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Redesign of the Double Hand Rim Modification of the "Whirlwind" Wheelchair for Manufacture in Developing Nations

by

Cameron M Bass

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

at the

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Abstract

In this thesis, I investigate possible improvements to the design of a wheelchair for manufacture in a developing nation, specifically one designed for use by persons with hemiplegia. Ralf Hotchkiss's "Whirlwind" Wheelchair is currently manufactured with local materials in many developing nations. It provides both an affordable source of quality wheelchairs for the populace as well as a source of employment. J.A. van Alphen and D.R. Arbib made modifications to the original Wheelchair design so that it would be usable by hemiplegics. However, on manufacture in Duranguito, Mexico, the chair was deemed unusable due to certain flaws. After analyzing the design of the chair, potential solutions for the two most critical problems are suggested, taking care to avoid undue increases in cost or complexity of manufacture.

Thesis Supervisor: Edward B. Seldin
Title: Senior Lecturer

Acknowledgements

Throughout the entire process, David Werner has been very helpful in providing links to information and people. In addition, Sally Susnowitz and the MIT Public Service Center paid for the trip to Mexico that inspired this thesis. In Mexico, Ming-Fai Fong was a part of the design process. Also, Raymundo, Gabriel, and all of the other guys working the Duranguito Whirlwind shop were invaluable. Finally, this thesis would have been absolutely impossible without the aid of Dr. Seldin

Contents

Chapter 1

Introduction

Low cost and manufacturing constraints severely limit the production of wheelchairs in developing nations. Many modern wheelchair designs are dependent on material qualities not present in low-grade steel or aluminum, so wheelchairs made in these areas tend to not have benefited any from advances made in the past decades. Many programs, such as Whirlwind Wheelchairs International (WWI), attempt to bridge this gap with technology specifically adapted for developing nations. They have had some measure of success, as wheelchair shops producing a chair designed by WWI exist in more than two-dozen countries. One particular wheelchair modification on the WWI chair is to adapt it specifically for use by hemiplegics. Hemiplegia is the loss of function on one side of the body; both left arm and leg, for example, and is usually due to a cerebrovascular accident (stroke). There are, however, numerous problems with the current design. This thesis evaluates two of the most serious design problems, and suggests possible solutions.

The current hand rim design makes the chair overly difficult to use for any length of time. It requires the user to simultaneously grasp two tubes at a distance of several inches from each other. This is an awkward grip in a single hand, and causes the user to tire quickly, especially on the rough terrain for which the chair is designed. Two alternatives, one using materials already part of the chair, and the other materials commonly found on site, are presented which make the grip much more natural, and less costly for the user. Both are presented in combination with the idea that a different hand rim shape might further improve ease of use.

The second of the two problems evaluated is the axle design, which currently renders the chair nearly impossible to use. The axle originally designed for the chair is a scissor extension that allows the chair to fold, but has a certain amount of implicit slack. This is magnified by the geometry of the chair, resulting in unproductive movement at the hand rim. This play makes turning very difficult, and straight forward and back motion completely unintuitive. Two possible solutions are presented, one of which is quickly eliminated due to manufacturing complexity. The other is then tested to prove it is in fact an improvement over the current design. The suggested modifications are made to a computer-generated model of the chair, and sketches are presented.

Chapter 2
Problem Criteria

Modern Wheelchairs are made with the newest materials and manufacturing techniques. They are lighter, faster, more stable, and more comfortable than anything ever made in the past. As a result, modern wheelchairs are also much more expensive. This makes quality, useful wheelchairs completely out of the reach of many, especially in developing nations. The cost for a finished chair is simply too high, and the means for working with anything more complex than simple aluminum does not exist.

2.1 Current Projects

Certain groups, such as Whirlwind Wheelchairs International (WWI), have developed a method for bringing modern wheelchair design to developing nations. They designed a wheelchair to be manufactured using only materials and tools commonly available in a third world country (sometimes nothing more than a hacksaw, drill, and oxyacetylene welder) at a fraction of the cost of a version with similar features. By giving people in these countries an achievable design, they both solve some of the wheelchair distribution problems and create jobs.

Other projects, such as the Gemini project, ship pre-fabricated wheelchair packages to these countries (in Gemini's case, Palestine), but this does not create a sustainable situation like the WWI chair does. Another organization, "The Mobility Project," refurbishes used wheelchairs and ships fully functioning models out, but again, is unsustainable in the long run without constant charitable support.

The chair designed by WWI is specifically made for a paraplegic who lives in an environment significantly rougher than a hospital floor. It has been proven appropriate in multiple countries. In every shop, they are encouraged to modify the chair to suit their particular demands, and are generally able to produce them for about a tenth of the cost of a new chair in America.

