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ONE-ARM MANUAL-POWERED WHEELCHAIR

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ABSTRACT

The goal of this project was the design and creation of a one-arm, manual-powered wheelchair. The customer need for this product derived from the desire for improved mobility for stroke patients. Following a stroke, it is normal for patients to lose some or all of the functionality in one side of their body. As a result, it is inconvenient for them to use a normal, two-arm wheelchair. This wheelchair provides the means for the patient to propel themselves with the use of only one arm. The wheelchair is light-weight and has easy-to-remove parts for transportation.

INTRODUCTION

Following a stroke, it is common for patients to lose functionality on one side of their body. This creates a challenge with regards to manual modes of transportation due to the fact that most existing manual wheelchairs are motivated through the use of two arms. The difficulty comes with designing a wheelchair which can be propelled by an individual with the use of only one side of their body.

Another alternative for a stroke patient is an electric wheelchair. These are controlled by a single joystick on the side of the wheelchair where the user still has functionality. One problem with electric wheelchairs is that they are heavy compared to other wheelchairs. Due to this weight, a custom-outfitted vehicle is often required to transport the wheelchair from one location to another. Another problem is that electric wheelchairs are very expensive. These can range from $1,500 all the way to $4,000. This can be too costly for individuals who may have difficulties procuring their wheelchair without assistance from an insurance company. Finally, electric wheelchairs do not contribute to rehabilitating the user like a manual might do.

The purpose of this project was to create a device that could be used by stroke patients to transport themselves effectively. This environment was assumed to be a long-term care facility or an individual's home, as well as the surrounding areas for each location.

The second goal of the project was the meet the customer requirements of both Bob Brinkman and Jack Allen. Both of these individuals were the primary customers for the project. Bob originally conceived of the need for the one-arm wheelchair and Jack is an individual who suffered a stroke and is currently residing at a facility in Penfield, New York. The success of this project was dependent on how well their critical design needs were implemented into the finished product.

Based on interactions with Bob and Jack, the following list of customer requirements was created to guide the creative process and to use as a benchmark for a successful product.

- Must be useable by an individual with functionality only on one side of their body.
- Must be able to fold easily for transportation.
- Must be relatively lightweight.
- Must be easy to maneuver by the user.

- Forces applied to propel wheelchair must be safe to the user.
- Should be within the safe range of upper extremity joint motion.
- Should handle the user weight of 95th percentile male user and below.
- Must be able to remain stationary on ramps using brakes.

METHODOLOGY

Summary of Specifications

Based on the complete list of the customer's primary needs, a table of clear and quantifiable engineering design specifications was established. Each specification was given a rating on a scale of 1 to 10 of the importance to the success of the design. The design team established marginal and ideal values for each specification.

The marginal values represent a specific value which is acceptable to the customer. The ideal values represent a value which exactly matches the expectations of the customer. The list of customer specifications can be seen below in Table 1.

Spec No.	Specification	Importance	Units	Marginal Value	Ideal Value
1	One-Arm Compatibility	10	Binary	Yes	Yes
2	Doorway Maneuverability	10	Inches	< 30"	< 28"
3	Turning Radius	10	Feet	3	0
4	Straight Line Deviation	10	Ratio	1	0.25
5	Force to Start Wheelchair Motion	8	Newtons	< 120	< 105
6	Pinch Points during Operation	8	Severity Level	2	1
7	Foldable Area	7	Area	42"x38"x23"	< 42"x38"x23"
8	Grip Strength	7	Pounds	13	< 13
9	User Weight Limit	7	Lbs.	250	≥ 250
10	User Control Interfaces	7	#	6	4
11	Traverse Common Terrain	6	Binary	No	Yes
12	Maneuvered by Attendant	5	Binary	Yes	Yes
13	Able to Remain Stationary on Ramp	5	Grade	1:20	1:12
14	Range of Motion of Arm	5	Degrees	45-170	120
15	Comfort of Seating and Lever Propulsion	4	Hours	3	8+
16	Wheelchair Weight	4	Pounds	50	< 35
17	Ease of Assembly/Disassembly	4	Minutes	≤ 4	≤ 3
18	Reproducible	4	US $	~1000	≤ 1000
19	Anthropometric Adjustability	4	Percentile	5th Percentile Male	95th Percentile Male
20	Acceptable Style	3	Binary	Yes	Yes

