

# Design of a Stair-Climbing Hand Truck

by

Marissa L. Jacovich

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

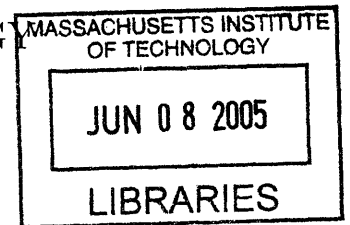
Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2005

© Marissa L. Jacovich, MMV. All rights reserved.



The author hereby grants to MIT permission to reproduce and  
distribute publicly paper and electronic copies of this thesis document  
in whole or in part.

Author ..... *Marissa L. Jacovich* .....

Department of Mechanical Engineering

June 6, 2005

Certified by ..... *Ernesto E. Blanco* .....

Ernesto E. Blanco

Adjunct Professor of Mechanical Engineering

Thesis Supervisor

Accepted by ..... *Ernest G. Cravalho* .....

Ernest G. Cravalho

Professor of Mechanical Engineering

Chairman, Undergraduate Thesis Committee

**ARCHIVES**



# Design of a Stair-Climbing Hand Truck

by

Marissa L. Jacovich

Submitted to the Department of Mechanical Engineering  
on June 6, 2005, in partial fulfillment of the  
requirements for the degree of  
Bachelor of Science in Mechanical Engineering

## Abstract

Every year, both at home and in the workplace, thousands of adults injure themselves while attempting to move heavy objects. Devices such as hand trucks are used to relieve the stress of lifting while on flat ground; however, these devices usually fail when it becomes necessary to negotiate a street curb or a short flight of stairs. The objective of this thesis was to design and test a consumer-grade hand truck capable of climbing stairs. Several designs were conceived that would allow a non-industrial hand truck to travel over stairs, curbs, or uneven terrain while putting minimal strain on the user. One strategy, referred to as the Blanco Stair-Climbing Wheel, was selected for development; several solid models were created and a prototype was constructed. The finished prototype was tested with a payload of approximately 300 lbs, and it was determined that the hand truck design using the Blanco strategy is a viable option for a stair-climbing consumer product.

Thesis Supervisor: Ernesto E. Blanco

Title: Adjunct Professor of Mechanical Engineering



## Acknowledgments

I would like to thank Prof. Ernesto Blanco for his support and guidance throughout this project. Special thanks to the staff of MIT Pappalardo Labs, for helping this project come to life; to Kate Thompson, for her wisdom, experience, sanity, and textbooks; and to Ross Hatton for the design advice and panic suppression. Finally, thanks to Profs. Alexander Slocum and David Wallace, who have provided far more inspiration to me in the past three years than they know.



# Contents

<b>1</b>	<b>Introduction and Background</b>	<b>13</b>
1.1	History of the Blanco Stair-Climbing System . . . . .	14
1.2	Previous Work . . . . .	15
1.3	Marketability of a Stairclimbing Device . . . . .	15
1.4	The Stair-Climbing Hand Truck: A New Product Concept . . . . .	15
1.5	Design Objectives . . . . .	16
<b>2</b>	<b>Theory of Stair-Climbing</b>	<b>19</b>
2.1	Analysis of Basic Stair Ascension . . . . .	19
2.2	The Dynamic Ramp Design . . . . .	20
2.3	The Tri-Star Wheel Design . . . . .	21
2.4	The Blanco Stairclimbing Mechanism . . . . .	22
2.4.1	The Jamming Effect . . . . .	22
2.4.2	Optimal Stair Compliance . . . . .	25
<b>3</b>	<b>The Design and Construction Process</b>	<b>27</b>
3.1	Design . . . . .	27
3.1.1	Blanco Wheel . . . . .	28
3.1.2	Propulsion . . . . .	29
3.1.3	Spoke Locking and Release . . . . .	30
3.1.4	Safety Factors . . . . .	30
3.2	Modeling and Construction . . . . .	32

<b>4 Results</b>	<b>35</b>
<b>5 Discussion and Conclusion</b>	<b>41</b>
5.1 Design Problems . . . . .	41
5.1.1 Wear and Fatigue . . . . .	41
5.1.2 Weight and Cost . . . . .	42
5.2 Conclusion and Recommendations . . . . .	43
<b>A Diagram of the Blanco Stair-Climbing Wheelchair [2]</b>	<b>45</b>
<b>B Motor Specifications [1]</b>	<b>47</b>