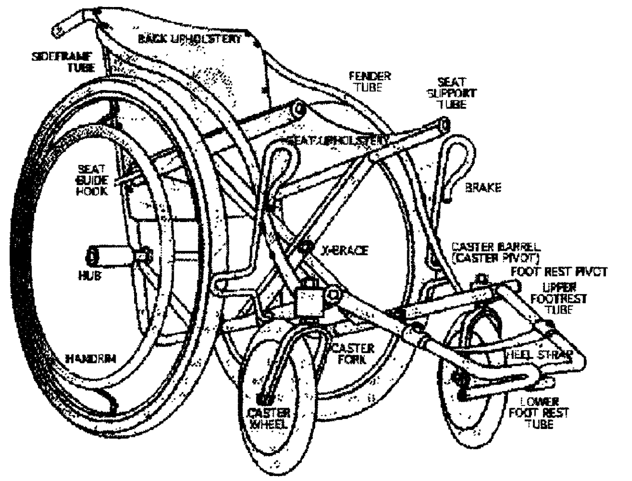
2.2 Whirlwind Wheelchairs International

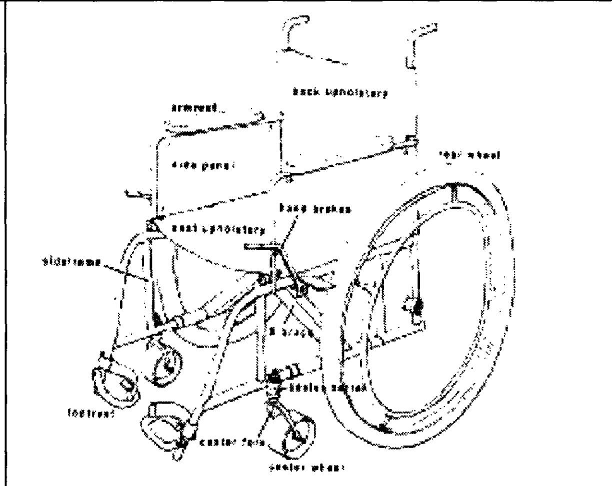
. Many countries, such as Mexico, Zimbabwe, and The Philippines currently use a version of the Whirlwind-style wheelchair described in the book Independence through Mobility by Ralf Hotchkiss. He won the MacArthur award in 1989 and has founded many organizations, including Whirlwind Wheelchair International (WWI) and Alternative Technology International (ATI). WWI has designed a plan for creating a wheelchair manufacture shop with an absolute minimum of materials. It assumes that the people in question have basically nothing, except a source for a loan and the ability to receive parcels. The book then details a method for setting up a shop, including a list of tools and materials needed, the number of man-hours supported by each chair, a price per chair that will repay the loans, and instructions on how to manufacture a chair for a specific-sized person. The company (ATI) also sells at a reasonable price a package including all of the jigs needed to make their custom-sized chairs. As such, modifications that use the same materials, jigs, and tools needed for the Whirlwind-style chair can be easily implemented into the manufacturing process already set up.

Chapter 3

Existing Technology

The Whirlwind chair looks like this:





The Whirlwind chair weighs between 20 and 35 lbs based on what materials and specific design modifications are used (Hotchkiss 125). The left shows the original frame design, while the right shows the adaptation used in Mexico, which will be used for the rest of the thesis.

3.1 The Whirlwind Wheelchair

The estimated cost per wheelchair, including wages for labor and administration, rent, materials, tool depreciation, and interest on the recommended loan amounts, in 1986 figures, works out to $197 (See Appendix A-1 for calculations). It is important to keep in mind that this figure includes everything needed to take a shop based on a loan out of debt. After applying inflation figures, this comes to approximately $320 (NASA). The cheapest folding wheelchairs at approximately the same weight (30-35 lbs), with no additional features, retail from Quickie © for around $875. The quickie 2, a folding chair that weighs in at 29 lbs retails for $1995 from Quickie ©, and, while there are numerous discounts available, prices for chairs in the same price range as those made in a Whirlwind shop are much heavier and do not have comparable features to the Whirlwind.

Beyond the simple matter of cost to the final user, the Whirlwind chair provides the immense advantage of creating a source of local employment. Each chair takes an estimated 40 man-hours to produce, and after the initial starting loan is paid off, there is a profit margin built into every chair. The combination of employment (specifically employment that can be filled by disabled people) and a potential source of emergency funds can have immeasurable benefit for a disabled community. Thus, while keeping final costs low with necessary features is the most important part of the design, creating a product that can be completely manufactured on site is additionally beneficial.

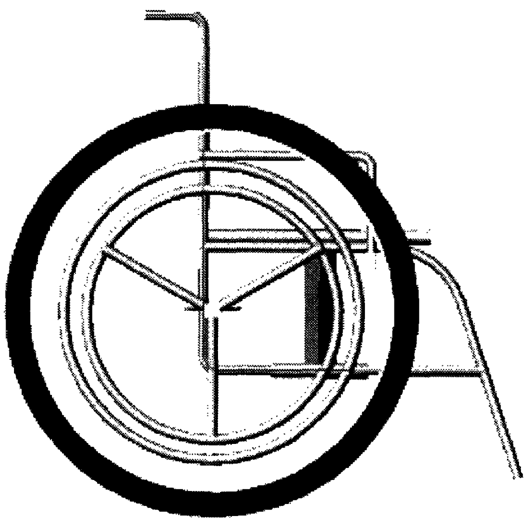
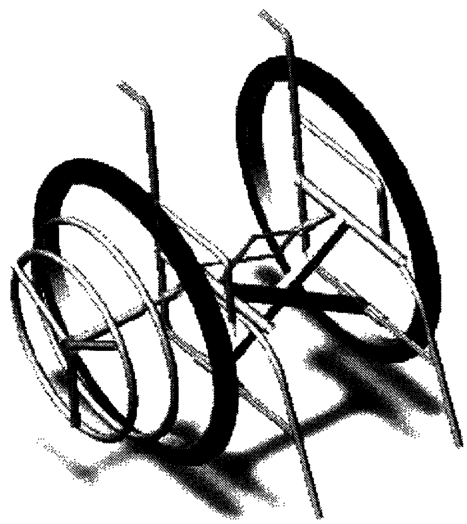
The current design is able to maintain such a low cost because it minimizes the number of different sized parts and materials needed. Most modern wheelchairs use a great number of parts, some of which are specially mass-produced for the chair, and a great variety of sizes of materials. The Whirlwind chair is based on the fact that labor is plentiful in many developing nations, while the initial investment in order to mass-produce or special order a part is not. The only parts that have to be ordered are common bicycle rims and spokes, which are cheaply available almost everywhere. A complete suggested parts list is shown in Appendix A-2 (prices are in 1986 figures). This list does not include the new, polymer front wheels that have been accepted nearly everywhere the Whirlwind is built, but they would simplify the list even further (WWI website).

The manufacturing required to make a Whirlwind chair involves significant skill. The initial assumption is that welding is done with Oxy-acetylene welders, although more complex welding techniques can be used. In order to start a shop, a skilled welder must be available. The bending of tubes also requires a lot of practice. This again is all predicated on the basis of labor being much more plentiful than capitol. While modern manufacturing techniques could make these parts faster, the setup costs are too high to make them feasible.

