf from the thin front edge of the seat pan.  One of the users solved this problem by wrapping the front edge of the seat pan with a piece of rubber tubing cut down the middle.

Neglecting the sharp edges on the chair was a substantial oversight.  One of the main duties as lead student was to make sure the device was safe for users prior to testing.  With all of the reoccurring incidents as well as the investigators clinical and personal knowledge about the dangers of stress concentrating narrow areas, prior to testing these issues should have been addressed.

Nearly all of the parts on this chair were designed to be made using wire EDM.  This tool can efficiently make prismatic parts.  It functions similar to a cheese cutter which can accurately cut profiles in stock.  The finished product has very sharp edges.  This problem could have been avoided by either heavily tumbling the parts prior to final finishing or chamfering all of edges using a secondary CNC milling program.  If the edges were too thin (such as on the edge of the seat pan) they should have been padded.

For the next version all edges that easily come into contact with a user should be blunted or padded.  It would also be useful to do the same for any sharp edges that may come in contact with the environment.  During the airplane simulation the sharp edges of the axle receivers were constantly getting stuck on the seats and along the small wall.  This made the chair more difficult to maneuver down the aisle as well as scraped up the simulation.

***Rearward instability due to compression of gas spring.***  The addition of the gas spring was originally intended to distribute impact loads over a greater distance and period of time which minimized forces on the middle bar of the seat pan.  Implementing this solution had unintended consequences.  First, the spring that was chosen was inappropriate because it has 2 inches of travel.  To protect the joint from impact forces much less travel is adequate (probably about a quarter of an inch). In anticipation of testing to determine the correct amount of pressure the springs needed to function properly, each of the springs were purchased with a release valve. During assembly some of the release valves may have been pushed making the spring weaker than expected. This variation may have been due to variability coming from the factory or from slow leaking between purchase and installation. The soft spring affected the chairs like this: because the air spring was weak, the weight of a users torso could push the backrest backwards, as the backrest angle widened, the hips and torso moved backwards in respect to the rear axle changing the center of mass, once the center of mass shifted enough to unweight the front casters the gas spring would extend lifting the user's legs upwards effectively throwing the user backwards (Figure 47). Two of our participants had major problems with this. One of them fell over while still doing the in lab phase of testing. The other nearly fell over multiple times during the in-home phase. This was remedied by replacing the weak gas spring and by moving the rear axle rearwards by putting an axle insertion point in the plug in the middle of the frame's axle tube. The suspension was easily activated while descending curbs which led to possibly lower forces on the user but it still sacrificed stability.

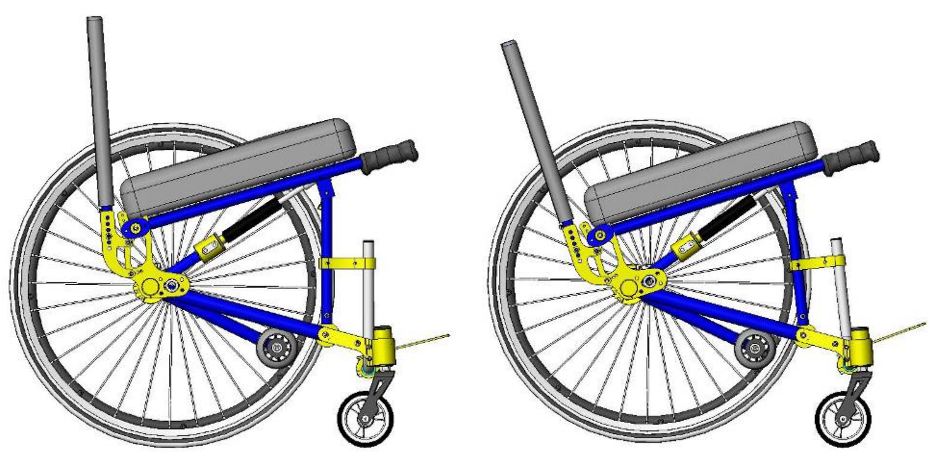


**Figure 47.** Geometry change with spring compression

This spring assembly should be redesigned, tested and sent out as an upgrade to the current version of the chair. The requirements for this assembly would be to distribute impact loading from the 100 kg test dummy during the double drum cycle over the distance of a quarter inch without bottoming out. By using a coil spring or elastomer system with much less travel, it would be cheaper, lighter, safer and more robust. Possibly through more global redesign for future generations, the spring may become unnecessary.