Table 1: Design Specifications

Straight-line deviation refers to the distance that the wheelchair strays from a straight-line path during operation. The ratio mentioned for the marginal value and ideal value refers to a ratio of corrections to power pulses. A "power pulse" is considered to be one full movement of the propulsion system; the lever would travel from rest forward to the extended position and then return. If the user needed to make one trajectory correction after making four power pulses, the ratio would be 1:4 or 0.25.

User Control Interfaces refers to the number of options that a user is presented with during operation. It is necessary for the user to move straight, turn left, turn right, and stop fully, so the best system for this specification would be one that has only four interfaces for these four options.

Anthropometric Adjustability refers to the need for the wheelchair to be useable by different portions of the population.

Concept Selection

The first step in developing concepts to meet customer needs was to evaluate existing options for one-arm wheelchairs. By visiting a local wheelchair distributor and searching through their literature, the team researched concepts in order to assess concepts that have already been developed.

An example of an existing one-arm, manual-powered wheelchair can be seen in Figure 1. This model works similar to a traditional two-arm wheelchair. The difference between these types is that the wheelchair depicted in Figure 1 is operated using two push-rims on one side of the wheelchair. The push-rim closest to the chair powers the wheel on that side, while the outer push-rim controls the opposite wheel through the rear axle. This method of propulsion created a problem when the user attempted to grip both push-rims simultaneously. It was difficult to grab both rims with an equivalent amount of force, which lead to the wheelchair deviating in one direction based on the relative forces. This issue is reflected in the straight-line deviation specification listed previously in Table 1.

Figure 1 – Benchmarked One-Arm Wheelchair

Using the engineering design specifications and the experience gained from conducting a review of existing technology, the design team began generating potential design solutions. Ideas were generated through brainstorming sessions. These sessions involved each member contributing many ideas related to possible design options. To facilitate the process, the wheelchair was broken down into logical subsystems. These subsystems included the propulsion method, the braking system, the drive train, the method of steering, and method of folding. Once an appropriate number of ideas had been generated for each category, the options were grouped into logical design systems. This resulted in eight different designs to evaluate against each other, as well as against existing one-arm wheelchairs.

A system designs evaluation method was developed to rate the quality of each design. Each specification was given a rating based on its importance in the design specification table. Then each system was rated from 1 to 10 on each specification. The rating was multiplied by its respective weight and a weighted rating was obtained. Each weighted rating was summed for each system, resulting in 10 totals. These 10 totals represented the eight design systems plus the current wheelchair used by Jack Allen and a benchmark wheelchair. A sample of this evaluation method may be seen in Figure 2.

	User Control Interfaces		Foldability		Weight	
Specification Weight	0.7		0.7		0.4	
System	Rating	W-Rating	Rating	W-Rating	Rating	W-Rating
Existing (Jack)	10.0	7.0	10.0	7.0	9.0	3.6
Monroe Wheelchair	8.0	5.6	9.0	6.3	8.0	3.2
Trackball System 1	8.0	5.6	7.0	4.9	9.0	3.6
Trackball System 2	10.0	7.0	7.0	4.9	8.0	3.2
Zip-Tie	10.0	7.0	8.0	5.6	7.0	2.8
Foot Ratchet 1	10.0	7.0	4.0	2.8	5.0	2.0
Foot Ratchet 2	6.0	4.2	3.0	2.1	4.0	1.6
Lever Differential	10.0	7.0	5.0	3.5	6.0	2.4
Push	10.0	7.0	4.0	2.8	5.0	2.0
Hand Crank	6.0	4.2	4.0	2.8	5.0	2.0

Figure 2 – System Designs Evaluation Method

As mentioned previously, each specification was given a weight based on its importance. These specifications are listed along the top of the evaluation method. User Control Interfaces, Foldability, and Weight are just a small sample of the specifications.