# List of Figures

2-1	Force diagram of a wheel driving over a stair. . . . .	20
2-2	Tri-star wheels. . . . .	23
2-3	Forces on the Blanco wheelchair during ascent. [2] See also Appendix A.	24
2-4	Approximate beam bending and shear diagrams for a jammed spoke.	25
3-1	Welded wheel base design. . . . .	29
3-2	Assembled dodecagon wheel base design. . . . .	32
4-1	Hand truck standing on safety stops. . . . .	35
4-2	Stair-spoke compliance. . . . .	36
4-3	Close view of clutch control handles and cables. . . . .	37
4-4	Hand truck during climbing operation. . . . .	38
4-5	Hand truck climbing with jammed spoke. . . . .	39
5-1	Welded tubing wheel base design. . . . .	42
A-1	Diagram of the Blanco wheelchair during the climbing process. [2] . .	45



# List of Tables

3.1 Stair-Climbing Strategy Selection . . . . .	28
B.1 Specifications for Ford Windshield Wiper Motor . . . . .	47



# Chapter 1

## Introduction and Background

The mechanical design process by definition defines a device that will carry out a specified task when appropriate inputs are given. In reality, however, this definition provides a tunnel-visioned view into the world of design. Mechanical engineers who design consumer products have a twofold responsibility. In addition to designing functional machines, successful product designers must create devices that consumers will want to purchase and use. While there are many possible factors that can make a product appealing to a buyer, perhaps the most important factor is an ability to make the user's life easier in some small way. In this way, product design is a service profession.

One basic principle of design that has become central to this product design project is that of reciprocity. Strictly speaking, the law of reciprocity applies to modal vibration problems; however, in a broader, more philosophical sense, the concept of reciprocity allows every problem to become an opportunity.[6] By turning a problem upside down or inside out, an improved design can emerge. This principle encourages creative thinking as well as reversal-based design. In this case, by the principle of reciprocity a stair-climbing wheelchair, a device that failed commercially because of liability concerns, inspired a new project, the goal of which was to create a product that would increase safety in a situation with an existing liability problem.

## 1.1 History of the Blanco Stair-Climbing System

The Blanco method of stair-climbing uses a surprisingly simple, purely mechanical system to climb up stairs and over varied terrain. This clever mechanism was conceived by Prof. Ernesto Blanco as part of his design for a stair-climbing wheelchair. In response to a challenge issued by the National Inventors Council in 1962, Prof. Blanco created several designs for a manually powered wheelchair that could ascend stairs. Since his design relies only on the occupant of the chair for power, his design is inexpensive compared to the electric stair-climbing wheelchairs currently on the market.

The most noticeable feature of Blanco's wheelchair design, and that which enables it to climb stairs, is the set of unusual wheels the chair rolls on. Spring-loaded spokes protrude radially from each wheel and are supported by two sliding bearing surfaces. A spoke can recede back into the wheel if a load is applied to it along the direction of the wheel's radius. If a load is applied to a spoke in any other direction, the bending moment will cause the spoke to jam in its sliding bearings, and the spoke will not move. The spokes thus conform to the stairs, and each wheel becomes a kind of compliant pinion gear against the stairs, which act as a rack (See Section 2.4 and Appendix A.) The wheels can thus adapt to stairs of different dimensions. The spokes terminate in rubber tips, which provide additional friction against the stairs and reduce the chance of slippage during climbing.

In stair-climbing mode, the chair is moved to a reclining position, such that when the chair begins ascent the seat of the chair is approximately horizontal. An additional set of smaller wheels with fixed spokes was added to the rear of the wheelchair for additional support during climbing. A 1/4 scale model of the wheelchair design equipped with a small electric motor demonstrated the wheelchair's independent stability.

## **1.2 Previous Work**

In cooperation with Prof. Blanco and fellow student Christina Laskowski, a full-size prototype was constructed as part of an Undergraduate Research Opportunity (UROP) during the summer of 2003. Before constructing the prototype, the design was modified to become more adaptable to existing standard wheelchairs. Wheel ratchets were added as a safety mechanism, and several new rear support assemblies were considered.