***Front handles.*** The front handles that stick out in front of the seat frame get in the way during transfers. They can get caught on loose fitting clothing and any interfering body parts. This can lead to bed sores and botched transfers. One participant stated that the handles made him nervous to transfer from a lower-level or if he needed to transfer 180 degrees into the chair. Ironically, when these handles are removed the participant legs have a tendency to splay outwards. On most wheelchairs a tube runs along the side of the user's leg preventing this. In the Endeavor that structure does not exist. Some users found that they liked the handles for transferring at an equal level because they gave them a good handhold.

The handles should be retrofitted to be removable. First, the tube in the middle of the handle would be sawed flush to the front of the seat pan. A smaller diameter tube or solid bar would fit within the seat frame on which the handle would be mounted. Some sort of quick release method would be installed possibly similar to that used on the anti-tippers. Depending on how drastic the next phase of redesign is, the structures may no longer exist. However, if they do they must be removable.

***Footrest.*** The current footrest design is a total departure from previous generations. It is also unique to this chair. Two sets of clamps attach a U-shaped bar to link two allowing for vertical adjustment. All of these tubes near a users feet makes it easy to get a foot caught during transfers. The chair can be totally redesigned for more traditional leg rest adjustment in future versions. For the current chair a molded plastic shield could block a user's feet from entering this area.

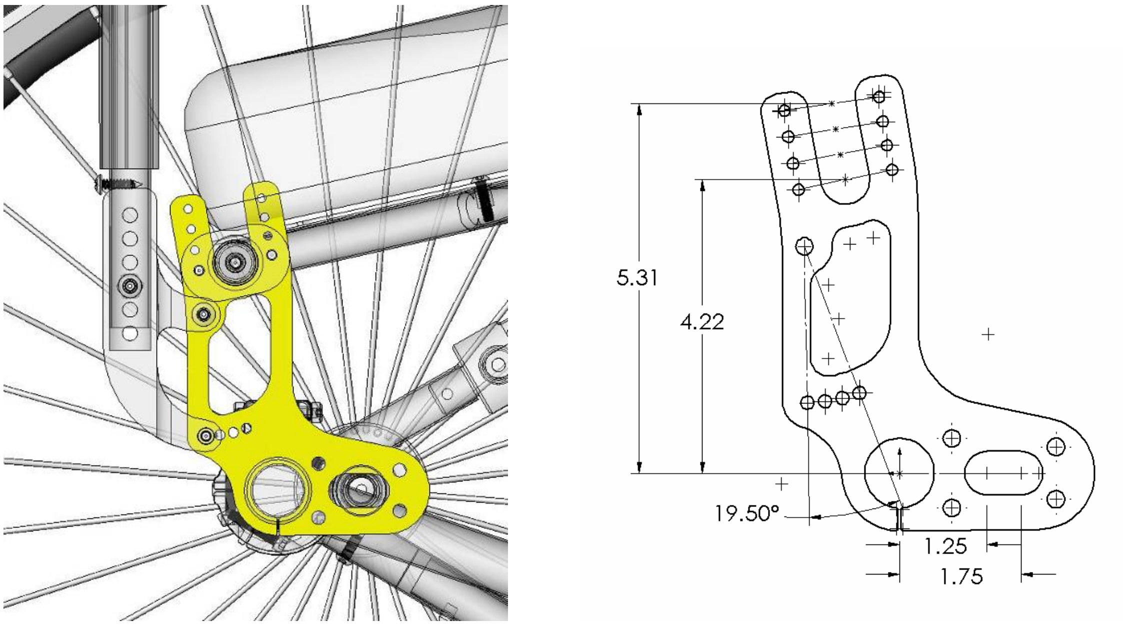



**Figure 48.** Axle plate

***Axle position.*** During examination of the axle plate diagram, notice the horizontal slot with two rounded ends (Figure 48). This is the current method of adjusting fore and aft axle position. It also defines the limits. The current set up only allows for ½ inch of adjustability. This is obviously very minimal. Most users felt that the most stable position ~3.5" in front of backrest cane (most rearward) was still too unstable. That feeling may have been also attributable to the compressing gas spring.

To give the appropriate amount of adjustment to match most users' chairs, the axle plate should allow for axle positions from 1 1/2 to 4 inches from the backrest cane. Currently the axle plate is made by wire EDM. After a relatively simple redesign of the geometry they can be remade quickly. The greatest difficulty is that the location where the most adjustability should be located interferes with the current location of the axle tube.