The highlighted rows are the design systems that received the highest overall rating. Based on the results of the systems evaluation, the Lever Differential and Zip-Tie systems were selected.

The Zip-Tie system used two push-rims similar to existing one-arm manual wheelchairs. Instead of the user attempting to push both rims simultaneously, a handle device would connect the rims together. The user would grab this handle to push both rims at the same time, and with the same amount of force. This would attempt to minimize straight-line deviation during operation. The user would have some method of selecting which rim to push, whether through the use of buttons or some other mechanism, which would allow them to turn in a particular direction.

The Lever Differential system used a lever to propel to wheelchair forwards. The lever connects to a front axle, which spins the rear axle through the use of a chain. The two brake handles located on the top of handle would control turning the wheelchair. By gripping one of these handles, one of the brake discs would be engaged, ceasing movement on one side of the rear axle. Through the differential, the force being applied to the lever would be transferred to the other wheel, which allows the user to turn. To stop the wheelchair from moving, the user simply grabs both brake handles simultaneously.

To break the tie, the system with the higher ratings in the most important specifications was selected. As a result, the Lever Differential system was selected for further development. A Pro-Engineer model of the initial design concept is shown in Figure 3.

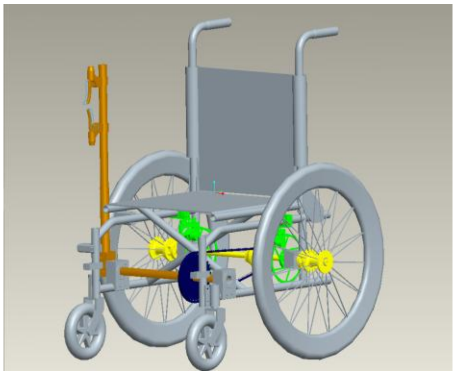

Figure 3 – Lever Differential Model

Feasibility Assessment

Once the concept had been selected it was necessary to perform a comprehensive feasibility assessment of the chosen design (Lever Differential System). The Lever-Dif System needed to be analyzed to affirm that it would not only function and meet the aforementioned specifications, but also that it would not exceed any ergonomic limits during operation.

Significant time and resources were dedicated to determining the force that would need to be applied to achieve the desired force of 2 MPH, which was determined to be comparable to average walking speed. This decision would affect the components of the drive train as free-wheel teeth and other components would be dependent on these calculations.

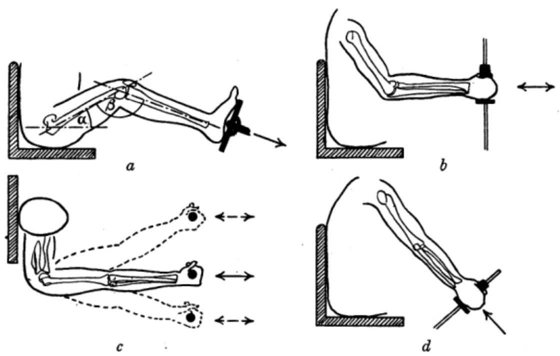

Figure 4 - Diagram demonstrating the different orientations of how a seated force could be applied

Based on the selected design, lever positioning was integral from an ergonomic perspective as well as what the maximum applied force will be. Hugh-Jones (1947) in Figure 4 above shows the conditions under which a seated operator could provide the maximum applied force. In particular, example *b* coincides with the choice of the lever positioning to allow for maximal force application. Aspects of *d* are also incorporated as the lever does not merely traverse a horizontal axis (p. 23-2).