## **1.3 Marketability of a Stairclimbing Device**

While the Blanco wheelchair has been proven stable in both scaled and full-size prototypes, this design has never been adopted for mass production. The perceived liability inherent in any device that puts a human payload in a potentially dangerous position has prevented any wheelchair company from using the design.

The physical appearance of the wheelchair may be another factor that has prevented commercial development of the chair. With many metal spokes protruding from its sides, the appearance of the wheelchair in climbing mode is somewhat intimidating and entirely unlike any other stairclimbing device currently on the market. Focus groups composed of wheelchair users have expressed concerns of becoming stranded on a stairway. Potential users also worried that ascending a staircase in such a manner might cause dizziness or nausea, since one cannot prevent looking down at the distance traveled. User fatigue is also a concern, since it takes considerable effort to operate the chair.[5]

## **1.4 The Stair-Climbing Hand Truck: A New Product Concept**

Although the wheelchair may not have been successful, the principles behind its operation are sound. Since the main obstacle to its success was increased liability,

reciprocity dictates that a product that decreased an existing liability concern might meet with more success. Thus, several brainstorming sessions were conducted, focusing on how injuries occur near stairs, on people who encounter stairs in their work, and on what existing products might benefit from stair-climbing capability. The idea deemed most promising was that of a stair-climbing hand truck, an adaptation of an ordinary device used both in homes and in industry to move heavy objects.

The stair-climbing hand truck is designed to reduce liability rather than increase it. Conventional hand trucks work well on flat ground, but their usefulness decreases when it becomes necessary to move an object over an irregular surface. Package deliverymen, for example, often find it necessary to drag loaded hand trucks up short flights of stairs just to reach the front door of a building. The entire purpose of using a conventional hand truck is to avoid having to lift and carry heavy objects around. Lifting a hand truck up the stairs defeats the purpose of the device, since the user must provide enough upward force to lift the entire weight of the cart and its contents. Furthermore, the geometry of a hand truck makes it nearly impossible to lift with one's legs, as is the proper form. Considerable strain is placed on the back muscles and the risk of operator injury is sharply increased. Pulling a standard hand truck up the stairs results in bumpy, jarring motion. This motion may damage the items loaded on the hand truck or cause them to fall off entirely. A hand truck that could climb stairs without requiring the user to lift would improve the safety of moving heavy objects over irregular surfaces.

## 1.5 Design Objectives

The functional requirements set forth for this stair-climbing hand truck are:

- The device should be able to provide most or all of the upward force necessary to ascend a flight of stairs.
- The device should be able to bear up to 300lbs.<sup>1</sup>

---

<sup>1</sup>Three hundred pounds is a typical maximum load for an ordinary consumer-grade hand truck.



- The cost of the device should be comparable to that of a conventional consumer-grade hand truck. (retail < \$40)
- The product should be ergonomic and intuitive to use.
- The weight of the product should be comparable to that of conventional models.
- The appearance of the product should be similar to that of conventional models.

A hand truck with the ability to climb stairs would decrease the possibility of injury from having to lift a wheeled cart or its contents over an obstruction. If successful, this device should provide increased safety both in the home and in the workplace. Also, it is hoped that a simple stair-climbing device such as this one might increase public acceptance of other, more complex stair-climbing devices such as wheelchairs.



# Chapter 2

## Theory of Stair-Climbing

During the design process, several different stair climbing mechanisms were considered. The merits and faults of each approach were examined and some preliminary analysis was done. In the end the Blanco mechanism was chosen as the most fitting for the scope of this particular project.

### 2.1 Analysis of Basic Stair Ascension

Before delving into the theory behind complex stair-climbing mechanisms, it should first be noted that it is possible to climb stairs using an ordinary wheel. As shown in Figure 2-1, a properly applied force  $F$  will allow a wheel to drive over a stair.

In Figure 2-1,  $F_M$  is the force of gravity acting on the machine,  $F_S$  is the horizontal force exerted on the wheel by the stair,  $N$  is the normal force, and  $d$  and  $h$  are the diameter of the wheel and height of the stair, respectively.