The Whirlwind design is impressively simple and inexpensive to manufacture. Unfortunately, one of the costs of this simplicity is that the chairs basically function only for paraplegics who still have full use of both arms. This often means that the manufacturers are forced to jury rig solutions for specific disabilities. In many cases this can be done simply without a great deal of modification to the chair design, for example by using a wooden plate behind the cloth seat to provide additional trunk support. In the case of disability in one of the arms, however, such as in the case of hemiplegia, more significant modifications must be made. WWI has begun to distribute a packet written by J.A. van Alphen and D.R. Arbib that details modification to the Whirlwind chair for hemiplegic users that they called the Double Hand Rim Model (DHRM).

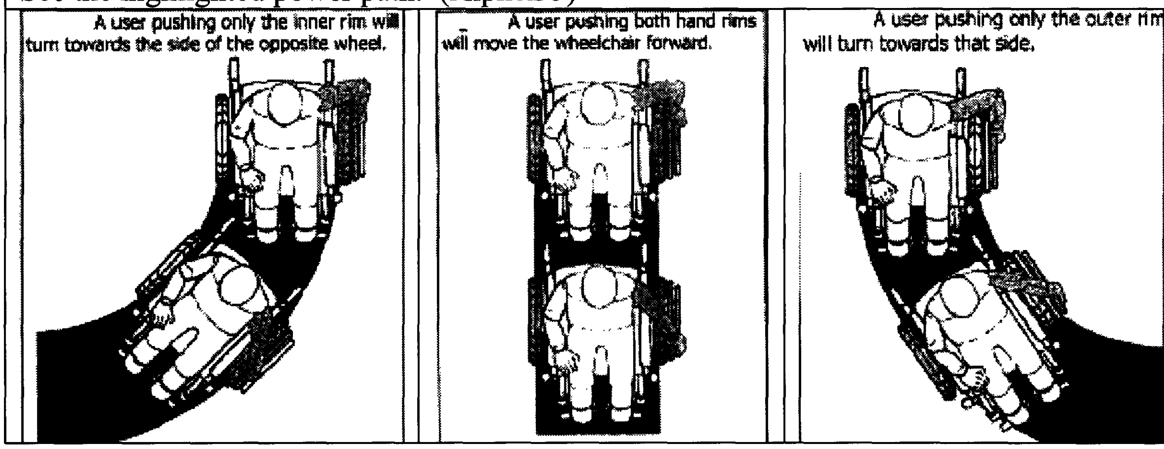
3.2 The Double Hand Rim Model Modification to the Whirlwind

The DHRM looks like this:

Front	Isometric
	
The DHRM weighs approximately two pounds more than the standard Whirlwind model wheelchair. It adds an additional inch of width to the overall chair, but this is still reasonable for most doorways.	

The basic idea behind the DHRM is the most popular one in use in US-manufactured chairs for hemiplegia. Instead of one hand-rim on each side of the chair controlling that side's wheel, there are two hand-rims on one side. One actuates the wheel on that side, while the other, by way of an axle, actuates the wheel on the opposite side of the chair. This allows a patient to move in a straight line by gripping both rims simultaneously with both hands, or to turn by using a single rim. Also, it allows the user to make very sharp turns by using the rims in alternation, one forwards and the other backwards, so that not much area is needed to complete a turn. This is very important for maneuvering inside the rooms of a house, as opposed to the open hallways of a hospital.

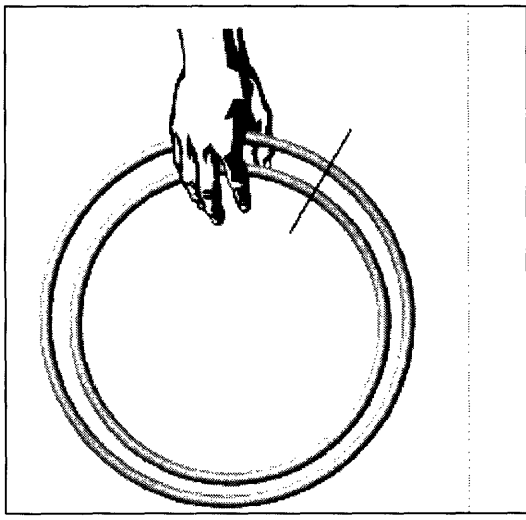
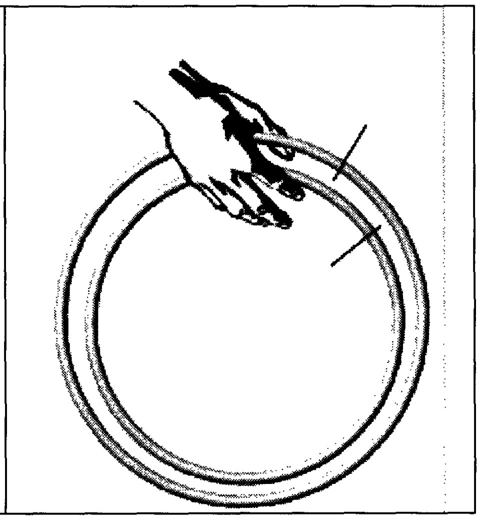
See the highlighted power path. (Alphen 5)



The modifications to the chair were designed to avoid disrupting the standard features of the Whirlwind chair. Thanks to a collapsing axle, the folding capabilities are undiminished, and since there is no rim on the non-actuating side of the chair, weight is increased only slightly (due to the axle). This also means that the manufacturing process was modified only slightly, requiring an additional bearing hub in order to accommodate the shaft that transmits power from the hand rim to the far wheel.

3.3 Problems with the DHRM

The DHRM wheelchair has been successfully manufactured once in Duranguito, Mexico, but was put on hold after that. It has not yet been put into production because it was deemed overly difficult to use. The most serious problems concern using both hand rims at once in order to move in a straight line. This is especially an issue since the chair is intended for use in places without paved roads, sometimes without finished floors, so a great deal of force is necessary even for a standard chair. The different height rims make it convenient to use one at a time, but almost impossible to grip and apply force to both. Also, due to the axle design, there is significantly more play in the control for the far wheel than for the near one. This means that every attempt to move in a straight line began with a turn away from the strong side:

	Goes To	

Chapter 4
Details of New Design

Since the manufacturing process has been proven as feasible in Duranguito, every attempt should be made to avoid changing significant portions of the chair. Still, modifications on the hand rims and axle seem essential, since the chair is basically un-usable as currently designed. Between the difficulty in gripping both hand rims and the play in the folding axle, it is very difficult for a strong person to maneuver in a straight line, even on a paved surface. On a hilly, or unpaved area, it is almost impossible. Thus, those two aspects were the focus for this redesign.