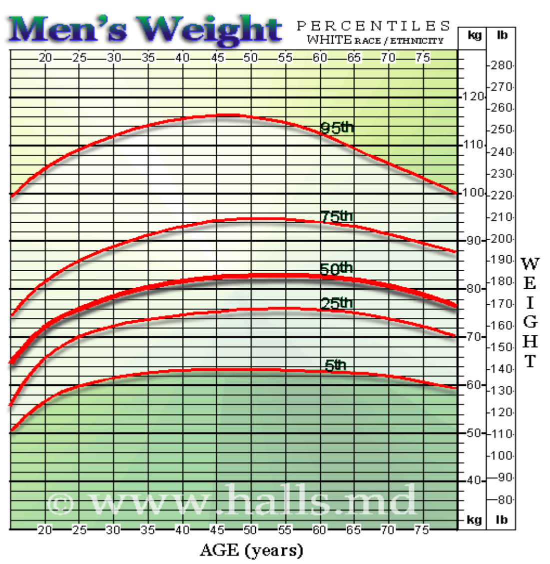

Figure 5 – Chart of male weight by percentile and age

For force calculations, it was necessary to determine the mass of the entire system, which included both the chair and the occupant. The target customer was Jack Allen, and therefore, the assumptions for weight and other ergonomic metrics were based off the assumptions for a 50th percentile male. According to the chart by Halls and Hanson (2000) 50th percentile male at age 50 weighs approximately 83 Kg (see Figure 5). This weight, combined with the weight of the chair (23 Kg), totals 106 Kg of the total system to be moved by the lever. This figure was used in subsequent force calculations as well as research into male strength capabilities to move this weight.

100 N impulses							
Hand Force (N)	Hand Force (lb)	Time of forward push (s)	Reset time (s)	Total time (s)	Gear ratio	Speed @lever (m/s)	Speed of chair (miles/
							0
100	22.481	0.65	0.4	1.05	2.25	0.494	1.243
					2.25	0.460	1.158
100	22.481	0.43	0.4	1.88	2.25	0.750	1.887
					2.25	0.701	1.764
100	22.481	0.35	0.4	2.63	2.25	0.923	2.323
					2.25	0.864	2.175

Figure 6 – Example of force calculations to achieve desired speed based on 100 N of force for initial pushes

The push force required to operate the lever would be a critical metric to the wheelchair's overall success or failure. It had to be determined what forces would be necessary to achieve the desired speed of approximately 2 MPH, as well as the duration of these forces. Scenarios were run for each of the four force levels to determine the number of pushes required to achieve the maximum speed. All four were based on the gear ratio of 2.25 since this was the available set-up for the drive train system. Figure 6 demonstrates that three 100 N pushes at the specified times would achieve a top speed of 2.323 mph. Once this speed has been achieved, the required force to maintain this speed will merely be the force to overcome friction (approximately 30 N). Based on previous data, these forces should be acceptable.

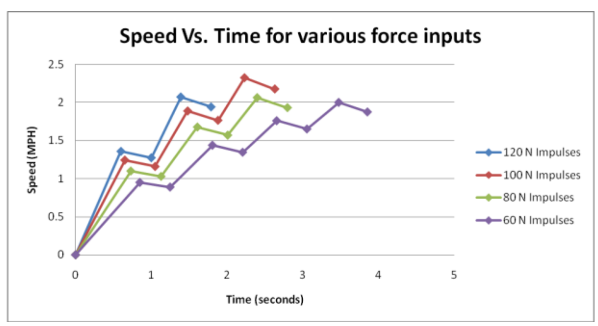

Figure 7 – Relationship between time to reach a maximum speed at different applied forces

Using the aforementioned force calculations, it was possible to generate the chart in Figure 7. This chart provides a quick visual demonstration of the time it would take to achieve maximum operating speed based on four levels of applied force. The forces chosen to be applied by the operator to the lever were 120 N, 100 N, 80 N and 60 N. These values were chosen based on the previous research of 50th percentile male push force capabilities. It is these forces and times that will be justified as feasible in the following analysis.

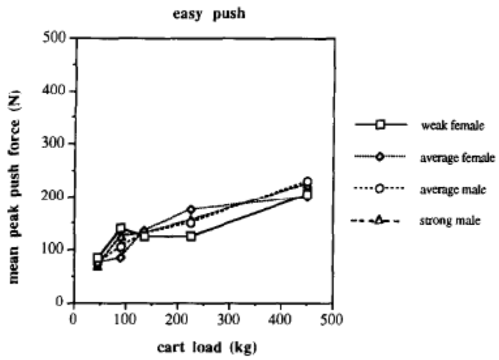

Figure 8 – Mean peak easy push force on cart handles based on load. (Chaffin and Resnick, 1995)

Once the force scenarios and analysis had been performed, the next step was to justify that these forces could be achieved safely by the potential user. Chaffin and Resnick (1995) in Figure 8 showed that at approximately 100 Kg of weighted loading, the mean easy push force for an average male just exceeds 100 N. Meanwhile, values for strong male, average female, and weak female ranges from 80 to 150 N. This validated the decision to examine forces applied between 60 and 120 N and also demonstrates that the projected force requirements are not excessive.