Balancing the forces shown in Figure 2-1 yields

$$\begin{aligned} \Sigma M &= 0 \\ F\left(\frac{d}{2} - h\right) - F_M\sqrt{dh - h^2} &= 0 \end{aligned} \tag{2.1}$$

By simplifying the force and moment balance equations (2.1) an expression for the force necessary to drive a wheel over a stair can be determined. This force is given by

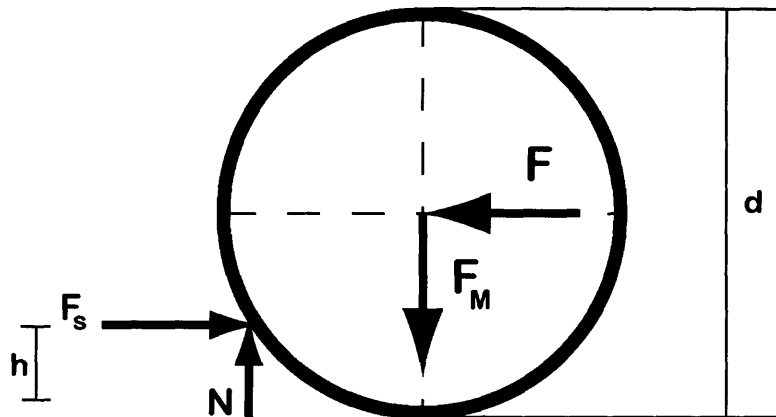


Figure 2-1: Force diagram of a wheel driving over a stair.

$$F = F_M \frac{\sqrt{dh - h^2}}{\frac{d}{2} - h} \quad (2.2)$$

As equation (2.2) demonstrates, this method of stair-climbing is only viable for stairs in which stair height  $h$  is less than the wheel radius  $d/2$ . To climb a over a step seven inches high,<sup>1</sup> each wheel would need to be at least fourteen inches in diameter. The large wheels necessary for this task make this method of stair-climbing somewhat undesirable. Also, the climbing motion produced by simply rolling over stairs is a jarring motion rather than a smooth one. In addition, the frictional force between the wheel and the edge of the stair must be sufficient to allow the wheel to grab and roll over the stair. A friction coefficient of too small a magnitude will cause the wheel to slip against the stair rather than climb.

## 2.2 The Dynamic Ramp Design

The most basic way to move a rolling object over a step is to employ a ramp. Some facilities have ramps permanently installed; in other places, a metal or wooden platform can be used to temporarily connect the top stair to the ground, creating an

---

<sup>1</sup>Seven inches is a standard riser height, determined by human factors.

inclined plane. A wheeled vehicle can roll up an inclined plane smoothly; however, it is often highly inconvenient for a user to need to supply such a ramp where no permanent one exists.

The dynamic ramp design is the most common method of moving heavy objects up stairs currently in use. The majority of such machines are for industrial use and can move refrigerators, vending machines, and other large pieces of equipment. Dynamic ramp designs generally involve at least two pairs of wheels mounted on the same frame. In addition to having rotational freedom, each pair of wheels is driven by an independent chain drive that allows the wheels to move laterally along the frame. While the lower pair of wheels rests on a step, an upper set is pulled upward on the frame. After reaching the next step, the upper wheels rest on the step and begin to push downward. Since a stair is blocking the downward motion of the wheels, the rest of the machine rises instead. This motion creates a "dynamic ramp" because the payload of the device moves as if it were on an inclined plane with a constantly changing angle.

This design provides a very smooth ascension; though the angle of the machine relative to the stairs is constantly changing, there is no jarring motion. The climbing process is very slow, however. Also, this fully powered method is expensive and is more suited to moving large, extremely heavy objects.

## **2.3 The Tri-Star Wheel Design**

The tristar wheel was designed in 1967 by Robert and John Forsyth of the Lockheed Aircraft Corporation.[7] They were first developed as a module of the Lockheed Terrastar, a commercially unsuccessful amphibious military vehicle. A tri-star wheel functions as an ordinary wheel on flat ground, but has the ability to climb automatically when an impediment to rolling is encountered.

This wheel design consists of three tires, each mounted to a separate shaft. These shafts are located at the vertices of an equilateral triangle. As shown in Figure 2-2(a), the three shafts are geared to a fourth, central shaft to which a motor is

attached. When geared in this quasi-planetary fashion, these triangular sets of wheels can negotiate many types of terrain, including sand and mud; they can also allow a vehicle to climb over small obstructions such as rocks, holes, and stairs.[4] The wheel assembly is gear-driven at all times, with two wheels in rolling contact with the ground. The third wheel idles at the top until the lower front wheel hits an obstruction. The obstruction prevents the lower front wheel from moving forward but does not affect the motion of the driving axle. This causes the top wheel to roll forward into position as the new front wheel. This wheel usually lands on top of the obstruction and allows the rest of the assembly to vault over the obstruction. Figure 2-2(b) illustrates motion of the tristar wheel on stairs.