## E.2 FITTING

***Rear seat to floor height.*** Refer back to the picture of the "Axel plate" (Figure 48). You will notice the sets of paired nearly vertical holes towards the rear of the plate. A small plate coming from the seat interfaces with these holes. The current range of adjustability is between about 16 3/4 inches and 18 3/4 inches. The range of rear seat heights of our user group was between 15 and 18 inches with more than three users having a 15 inch rear floor to seat height. The benefit of having a lower rear seat to floor height (as well as fore-aft axle adjustment) is that a user has more access to the push rims making propulsion more efficient [8].

For the next version, the axle plate should also be able to accommodate rear floor to seat heights encountered in our group of participants. To do this, at the lowest position the top surface of the seat should be at most 3 inches higher (15 inches from ground using 24 inch standard rear wheels) than the horizontal axle adjustment slot. The upper limit of adjustment should be 18 inches (measuring from the top surface of the seat). If it is impossible to safely address this range of adjustment two different models of axle plates could be made.

***Backrest angle.*** The current version of the backrest mounting assembly allows for nearly 20 degrees of angle adjustment from vertical (90 to110 degrees from horizontal). From the dimensions collected on the participants' chairs, the current amount of adjustment is actually more than necessary. Participants' had backrest angles ranging between 90 and 100 degrees. In the next redesign, 15 degrees of adjustability in three degree increments is probably all that is needed.

***Footrest adjustment.*** The footrest assembly attaches to the tubes containing the pinch disconnect through the use of two split clamps. To adjust the footrest height, it is necessary to disassemble the split clamps and pound them to the proper position with a rubber mallet. This is impossible to do when a user is in the chair making fitting difficult. Even so, after the footrest length is properly adjusted adult users rarely ever adjust them again. The current footrest assembly can go from the floor all the way up to four inches from the seat pan. This range of adjustment is unnecessary. Our users had a range of footrest lengths between 14 to 18 inches when measured from the top of the cushion. In practice four inches of adjustment may also be excessive. The large range of participant sizes may have been better suited to multiple size chairs. The footrest assembly should be redesigned to minimize weight, and increase ease-of-use during folding. In the future, the footrest only needs to accommodate lengths between 15 and 18 inches. Height should also be more easily adjustable.

*Seat pan length*. It is difficult to adjust to the seat pan to the proper length. In the trials, a secondary set of holes were drilled into the seat pan, which only added 1/2 inch of rearward adjustment. This was not nearly enough to properly fit our users. When the pan was repositioned, the hole made for clearance of the top joint of the middle tube no longer aligned properly.

Our users had a range of seat cushion depths from 15 to 18 inches. Even so, their cushion length did not always match their leg length. This dimension is very important. If this length is not correct, a user's body is not properly supported by the seat and more importantly, it forces their legs to bend more than 90 degrees and their feet can't be properly supported by the foot plate. Because the legs no longer hang to contact the foot plate they have a tendency to fall off the front of the foot plate frequently. In future versions, different versions of the chair may need to be made to accommodate different seat depths.

## E.3 COMFORT

***Hard seat pan.*** Most manual wheelchairs do not have a solid metal seat pan. Users who are not used to solid seat pan find the chair very uncomfortable. This unforgiving cushion base made the chair unusable for one of our participants. It was also commented on by three of our other participants.

To improve comfort, the solid seat pan should be replaced with a seat sling, strap seating system, a molded plastic seat base or even a sprung support structure (like a couch) in the next prototype. But to do so, the rear bar of the seat frame must be removed because this sits directly beneath a user's tailbone. Because this is one of the pivot points of the frame, this removal requires some redesign. Possibly by cutting the middle section of the rear bar out and replacing it with a curved piece and adding other pieces to decrease the stress concentrations formed by the newly cut ends would work. This would allow users to use lighter and thinner cushions (like the ones they currently use) more safely. The impact cushioning properties of these more flexible seating systems may also make the spring assembly unnecessary. Choice of back support and cushion has been shown to affect the amount of vibrations transmitted to a user [44]. Redesign of the structures beneath the cushion promised to be even more effective.

## E.4 USABILITY OPTIONS

***Caster size.*** Three of our participants felt that the front caster size was too small to be functional. It may have also contributed to the lack of use by another of our participants. These four participants had six inch front casters on their personal chairs. Our chair has four inch casters.