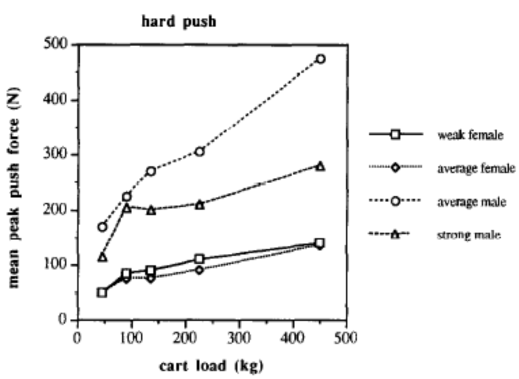

Figure 9 – Mean Peak hard push force on cart handles based on load (Chaffin and Resnick, 1995)

Chaffin and Resnick (1995) also generated similar data for a hard push scenario. This scenario would be more readily comparable to the initial push force required to achieve 2 MPH. After the desired speed is achieved, the required force will drop significantly to maintain the speed. Examining the above graph, at slightly over 100 Kg load, the mean peak push force is upwards of 200 N. This value well exceeds the tested values used in trial scenarios (60-120 N). This provides further evidence that the initial targeted 3 pulses at 100 N could be safely applied by the 50th percentile male.

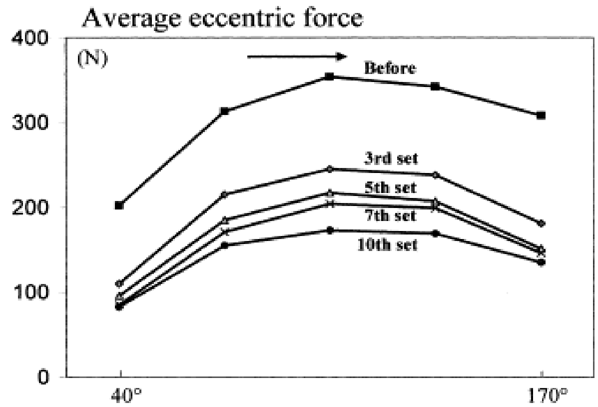

Figure 10 – Graph of avg. forces on biceps brachii in eccentric elbow exercise over several repetitions (Bottas, Komi and Linnamo 2000)

Bottas, Komi and Linnamo (2000) performed a study utilizing 8 male students age 21-33 on an isokinetic machine. The study measured eccentric and concentric forces operating a lever at an elbow joint range during operation was 40 to 170 degrees (equivalent to the wheelchair lever range). Figure 10 shows the results of multiple force repetitions. Again, this data suggests that the 100 N initial pushes are within the acceptable range of capacity. This data also incorporates the applied forces over the desired arm angle when operating the wheelchair.

STEP 1. Measure and record task variables

Object Weight (lbs)		Hand Location				Vertical Distance	Asymmetric Angle (deg.)		Frequency Rate	Duration	Object Coupling
		Origin		Dest			Origin	Destination	lifts/min	Hrs	
L(AVG)	L(MAX)	H	V	H	V	D	A	A	F		C
33	45	12	15	18	38	23	0	30	<.2 (.004)	<1	Good

STEP 2. Determine the multipliers and compute the RWLs

	RWL =	LC	x	HM	x	VM	x	DM	x	AM	x	FM	x	CM		
ORIGIN	RWL =	51	x	.83	x	.89	x	.9	x	1	x	1	x	1	-	32.37 lbs.
DEST.	RWL =	51	x	.56	x	.94	x	.9	x	.9	x	1	x	1	-	22.88 lbs.