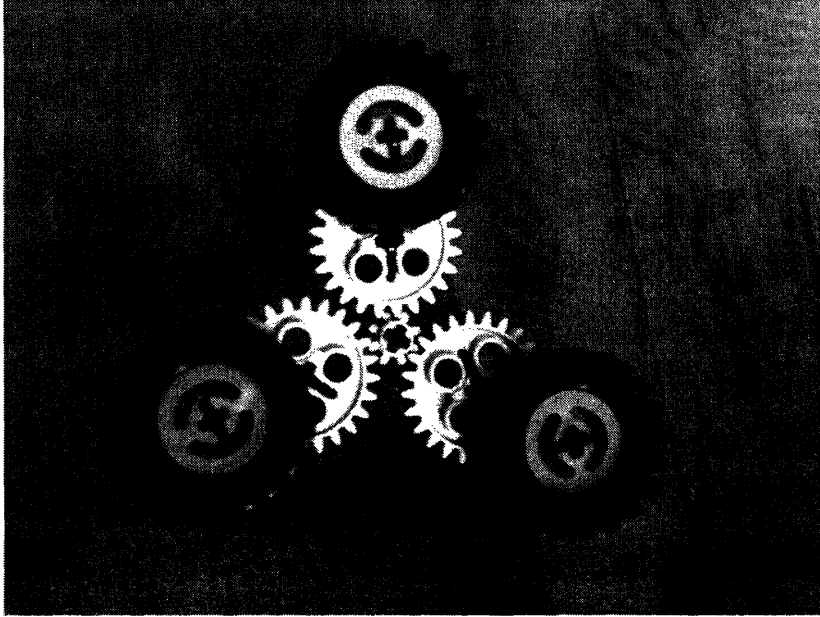
The tri-star wheel design allows relatively smooth ascension of stairs. The assembly functions in a similar fashion to a large wheel (as in Section 2.1) with several chunks missing. The compliance of the tri-star is greater than that of an irregular wheel, however, because of the gearing of the tri-star. In most cases, the gearing allows the mechanism to interact only with the horizontal and vertical stair surfaces, avoiding the points and wrapping around each stair. Unfortunately, this gearing system is relatively complex and expensive for its size. Its weight and cost make the full tri-star system overkill for a simple consumer-grade product; however, tri-star wheels might still be a realistic option if lighter, simpler wheels were to be designed.

## **2.4 The Blanco Stairclimbing Mechanism**

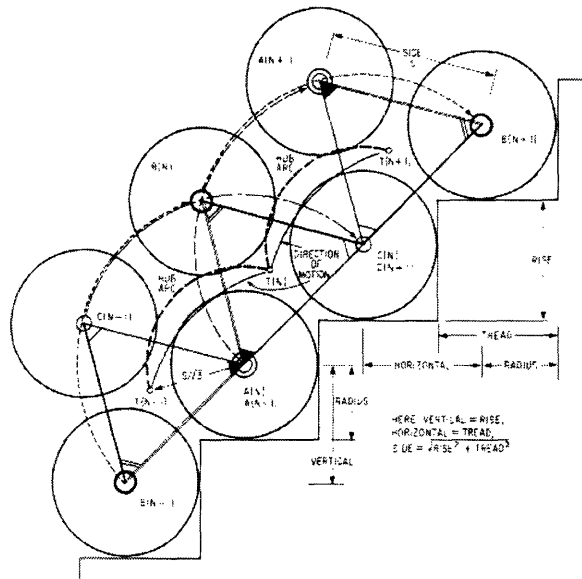
As was discussed briefly in Section 1.1, the Blanco wheel is able to climb because of the alternating compliance and support that its spoked wheels provide.

### **2.4.1 The Jamming Effect**

If a shaft is supported by two round bearings, it can slide and rotate freely. However, if a load is applied to the end of the shaft in any nonparallel direction, the shaft will jam between the bearings and will be unable to move. Known as the "jamming effect," in most machines this effect is extremely undesirable and is an impediment



(a) Tri-star wheel sketch model.