To operate properly, the stem of the caster must be normal with the ground at all times. On the Endeavor, the caster housings are bolted and clamped to the mainframe of the wheelchair. Most wheelchairs allow for angle adjustment to accommodate different rear axle positions and caster heights. Because on this chair the seat height can be adjusted independent of the axle height, as long as the same sized caster is used there is no need to adjust the angle of the housing. There is some minor adjustability available by sliding the caster housings up or down inside of the clamps. The current caster diameter and fork combination is at the housings upward limit making the use of six inch casters impossible.

Using six inch casters would also interfere with the footrest assembly. Most likely the best way to deal with the needs of users who would like greater than four inch casters is to design a whole frame option around this need. Because the six inch casters would be taller than four inch, the chair would no longer be able to fold as small. Offering the option of detent removable casters for these users may be necessary.

***Weight.*** Unlike some ultralightweight rigid wheelchairs when fully assembled, the chair is too heavy to be easily lifted with one arm. One of our participants loaded his personal chair by pulling it fully assembled across his chest and into the backseat. He felt that loading the Endeavor into his car fully assembled may cause damage to his shoulders. As it was difficult for him to assemble and disassemble the chair he declined to participate in the in-home phase.

Another participant declined participation because of the weight even though he could disassemble the chair prior to loading relatively easily.

It is difficult to determine the actual weights of wheelchairs from literature. The reported chair weight may or may not include wheels, armrests, casters, splash guards or even footrests. So, until physical models are actually examined, determining and appropriate weight for our chair is difficult. Currently it weighs 19 1/2 pounds without cushion or wheels and participants felt that it was too heavy. Other alternative folding chairs report weights between 10 and 23 pounds. The next version should shoot for somewhere around 14 or 15 pounds without push wheels or airplane wheels.

Many of the parts could be made lighter and more efficiently in plastic without dramatically decreasing strength. Some obvious places are the cylindrical joints at either end of the middle tube and at the connection between link b and c at node two (Figure 1), the middle tube disconnect, the capturing blocks and handles of the pinch disconnect, the proposed detachable front handles, and the connecting hardware of the airplane wheels. Given the proper amount of testing of computer and physical models (the full battery of durability standards testing) other large milled pieces subject to higher forces such as the caster clamps and the axle plate could also be made from plastic.

This weight goal might be met by adding a seat sling, building the bottom frame out of aluminum, getting rid of the gas spring, simplifying the height adjustable footrests, replacing fasteners with strong and lightweight titanium fasteners, making a low load currently milled pieces from plastic, and cutting weight from the backrest adjustment brackets. If these modifications are not enough, some serious redesign may be in order.

***Splash guard.*** Many wheelchair users prefer a Roho cushion. This cushion is comprised of many inflatable air cells. The pressure in the cells can be adjusted to increase the comfort of the user. When this type of cushion is sat upon, it squishes out to the sides making it wider than it was before. The Endeavor wheelchair is very narrow between the push wheels. This expansion causes the seat cushion to rub against the insides of the tires.

The splash guards which were originally intended to be used on this chair were cloth clothing guards manufactured by quickie. They had the tendency to peel off of the seat plate when removing the cushion. They also rubbed against the tires and did not adequately constrain the seat cushion. With one of the users, the team attempted using solid splash guards. These still splayed out and rubbed heavily on the wheel (so much that it rendered the chair impossible to push effectively). If the solid splash guards interfaced with the backrest canes as well as the seat frame this would not happen. Splash guards similar to those found on the Kuschall chairs would work perfectly.

***Airplane wheels.*** It is nearly impossible for a user to independently extend the airplane wheels to the anti-tipper position independently. Currently it takes three hands to extend the anti-tippers. A user must simultaneously push down on both buttons while sliding the telescoping tube downwards. All of this must be done behind a person's back. They must be redesigned to lower the manual dexterity requirements. Participants also had difficulties maneuvering through thick carpeting and over thresholds because of the small wheel diameter. Increasing the wheel diameter may increase weight but there are a few other drawbacks.

***Folding backrest.*** The current chair is difficult to fold and unfold when trying to load into a car independently. A quick and easy solution would be to install a folding backrest. This would allow for easier maneuvering of the chair within the car while in the unfolded position.