4.1 Hand Rim Redesign

Tests on non-disabled persons showed a unanimous preference for gripping a single tube or two adjacent hand rims at the same level as opposed to the two split-level hand rims currently in the DHRM. The easiest configuration to actuate would be a single tube, but, without a freewheeling system and gears, this would make turning impossible. The next best solution is having the two hand rims positioned as closely together as possible. There exists, however, the need to actuate one rim at a time. This means that in order to allow a hand to fit in between the two hand rims, there has to be some flexibility.

4.1.1 Spring Steel Spokes

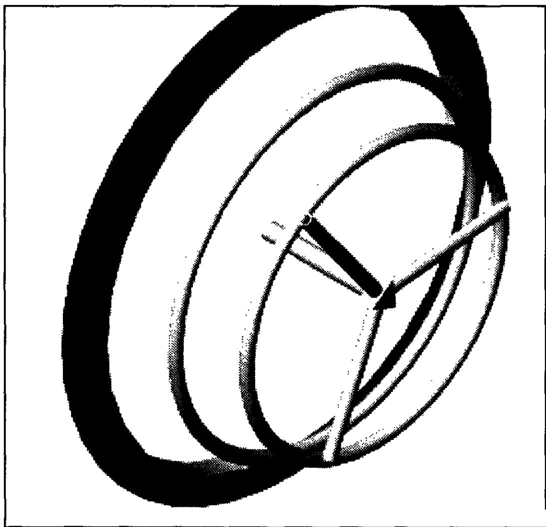
Using the available materials, it is possible to make a set of flat spokes that will act as cantilevered springs. The cantilever equations give the stiffness constant k as:

$$k = \frac{3EI}{l^3}$$

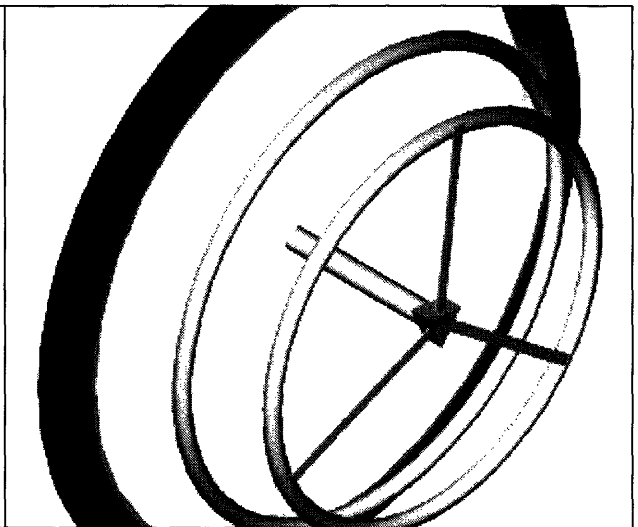
where the moment of inertia I is given by

$$I = \frac{bh3}{12}$$

Using the thinnest bar stock already available in the Whirlwind shop, $^1\!/_{16}$ " steel, in the dimensions necessary to connect the hand rim to the axle, the stiffness comes to less than 1 pound per inch in the direction which brings the two hand rims together. For example, if the two rims have a two-inch displacement, which allows a relaxed hand to slide through, then only 1.8 lbs of force are required to bring them together. The stiffness in the direction of rotation, however, is closer to 1500 pounds per inch. This ensures there will be no noticeable addition to the play when using the rim to move. The two-inch displacement also is well within the elastic range of the steel, so failure and deformation are not an issue (Please see Appendix B for spreadsheet of equations). The only problem that exists is that without spring steel, bending in the opposite direction, away from the other rim, will quickly deform the spokes. While they can be bent back into place, spring steel (commonly found in all wind-up machines and clocks) would make the design much more reasonable.



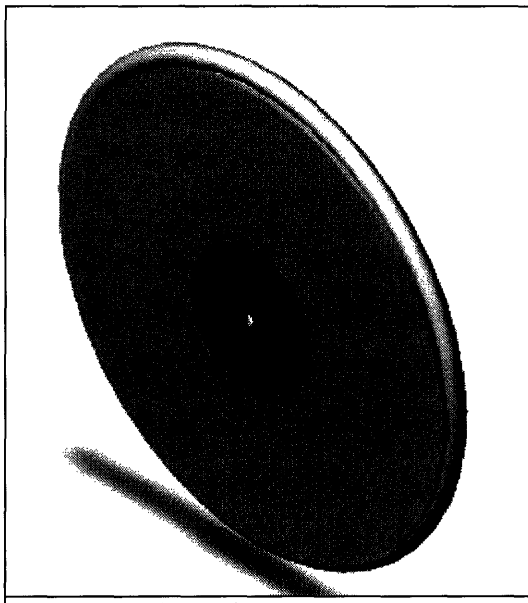
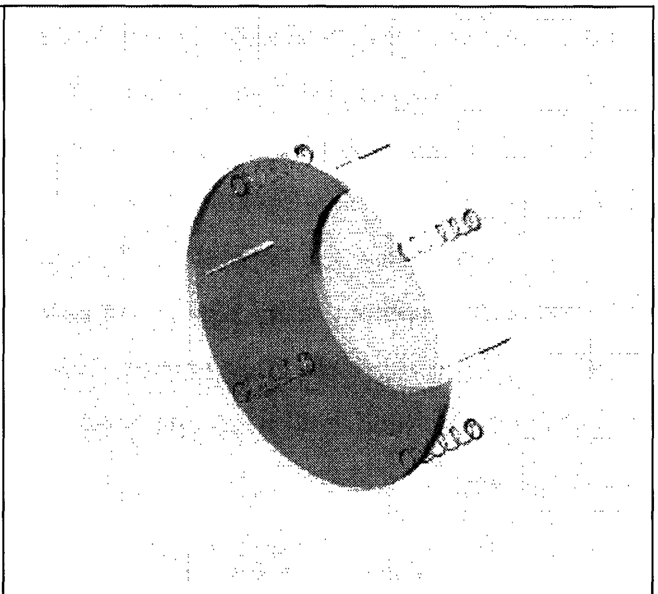
Currently, tubes are used as spokes