(b) Stairclimbing motion of a tri-star wheel assembly.[8]

Figure 2-2: Tri-star wheels.

to normal operation. However, in the true spirit of the principle of reciprocity, the Blanco design functions because jamming occurs.

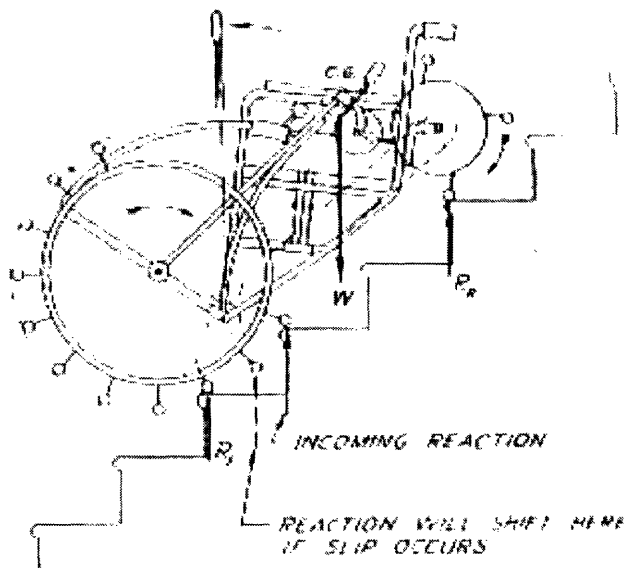


Figure 2-3: Forces on the Blanco wheelchair during ascent. [2] See also Appendix A.

Figure 2-3 illustrates the different states that spokes are in during the climbing process. One spoke at the very bottom of the wheel is vertical and completely compressed. Other spokes touching the side or bottom of the stair are compressed to varying degrees, and spokes not in contact with the stairs are fully extended. As the wheel turns forward, it slips against the stairs until an extended spoke hits the top of the next stair. The wheel continues to rotate, causing the stair to exert a force on the tip of the extended spoke. Acting as a circular member in simple beam bending, (see Figure 2-4) the spoke binds against its bearings. The now rigid spoke acts as a moment arm and can now carry the weight of the machine, vaulting it over to the next step. When this spoke becomes vertical, the sliding bearings unjam and, as the weight of the load exceeds the internal friction of the spoke mechanism, the spoke slides into compressed position.