STEP 3. Compute the LIFTING INDEX

ORIGIN	LIFT INDEX	OBJECT WEIGHT / RWL =	33 / 32.37 lbs.	=	1.01
DESTINATION	LIFT INDEX	OBJECT WEIGHT / RWL =	33 / 22.88 lbs.	=	1.44

Figure 11 – NIOSH analysis of lifting task (Weight is with footrests, armrests and wheels removed) (Gordon-Becker, Lee, Liu and Wickens 2003)

One of the specifications for the final wheelchair was that it be foldable and be able to fit into a trunk. It was necessary to make sure that this operation was ergonomically acceptable. A NIOSH lifting analysis (Gordon-Becker, Lee, Liu and Wickens 2003) was performed on the task of lifting the folded wheelchair into the trunk of a Ford Focus (Figure 11). The wheelchair's weight does not include the wheels, footrests, or armrests, which are removed prior to folding. Typically, an index in step 3 greater than one poses a risk for some and greater than three poses a risk for most. Both indexes in step 3 are slightly over one. This indicates that a large majority of the population should be able to handle the lifting operation. It also should not be considered a large concern due to the fact that this lifting task is not performed on a constant basis.

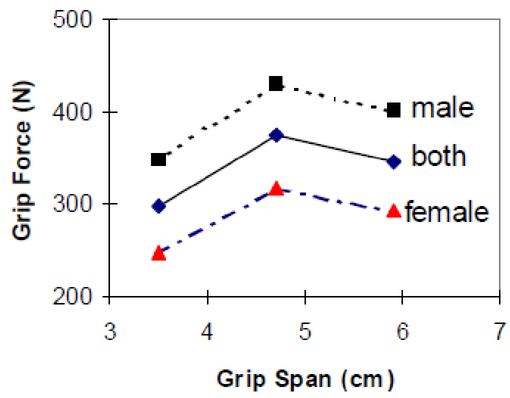

Figure 12 – Grip Span vs. the grip force for male and female subjects (Goonetilleke, Hamad and So)

The brake system was set-up very similar to bike brakes. Since this is the case, it needed to be assured that the brakes could be applied based on the grip force of the potential customers. Goonetilleke, Hamad, and So (1997) performed a study on grip span and grip force on a group of varying age and strengths. Assuming 300 N grip force average, this can be translated to approximately a 30.6 Kg force to brake. This value exceeds what our subject would be required to apply. While testing using a dynamometer, the subject recorded a value of approximately 25 Kg. These findings validated the assumption that the user should be able to exert the required grip force to engage the brakes.

	RHS, Left Hand (n=29)	LHS, Right Hand (n=14)	*t*	*P*
Selection and control variables				
Visual perception (MVPT) (/36)	30.7 (2.8)	31.0 (3.5)	-0.28	.78
Functional autonomy (SMAF) (/87)	11.1 (9.2)	8.8 (9.2)	0.78	.44
Cognitive function (3MS) (/100)	88.1 (4.9)	89 (4.8)	-0.55	.58
Depression (GDS) (/30)	11.4 (6.8)	9.1 (6.0)	1.06	.29
Affected UE motor function (Fugl-Meyer) (/66)	44.0 (22.9)	57.2 (13.2)	-2.39	.02
Unaffected UE tests				
Gross manual dexterity, No. of blocks	55.2 (9.6)	59.7 (12.0)	-1.33	.19
Fine manual dexterity, No. of pins	10.4 (2.1)	11.0 (2.1)	-1.01	.32
Global performance, s				
Coffee jar	1.8 (0.4)	1.8 (0.3)	0.49	.62
Water pitcher	9.5 (2.0)	9.5 (1.2)	-0.04	.97
Coins	9.7 (2.2)	10.0 (1.7)	-0.45	.65
Small objects	9.2 (2.4)	9.2 (1.7)	0.05	.96
Motor coordination, No. of nose-target movements	18.1 (5.3)	17.5 (4.9)	0.38	.71
Grip strength, kg	29.1 (9.4)	30.9 (9.3)	-0.57	.57
Static two-point discrimination, mm	5.0 (1.1)	5.6 (1.6)	-1.29	.20
Moving two-point discrimination, mm	4.8 (1.0)	5.1 (1.0)	-1.10	.28
Touch/pressure threshold, g	0.39 (0.47)	0.47 (0.50)	-0.55	.58
Kinesthesia (/10)	8.0 (2.2)	8.2 (2.3)	-0.27	.79