Also by adding this back rest, backwards forces by the torso on the back rest will never compress the gas spring. Quite likely, the whole spring assembly could be eliminated. Adding a folding backrest will allow users who currently use rigid manual wheelchairs with folding back rests to store their chair in their car the same way as usual. Folding for storage in the overhead bin of an airplane would be just an added feature.

***Push handles***. Even though many experienced wheelchair users do not have push handles on the backs of their chairs, some do. These are very useful when trying to traverse obstacles such as steps and large curbs. They are also useful when a user encounters difficult terrain and needs a push. Other users who drive large vehicles sometimes with the chair into their vehicle using the push handle. One of our users (who had multiple vehicles) never used the Endeavor in his van (unmodified besides hand controls) because there was no good way to grab the chair and lift it up into his vehicle. Another user added a strap to the back of his chair to ease loading. This chair does not currently come with push handles. Addition of these handles will also increase its functionality as an airplane boarding chair. It will allow attendants to more easily carry a user upstairs or assist in propelling them down the aisle. The handles should be able to fold into the canes on the back of the wheelchair. Otherwise, the overall height of the folded wheelchair would be too tall to fit in the overhead bin. Initially these could be ordered from another manufacturer and retrofitted to fit on the Endeavor chair.

***Armrests.*** One user found the chair unusable because of the lack of armrests. This participant used the armrests when doing pressure relief, toileting and dressing. At the moment, there's no way to attach usable armrests. Sockets to fit armrests to the current chair may be mounted to redesigned axle plates. Another option would be to add folding armrests mounted to the backrest canes and the side frame of the seat frame.

***Camber.*** Many of our users would have liked to configure the Endeavors with a small amount of camber. Most manufacturers offer a few different discrete camber options in the range of 0 to15 degrees with the most common settings near five degrees. It makes it easier to reach more of the push rim while sacrificing width. This chair has no camber and no camber adjustment.

Adding this option to the chair would not be difficult. This could be done by giving users different choices on axle receiver designs. If this is given as a option on future chairs users should be warned that adding camper will increase chair width at the axle receivers possibly decreasing the chair's usefulness as a boarding tool.

***"Handle" across backrest.*** Nearly all manual wheelchairs have a curved bar which joins the two backrests canes. This bar keeps the backrests canes from bending inwards and is very necessary on chairs with folding backrests. Most users are used to having this bar on the back of the chair. They use it as a handle to help lift and load the chair. Currently the Endeavor does not have this and that makes it difficult for an experienced user to load the chair. The major drawback of this addition of a curved tube higher on the backrest is that it increases the chair's height in the collapsed position. Because the backrest canes extend beneath the seat, a straight tube could connect the two tubes and serve as a handle.

*Redesign for suspension.* The current chair is suspended. Even so, it was not designed for suspension so it does not respond appropriately to an impact. Right now the only degree of freedom shifts the center of gravity backwards making the chair less stable. There's also the possibility of designing the chair for a functional type of dynamic seating. Before implementing any solution it must be thoroughly researched and tested.

### E.5 FOLDING

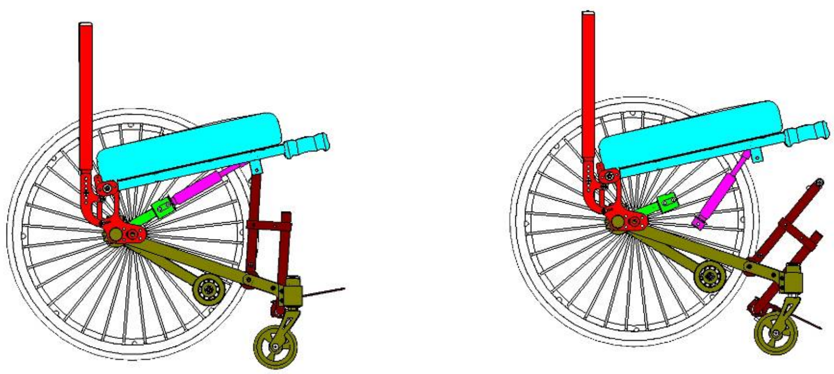


**Figure 49.** Disconnected Endeavor

***Restraining the collapsed chair.*** The concept of the chair as stated before is a four bar linkage locked by a crossmember which connects the second and fourth joints. By locking the system, it forms a truss consisting of two triangles similar to a bicycle frame. However when the chair is disconnected, it has five major degrees of freedom (Figure 49). If the airplane wheels, footplate and unintentional axial slipping are included, the degrees of freedom increase to 10. For optimal storage the footrest assembly is rotated all the way forward and the airplane wheels are locked underneath them effectively locking one of the joints. Luckily, when carrying the chair by the axle tube all of the members of the chair hang downwards and it is easier to deal with than one would expect. Even so it is awkward to handle disassembled.