Flat spring steel spokes could allow bending

4.1.2 Old Tire Universal Joint

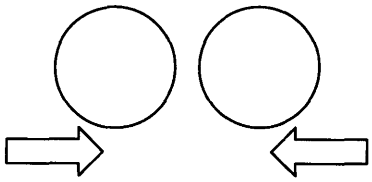
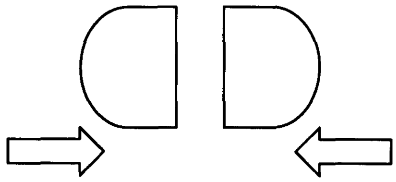
An alternative to the flat spoke solution would be to use the one polymer commonly found for free in many developing nations: old car tires. By cutting a disk from the sidewall of a tire, a universal joint can be created. Simply bolting the rubber to a wooden disk that supports the hand rim would make a cheap, simple alternative with a complete range of motion. This universal joint allows the rims to come together, is stiff in the direction of torque, and should wear very well. The effect is basically equivalent to a set of springs holding the disk in place:

	
Polymer Disk Joint	Equivalent mechanism

4.1.3 'D' Shaped Hand Rims

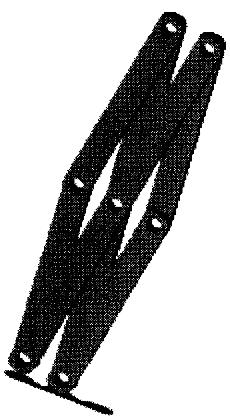
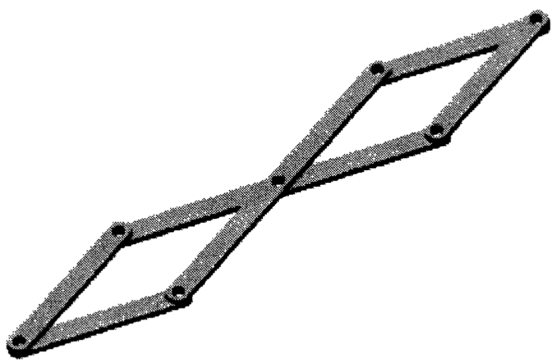
Since a secondary disability sometimes involved with hemiplegia is a weakness in the grip, something that allowed the chair to be used without needing to apply force to both sides of the hand-rim would be useful. Settings that locked the two rims into place when lateral force is applied would allow actuation of one or both without the need for a strong grip. The problem with adding this additional feature is the manufacturing situations in which this chair will be made. Regular machining requires the creation of expensive metal jigs, so creating matching surfaces on the two rims is not a possibility.

However, forming the rims in a "D" shape may be possible, and could provide a textured surface between the rims to ease the need for a strong grip. This could be done with a simple wooden block drilled to provide a curved surface. Without changing the weight of the rims, or requiring any additional materials, this would improve the ergonomics of gripping and moving both rims at the same time.

	
Current Configuration	D-rim

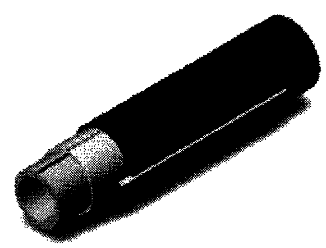
4.2 Axle Redesign

Much of the slack found in trials of the DHRM wheelchair was due to the method for transferring the power to the far wheel. The scissoring axle allows the chair to fold, but does not oppose the greatest dimension against the direction of torque. This means that while one hand rim is firmly attached to its wheel, the other has anywhere from a half inch to two inches of slack before actually beginning to apply torque. This makes going in a straight line a difficult prospect, and coming to a stop without turning nearly impossible. This problem becomes more severe with use as the holes in the scissor axle become slightly larger due to wear. Whatever solutions are found, however, must be feasible to make inexpensively in a Whirlwind shop, and also still allow the chair to fold.

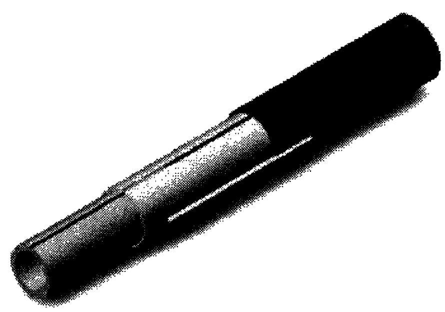
	
Current axle closed	Current axle open

4.2.1 Telescoping Tube Axle

Two modifications were evaluated in order to resolve this issue. The first was a telescoping set of tubes with slots and pegs in order to transmit torque. The different tube sizes are already available, and the pegs could be welded on. This would allow the chair to collapse, and would transmit torque with less slack then the scissor arms in the original design. Unfortunately, this design is only effective with a degree of precision not possible without a milling machine. Since these are unavailable to a typical Whirlwind shop, this solution was abandoned.



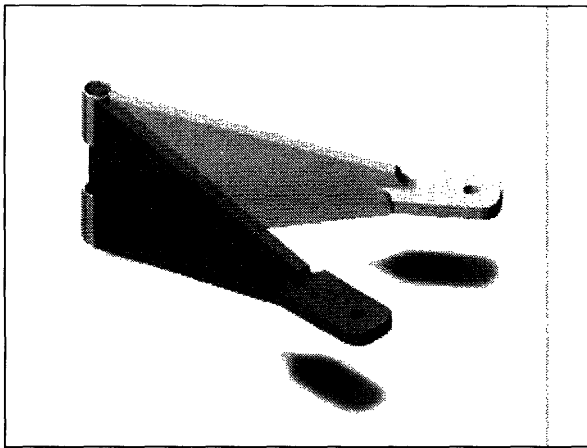
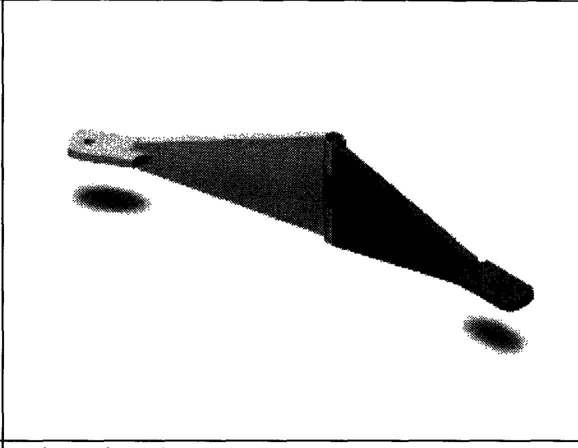
Telescoping Tube closed