Figure 13 – Comparison of RHS vs. LHS patients (Bourbonnais, Bravo, Desrosiers, Guay and Roy 1996)

Bourbonnais, Bravo, Desrosiers, Guay and Roy (1996) collected data on right hemiplegic/paretic subjects (RHS) and left hemiplegic/paretic subjects (LHS) patients. This data is summarized in Figure 13 and shows that stroke patients were capable of achieving grip strengths of approximately 30 Kg. This data confirms the capability of the user to engage the braking system.

TESTING PROCEDURE

A series of test plans was developed to evaluate the performance of the final product. The test plans were designed around the customer specifications. There tests were designed to evaluate the performance of the prototype under different conditions to verify the value of each specification. The idea results of these tests would be to have each value be at the ideal value from the design specification table.

Each test plan contains a description of the test and the specification it involves, the materials and equipment required, the resources required, the start and end date, the individual(s) who performed the test, the metric to be measured, Pass/Fail check boxes, and a section for comments pertaining to the test. The test plan description contains the scenarios by which the test passes and fails. It is important that the prototype passes each test in order to deliver the highest quality product to the customer.

RESULTS AND DISCUSSION

The results were recorded and analyzed upon the completion of testing. The device passed for nearly all of the specifications, conditionally passed for two of the specifications, and failed two of the specifications.

The highest rated specifications passed their tests, which was integral to the success of the design. The wheelchair was maneuvered successfully through a standard width doorway, had a sufficiently small turning radius, had minimal straight-line deviation during operation, was able to be folded for transport, and had an acceptable force required to start the wheelchair motion. Greater detail regarding the force required to start the motion can be found following Table 2.

The other conditionally passed specification was the comfort of seating and lever propulsion. Due to time constraints, the longest that any user operated the chair was 30 minutes. Also, it is believed that if the chair is being used "normally," that the user would not be propelling the wheelchair with the lever for 30 minutes straight. For example, the user would travel down a hallway to another location, and then remain stationary, or make minor adjustments.

The two specifications which failed to be met were Acceptable Grip Strength, and the budget for the project. The budget was unable to be maintained for a few reasons. First is that most of the material was ordered through McMaster Carr. The price for aluminum from this supplier was slightly higher than normal, and the team also ordered more than what was required. Secondly, the base wheelchair was very costly. This was due to time constraints, as there was a longer lead time, but cheaper alternative available. Finally, the cost of the differential was larger than anticipated, and the cost of shipping from Taiwan was expensive. Although this differential was expensive, it was the only model that fit the design's need in terms of size to fit under the wheelchair as those manufactured in the U.S. were typically larger.

The Grip Strength specification failed to be met due to unrealistic expectations during the formation of the specifications. The team expected to be able to control the required grip strength, and would ultimately make it negligible. This turned out to not be the case, and combined with the fact that the original specification was too ambitious, the test for this specification failed.