Many of our users have suggested a strap or a clip which connects the backrest cane to the bottom frame which would keep the chair from flopping when disassembled.

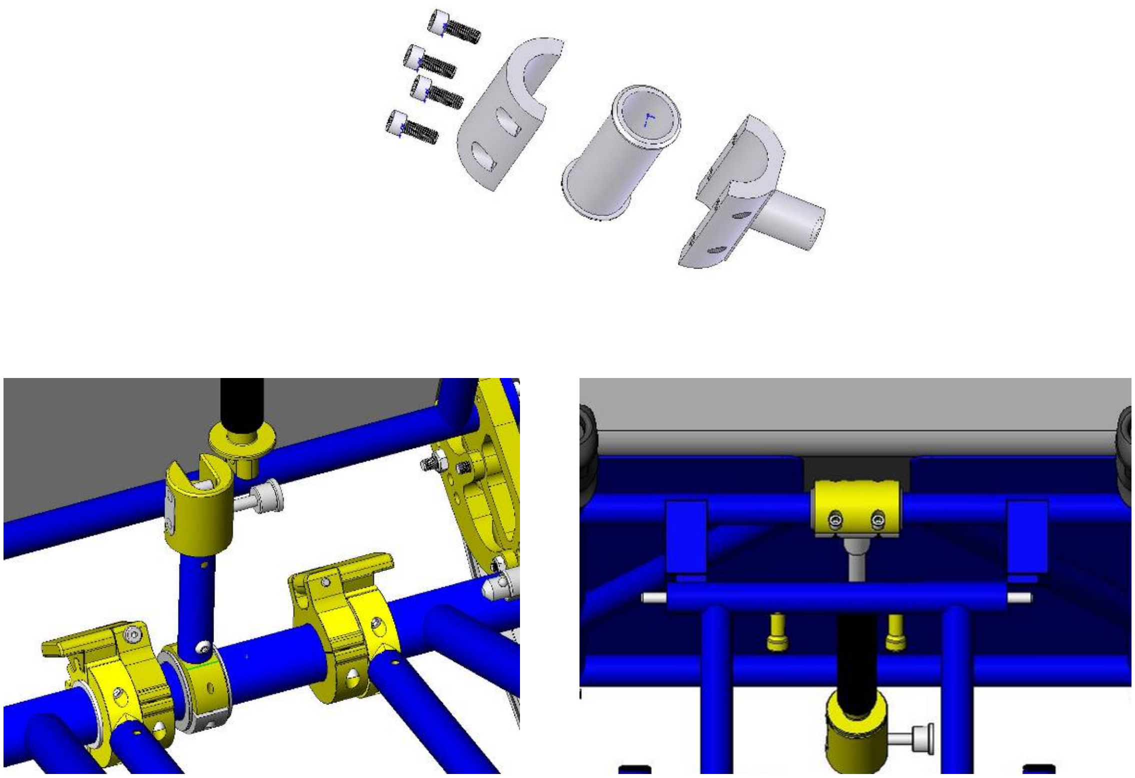


**Figure 50.** Joint misalignment

*Create stops*. Three of the wheelchair joints are constructed in the following method: a plastic bushing encircles a round frame tube, two semicircular aluminum pieces are joined together around the bushing using machine screws, a cylindrical plug protrudes from one of the semicircular pieces, this plug interfaces with an aluminum tube. This method of construction conveniently uses a frame member as part of the hinge but it does not constrain the joint from sliding axially along the frame member (Figure 50). This means that the joint can slide in either direction along the tube. This leads to frequent misalignment which greatly increases the difficulty of reassembly.

To constrain these axial joints from sliding, stops can be installed. These can come in the form of clamps or possibly even zip ties glued in place. It would also be helpful to constrain the functional rotation joints to only the range necessary for folding and storage. If the parts of the chair would stay stationary in locations where they need to be locked and not be able to rotate past the folded location it would greatly facilitate operation.

***Twisting footrest.*** Even though these clamps are sufficiently tight to support the footrests from sliding downwards, they are prone to slip axially (Figure 51). During folding, a misaligned assembly may interfere with the caster housings and side tubes of the mainframe. This interference will push the pivot joints axially leading to misalignment of the pinch disconnect during reassembly. It is not necessary to have four joints at this location. The clamps would function just as well if the rear parts were welded directly to the vertical tubes of link B.