Telescoping Tube open

4.2.2 Hinged Axle

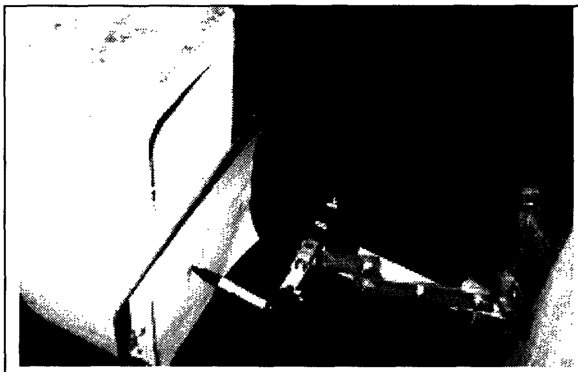
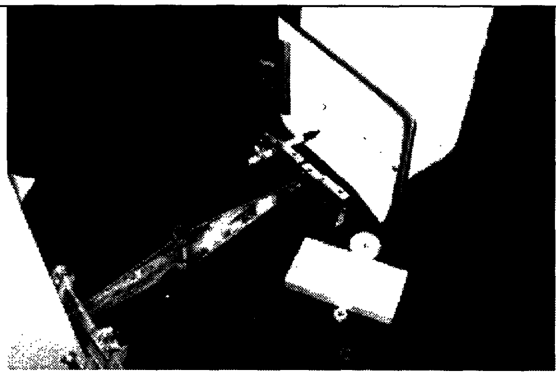
The second solution involved the use of a simple hinge with robust axial dimensions as the folding element in the axle. This allows the axle to fold in one direction, while still transmitting torque without significant slack. It also is significantly less dependent on precision machining than the rod and tube design, while wearing better than the scissor arm axle. It is able to fold to twice the diameter of whatever tube is used as the axle, which is more than is required by the rest of the frame. Also, if commercially produced hinges are not available cheaply enough (which is a possibility), then it would be reasonably simple to fabricate a hinge with the materials available in the shop.

	
Hinged Axle closed	Hinged Axle open

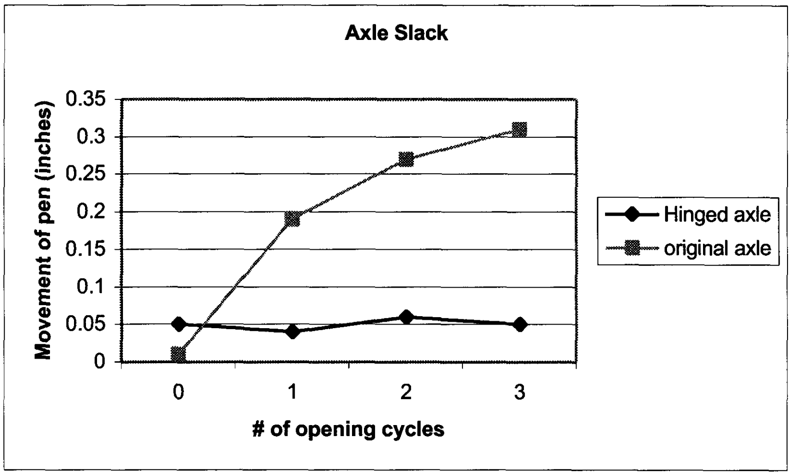
And additional potential benefit of the hinge is the ease involved in installing a locking mechanism. A simple deadbolt could lock the axle into the open position, making the power path even more rigid.

4.3 Testing the New Axle Design

Examples of the original axle and the hinged axle were fabricated and tested to see which allowed for more slack. The setup for the experiment simply measured the angle traced when a reasonable torque was applied in one direction and then the opposite. The setup is shown below:

	
Each axle is clamped in place at one end. A lever arm is then attached, and magnets are used to provide torque on the axle. Since the axles are both made of the same material (steel) it is not necessary to provide enough weight to deform the metal, only shift the axle pieces. The movement of the pen reflects how much slack is intrinsic in each axle.	

At first, the scissor axle, which was made with more precision than would ever be found in a Whirlwind shop, had no noticeable movement. However, when put through a single cycle of opening and closing the axle, slack appeared. Without that slack, the scissor axle would not be able to open and close at all. While locking nuts could prevent the extreme slack found after 3 or 4 cycles, without any slack it would be impossible to fold the wheelchair. The hinged axle performed consistently regardless of cycle number. Both axles weigh approximately the same, and so, with the additional benefit of better wear, the hinged axle is definitely the better option.



The quantitative results are presented in the preceding table. Using a similar triangle simplification, it is possible to generate a rough idea of how much slack the user would feel as a result of slack in the axle. Thus, after three cycles, the 1" scissor axle would cause approximately three inches of slack in the twenty inch diameter hand rim of the original chair. This is consistent with data from actual use in the field, and makes it very difficult to use, as each time the user attempts to change the direction of the far wheel, he or she has to rotate through three inches of travel before applying any torque. The hinge, on the other hand, generates only a quarter inch of play in either direction at the hand rim, which is much more reasonable.

The following chart summarizes the comparison between the two axles:

	Play at Rim	Dimension perpendicular to torque	Number of joints	Weight	Cost
Scissor	~3"	0.5"	6	0	0
Hinge	~0.5"	2" or more	3	0	-
The hinged axle is clearly better.					