Eng. Spec #	Specification (Description)	Marginal Value	Ideal Value	Actual	Spec. Met?
1	1-Arm Compatability	Yes	Yes	Yes	Yes
2	Can Be Maneuvered Through Standard Doorway (Width)	32"	< 30"	32"	Yes
3	Turning Circle	36"	0	20"	Yes
4	Straight Line Deviation in 25 ft.	1:1	1:4	1:5	Yes
5	Acceptable Force Required to Start Wheelchair Motion	< 120 N	< 105 N	TBD	
6	Pinch Points During Normal Operation	2	1	2	Yes
7	Foldable for Transport/Storage	42"W x 38"D x 23" H	< 42"W x 38"D x 23" H	<42"x38"x23"	Yes
8	Acceptable Grip Strength	13 lbs.	< 13 lbs	R: ~33lbs. L: ~22lbs.	No
9	Weight Limit	250 lbs.	? 250 lbs.	~250 lbs.	Yes
10	User Control Interfaces	6	4	4	Yes
11	Able to Traverse Through Common Terrain (Carpet, Tile, Concrete) by User	No	Yes	Yes	Yes
12	Wheelchair Can Be Maneuvered by Attendant	Yes	Yes	Yes	Yes
13	Able to Remain Stationary on a Ramp with Parking Brake On	1:12	>1:12	1:12	Yes
14	Range of Motion of Arm	45-170 Deg.	120 Deg.	50-170 deg.	Yes
15	Comfort of Seating and Lever Propulsion	3 hrs.	8+ hrs.	.5 hrs.	No*
16	Wheelchair Weight	50 lbs.	< 35 lbs.	46 lbs.	Yes
17	Ease of Assembly/Disassembly for Use	? 4 min.	? 3 min.	~2 min.	Yes
18	Reproducible	~$1000	? $1000	~$1000	Yes
19	Anthropometric Adjustability	5th Percentile Male	95th Percentile Male	5th-95th	Yes
20	Acceptable style	Yes	Yes	Yes	Yes
21	Cost	< $2000	< $1500	$2,113	No

Table 2: Results

The force necessary to apply to the lever in order to generate motion and the desired speed was integral to the successful usage of the wheelchair. It was extremely difficult to accurately measure the force applied during testing and usage, and for this reason a more subjective approach was used to verify acceptability. Due to the lack of a chain tensioner, the chain would skip if forces approached the originally anticipated value of 100 N. For this reason, less force over a greater number of propulsions was used to achieve the desired speed (for example, instead of 3 100 N pulses, 5 60N pulses). The end result was lower force required, but also increased the time until the desired speed was reached. The highest forces were required to turn as the brake must be engaged on one wheel while pushing to turn in place.

The wheelchair was taken to Jack Allen to allow for testing and feedback, and he used the chair for approximately a half an hour. Mr. Allen used the wheelchair in many day-to-day scenarios such as traversing halls, dining areas, doorways, and moving around in his room. During the course of the time spent using the chair, Mr. Allen expressed that he was comfortable moving the chair using the lever and that he feels he could utilize it daily. He did reiterate our concerns about controlling the brakes and performing sharper turns, but overall he had positive feedback regarding the lever.

Many subjects tested the wheelchair on the RIT campus with none expressing concerns regarding the forces required to operate the lever. Subjects ranged significantly in age and strength. This reinforces the team's belief that the wheelchair could be operated on a day-to-day basis by the potential users.

CONCLUSIONS AND RECOMMENDATIONS

As evidenced by the results of testing which are visible in Table 2, the device succeeded in meeting most of the customer needs. The wheelchair is able to move through the sole use of one arm, is able to be folded for transportation, has minimal straight-line deviation during operation, and is safe to use by the intended customer.

Some compromises were made during the development process to ensure that the product would be completed within the time constraints. Therefore, there are potential improvements that could be made in future iterations of this product.

To improve future performance, the project team suggests that the weight of the wheelchair be reduced, that the wheelchair has the ability to be left-arm compatible, is able to move in the reverse direction, has improved brake performance, and has a method to tension the chain properly to the gear system.

The current design doesn't include any method or mechanism for maintaining chain tension. Consequently, if the rider applies too much force to the lever, the chain will slip on the free-wheel. It would be relatively easy to attach a tensioning mechanism to the frame of the wheelchair, which would alleviate or eliminate this problem.

An additional issue is that the drive system and back axle are somewhat unstable. This is due to poor design, machining tolerances, or lack of information prior to machining. One large source of the wobble in the rear axle is the joint where the spline axle is inserted into and connected to the stub axle. This joint was not designed well, in that there was only about 0.5 inch overlap at maximum. The problem was compounded by the fact that the purchased spline axle was under diameter. As the team assembled the rear axle, it was necessary to insert a 0.005 in shim all the way around the spline axle. The stub axle had been designed and machined prior to receiving the spline axle and confirming its diameter. The team recommends that future teams confirm the dimensions of all purchased parts before beginning machining of custom parts.

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