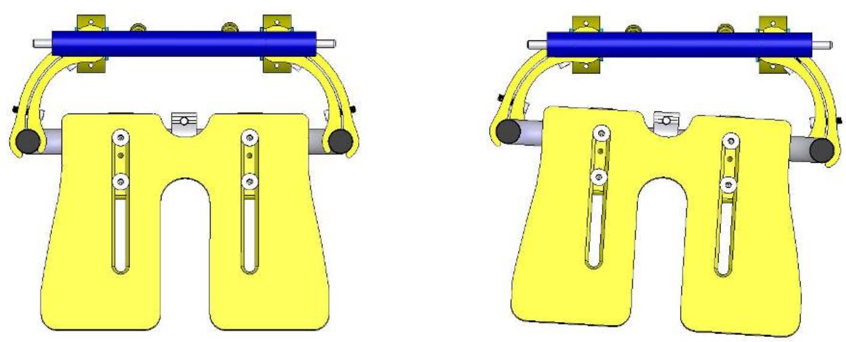


**Figure 51.** Twisting footrest assembly

***Middle tube disconnect.*** The first major step of reassembling the chair is to reconnect the male and female ends of the middle tube disconnect. This is difficult for most users especially in the confined area between the car and car door. They must be able to control four joints simultaneously while possibly realigning one of the members. Making matters worse, they have to do all of this blind because their vision is impaired by the solid seat pan.

*Redesign the middle tube connection.* Currently to fasten the middle tube disconnect, a user needs to perfectly align four different links. This is very difficult to do when vision is blocked by the seat pan and nearly impossible to do with one hand. To allow for the current method of dump adjustment, both ends of the middle link must be pivot joints. By using an assembly similar to the one shown this operation would be much easier (Figure 52). This assembly features a tapered hook with a spring pin locking mechanism. A cord would run up the inside of the tube and out through a hole in the tube. To keep it from wearing, a piece of rubber tubing could be inserted in the hole. A loop or ring at the end of the string would make it possible to operate for persons with less hand function.

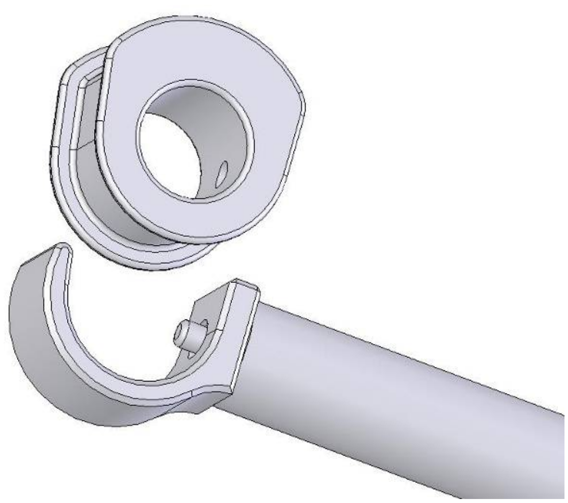


**Figure 52.** Proposed middle tube spring pin disconnect

*Replace the pinch disconnect.* The pinch disconnect gets jammed up quite frequently. By replacing these with OEM spring pins connected by a string, the assembly may be much more reliable and functional for persons with less hand function. Possibly by tapering the walls of the spring pins mounting block it may not be necessary to manually operate the spring pins while reassembling the chair.

*Develop a folding protocol.* Directions for folding and unfolding the chair have already been made. Even so, they do not take into account the limited space between the running board and the car door. They also do not account for physical limitations such as limited trunk stability and the awkward body position the person must assume while working on the chair from the car's driver seat.

***Fold with one hand.*** To make frequent folding less difficult it should be possible to fold and lift the chair into the car using just the left arm. This may take a total redesign. Possibly the addition of the rotation stops may take it a long way towards the one-handed goal. The total amount of time to fold and store the chair should take nearly the same amount of time as their personal chair. Making it possible to install the rear wheels while resting the footrest on the ground would also be useful.