4.4 Additional Desired Improvements

While the improvements above should make the DHRM usable in most instances, the power requirements in order to operate the chair in rough terrain or over long distances are still extremely high. Ideally, a mechanical advantage should be given to the user in order to resolve this problem. One possibility, based on a lever-arm propelled tricycle, is in production and available online (E-bility). Unfortunately, without gears or other precision parts, it is nearly impossible to fabricate such a solution. Using a lever arm such as is found in a hand tricycle or railway pump car, the user could not be given a mechanical advantage, instead he or she would get increased top speed at the cost of turning radius. In the end, the maneuverability of the chair is more important than racing down hills, so while the idea is attractive, the mechanical advantage is not attainable under current constraints.

Chapter 5
Conclusion

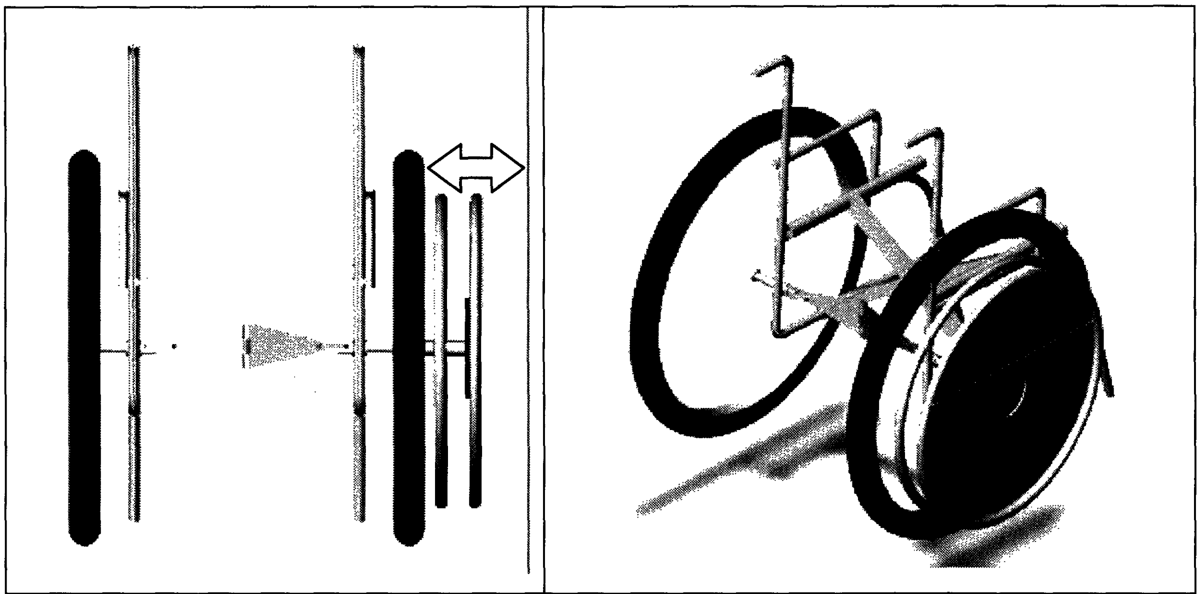
Since economic conditions inhibit importation, a wheelchair design for third-world manufacture is basically essential. Charitable organizations that ship chairs for free cannot hope keep up with the number of disabled, and the health care systems of developing nations often cannot provide adequate funds to import quality chairs. Programs such as Whirlwind Wheelchairs International also benefit the disabled community by providing jobs and a source of group income once the initial debt is paid.

The chair design offered by WWI is meant as a base to which disability-specific modifications can and should be made. The disability specifically considered by this thesis is hemiplegia. The design modifications written up by Alphen and Arbib provide a basis from which to work, but attempted manufacture shows that their final product is still unusable due primarily to two design flaws.

The first flaw, the axle, has too much slack to be usable. One rim spins significantly before encountering torque, while the other is hard-attached to the wheel. This makes it exceedingly difficult to travel in a straight line. The best solution to this problem is to use a hinged axle. The hinge allows the chair to fold, and can be manufactured from available materials, or bought commercially. The hinge also can easily be modified with a deadbolt to lock the axle in position. This axle redesign significantly reduces the amount of play in the outside rim, making chair use much more feasible.

The second problem addressed, the hand rims, are arranged in such a way that it is difficult for the user to grip both at the same time. This means quick fatigue when attempting to use the chair for any significant period of time, especially over rough terrain. Two possible solutions are presented, one relying on the shop being able to find spring steel in order to make spokes that will flex in a single direction, while the other uses used tire rubber to make a flexible polymer joint. Both solutions accomplish basically the same thing in that they enable the two rims to be brought together for easy gripping. This improvement is magnified if the rims are made to match up into a single tube.

Overall, the chair manufacturing process is practically unchanged. There is no significant increase in weight, width, or cost. This design is still not ideal for long distances, as, without precision gears, it is very difficult to grant the user a mechanical advantage. These changes, however, should make it possible to use the chair, which was not feasible with the original design.



The redesigned DHRM with hinged axle and polymer mounted hand rim.

Appendix A-1

Pricing

Debt Retirement and Interest (Paying back a Loan)

In calculating the expected cost per chair, we have assumed that the total capital investment of $11,300 was borrowed at a interest rate of 18% over a period of three years. This results in a monthly payment of $409. This figure will vary from one group to the next. Some groups will not need to borrow this much money (they may already have an established metal shop), and finance terms are likely to vary a good deal from one country to another. Be sure to use your actual figures to calculate your expected cost per chair.

The following chart is based on the first year's operation of the wheelchair factory of Asociacion Del Rehabilitacion Del Impedido De Asuncion, Paraguay. They have established a business with three mechanics producing 12 chairs a month; we have applied those figures to a four worker shop producing 14 chairs per month. This is 78% of a typical production capacity of 18 chairs per month. Fill in the blanks with the figures from your particular country and situation to estimate your own costs.

DIRECT COSTS PER WHEELCHAIR:		
Materials	$ 84	
Labor (40 hours at $0.75 per hour)	30	
Finishing (chrome plating parts of the chair and painting the rest)	15	
TOTAL DIRECT COSTS	*$129*	
INDIRECT COSTS PER MONTH:		
Rent	$160	
Administrative Wage (160 hours at $0.75 per hour)	120	
Accountant's Labor (16 hours at $3.00 per hour)	48	
Transportation (truck rental)	40	
Electricity	7	
Water	5	
Depreciation (Machinery, Tools, Jigs, Equipment)	109	
Equipment Maintenance	15	
Debt Retirement and Interest	409	
Office Expenses	8	
Phone	13	
Taxes	12	
TOTAL INDIRECT COSTS PER MONTH	$946	
INDIRECT COSTS PER WHEELCHAIR	**$ 68**	
(indirect costs per month divided by the number of chairs produced per month)		
TOTAL ESTIMATED COST PER WHEELCHAIR	**$197**	

(Hotchkiss 9)

Appendix A-1

Parts List

MATERIALS	Size	Metric Equivalent	$/Unit	Quantity (per chair)	Cost (per chair)
Bolts, N.F.	3/16" x 5/8"	5mm x 16mm	.02	8	.16
Bolts, N.F.	3/16" x 1-1/2"	5mm x 35mm	.03	10	.30
Bolts, N.F.	3/16" x 2"	5mm x 50mm	.03	8	.24
Bolts, N.F.	5/16" x 1-1/4"	8mm x 35mm	.05	4	.20
Bolts, N.F.	5/16" x 3-1/2"	8mm x 90mm	.07	2	.14
Bolts, N.F.	3/8" x 3"	10mm x 20mm	.18	1	.18
Bolts, N.F.	5/8" x 2-1/2"	16mm x 65mm	.36	2	.72
Bolts, N.F.	5/8" x 5"	16mm x 130mm	.62	2	1.24
Nuts, Locking N.F.	3/16"	5mm	.03	26	.78
Nuts, Locking N.F.	5/16"	8mm	.06	6	.36
Nuts, Locking N.F.	3/8"	10mm	.10	6	.60
Nuts, Locking N.F.	5/8"	16mm	.40	4	1.60
Screws, sheet metal	3/4 x #12	5mm x 18mm	.04	10	.40
Washers	3/16" I.D.	5mm I.D.	.01	20	.20
Washers	5/16" I.D.	5mm I.D.	.01	22	.22
Washers	3/8" I.D.	10mm I.D.	.01	4	.04
Tubing, per foot*	3/4" x .049"	See Chart	.49	20	9.80
Tubing, per foot*	7/8" x .049"	for	.89	11	9.79
Tubing, per foot*	7/8" x .125"	Equivalent	1.48	.25	.37
Tubing, per foot*	1" x .049"	Sizes*	1.00	4.25	4.25
Tubing, per foot*	1" sq. x .049"		.60	3	1.80
Tubing, per foot*	1-1/2" x .065"		.80	.75	.60
Bar, round, plated	5/16" diameter	8mm diameter	.40	3	1.20
Bar, round, per foot	3/8" diameter	10mm diameter	.40	1.3	.52
Bar, flat, per foot	1/16" x 1/2"	1.5mm x 12mm	.19	5.3	1.01
Bar, flat, per foot	1/8" x 1/2"	3mm x 12mm	.14	2	.28
Bar, flat, per foot	1/4" x 3/4"	6mm x 18mm	.37	2	.74
Bearings, sealed ball**	#6202 or 5/8" x 1-3/8"	See Chart**	.90	12	10.80
Pins, cotter	1/8" x 1"	4mm x 25mm	.10	2	.20

Handgrips*	7/8" I.D.	whatever fits	.49	2	.98
Plywood, square foot	3/4"	18mm	.70	2	1.40
Canvas, per yard	60" wide	1.6mm wide	7.00	1	7.00
Thread, yards or meters	heavy nylon	heavy nylon	.01	24	.24
Webbing, per foot	2" wide	5cm wide	.25	2	.50
Tires, solid rubber	8" x 1" or 1-1/2"	200mm x 25mm or 37mm	1.50	2	3.00
Tires, bicycle***	24" x 1.375"	no equivalent	3.50	2	7.00
Tires, bicycle***	24" x 1.375"	no equivalent	1.60	2	3.20
Rims***	24" x 1.375"	no equivalent	4.60	2	9.20
Spokes***	10-5/8" x 0.080"	270mm x 2mm	.05	72	3.60
Bands***	5/8" x 70"	1.6cm x 175cm	.15	2	.30
TOTAL MATERIALS					**$85.16**

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Appendix B

Spoke Calculation Tables

Using: $k = \frac{3EI}{l^3}$ and $I = \frac{bh3}{12}$

Force required to squeeze rims together

Force
7.8754883 Newtons
b

1.7704802 pounds

bracket width:	0.50	in
bracket length:	10.00	in
bracket thickness:	0.06	in
E of bracket:	200.00	GPa
displacement:	2.00	in

k= 0.88524 Lbs/inch

inertia 4.23413E-12

force to move wheel relative to hub in theta direction

Force
1701.1055 Newtons
b

382.42372 pounds

bracket width:	0.06	in
bracket length:	10.00	in
bracket thickness:	1.50	in
E of bracket:	200.00	GPa
displacement:	0.25	in

k= 1529.695 lbs/inch

inertia 7.31657E-09

Works Cited

Alphen, J.A. van and Arbib, D.R. "The Double Hand Rim Wheelchair: a mobility-aid for people with hemiplegia (half-body paralysis) in developing countries." Made possible by Health Wrights

E-bility. "Thompson Lever Arm Chairs." (http://e-bility.com/gtkrehab/products/thompson.php) 2003

Gemini Project, The. "The Gemini Project." (http://www.ntnu.no/gemini/1996-04/33.html) 2003

Hotchkiss, Ralf. Independence through Mobility: a guide to the manufacture of the ATI-Hotchkiss wheelchair. Appropriate Technology International, Washington D.C., ©1985

Quickie© Wheelchairs. (http://www.quickie-wheelchairs.com) 2004

Mobility Project, The. "The Mobility Project." (http://www.mobilityproject.org/wheelcha.htm) 2003

NASA. "The NASA inflation calculator." (http://www.jsc.nasa.gov/bu2/inflateCPI.html)