## E.6 CASTER HOUSING ISSUES

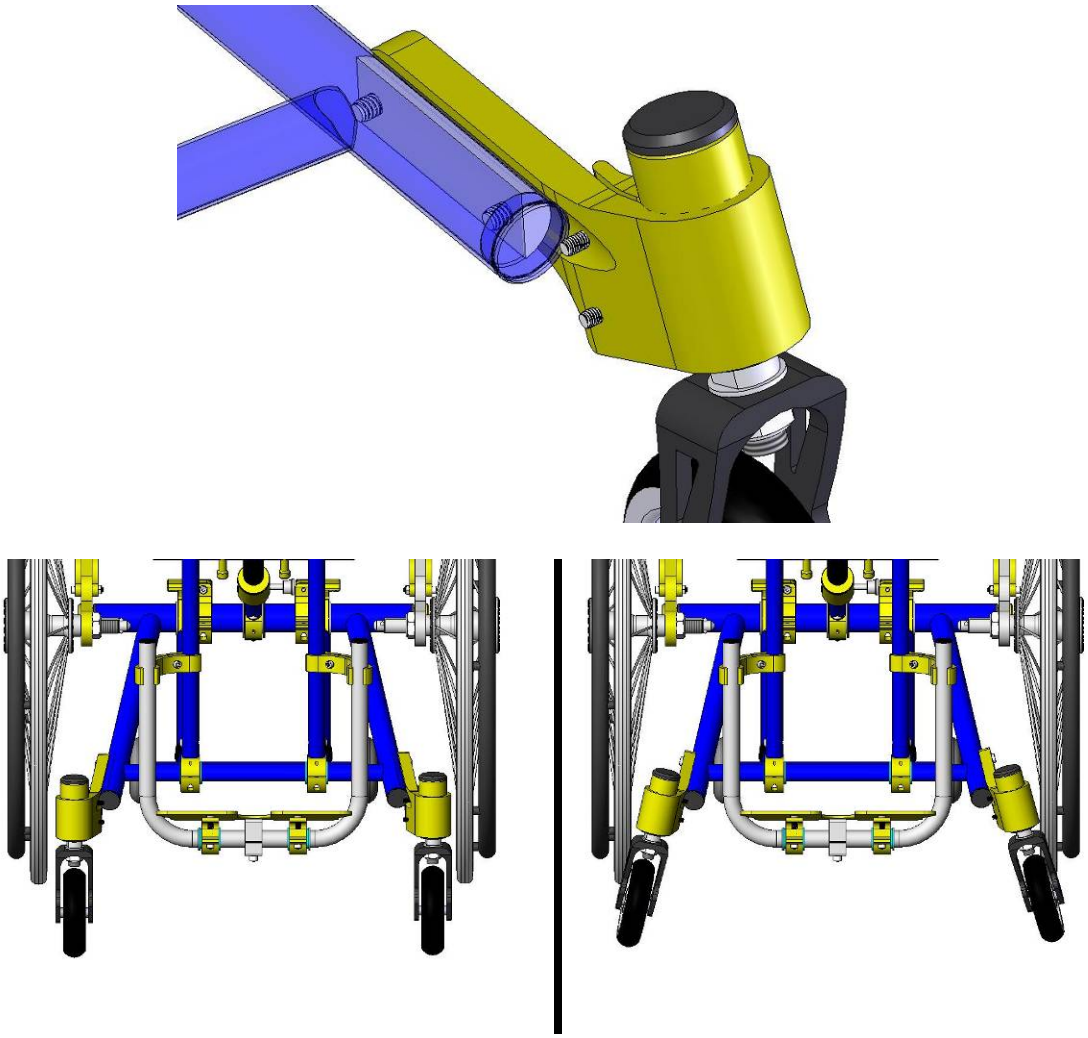


**Figure 53.** Twisting caster mounts

***Caster housing issues.*** When the frames of the chair were welded, the caster assemblies were used as part of the jig. Because the frames were removed prior to being completely cooled, they warped. After assembly the caster housing clamps on many of the chairs were splayed outward (Figure 53). There is no easy way to adjust the axial position (around the frame tube) of the caster clamps. They are constrained by the holes drilled into the tubes which access the half plug (which act as a clamp for greater strength). The current method of fixing this is by widening the holes in the frame and using epoxy to secure the assembly to the frame. This type of fix is beyond what can be expected from a user.

When the clamp of the caster housing over tightened it causes the bearings to seize up. This is because the wall thickness of the caster tube is too thin and that the clamping force can deform it. Increasing the wall thickness of the caster housing tubes will keep the bearings from seizing up when the housing clamp is over tightened.

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