The moment of inertia of a circular member [9] is given by

$$I = \frac{\pi r^4}{4} \tag{2.3}$$



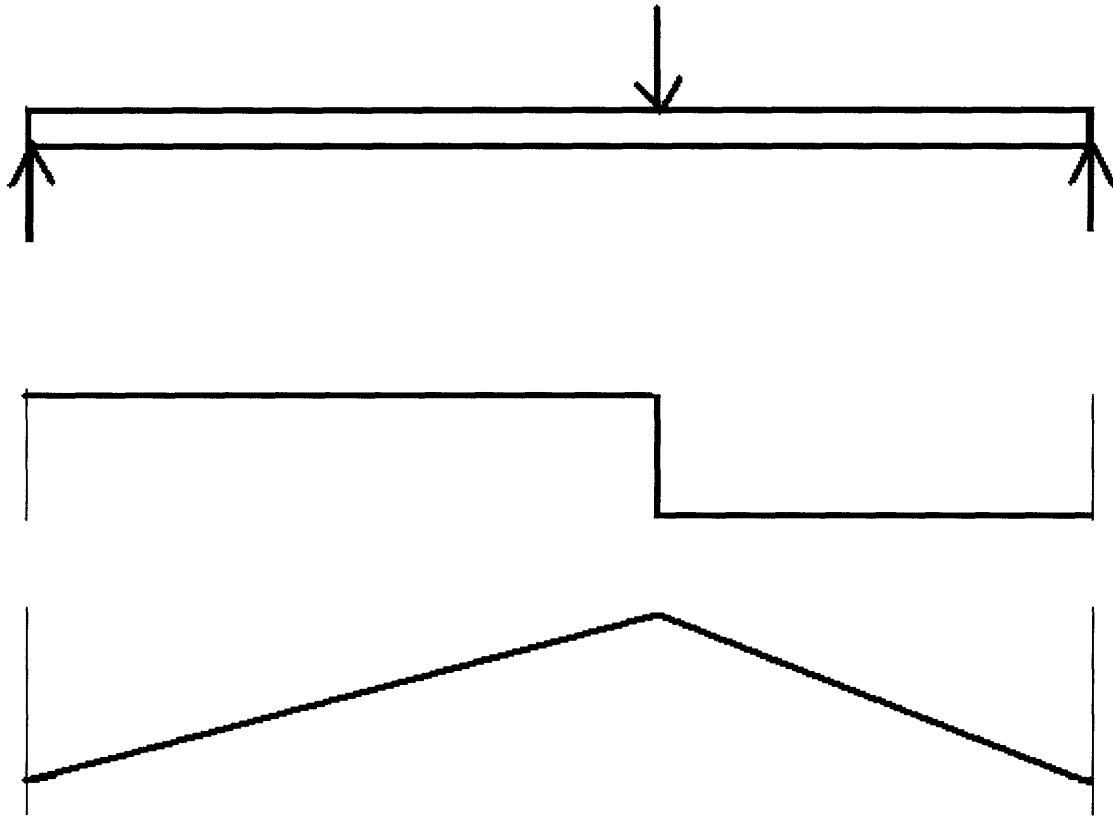


Figure 2-4: Approximate beam bending and shear diagrams for a jammed spoke.

### 2.4.2 Optimal Stair Compliance

Like the tri-star mechanism, the Blanco wheel interacts with the horizontal and vertical stair surfaces. The wheels are compliant with the points of stairs but no further loads are transmitted there. Clearly, the compliance of the wheel with a set of stairs increases with the number of spokes included in the wheel design. However, in practice the number of spokes in a wheel is limited by geometry as a function of spoke diameter and stroke. The absolute maximum stroke length for a spoke in this design is slightly less than one half the wheel radius. A long stroke length is desirable, since it creates a greater moment arm and decreases the likelihood of slippage. However, the wheels must not be made so large as to be ungainly and out of proportion to the device to which they are attached.



# Chapter 3

## The Design and Construction Process

This chapter discusses the evolution of the design from conception to its current state, as well as how the prototype was constructed and what tradeoffs were made.

### 3.1 Design

This section documents the decisions made during the design process. Possible implementations are discussed, as is the reasoning behind the final design choices.

Before any specific mechanical design could be performed, a basic method of climbing had to be chosen for focus. A stair-climbing strategy was selected from those discussed in Chapter 2. Each strategy was ranked according to its compatibility with the design objectives set forth in Section 1.5. Table 3.1 shows the full strategy selection ranking.

As Table 3.1 shows, the Blanco wheel seemed to have the advantage of simplicity over the other climbing designs.

Table 3.1: Stair-Climbing Strategy Selection

	Large Wheels	Dynamic Ramp	Tri-Star	Blanco Wheel
Quality of Climbing	-	+	+	+
Ease of Construction	+	-	0	+
Reasonable Cost	+	-	0	+
Low Weight	+	-	0	0
Familiarity	+	0	+	+
Total	3	-2	2	4

### 3.1.1 Blanco Wheel

The first task for this design was to determine the optimal method of adapting the basic Blanco wheel design to a hand truck. During the design process, multiple methods of constructing spring-loaded spokes and wheel bases were considered.

The simplest possibility was to drill a set of radial holes into a solid disc, creating a thick wheel base. A compression spring could be set in the bottom of each hole and a spoke could be attached to its top. This design is simple, properly constrains the spokes, and completely shields the springs and spoke ends from entanglement. Unfortunately this design is not practical on any reasonable scale: the amount of material required to manufacture this design is excessive, as is the weight this design would add to the machine.

Another simple design, in which each spoke was constrained by two bearing plates rather than a single long bearing surface, seemed more viable. In this case, the wheel base could be constructed by welding two concentric aluminum rings to an aluminum base. Holes could then be drilled radially through the welded assembly to ensure alignment. This design, shown in Figure 3-1, is robust and not excessively heavy.

With this wheelbase, a spoke would be allowed to slide through each pair of holes. A compression spring would be placed around each spoke and in between the two plates. One end of the spring would be fixed to the spoke such that the spokes are naturally in extended position. A hard stop would be placed at the end of each spoke to prevent it from flying out of the assembly.

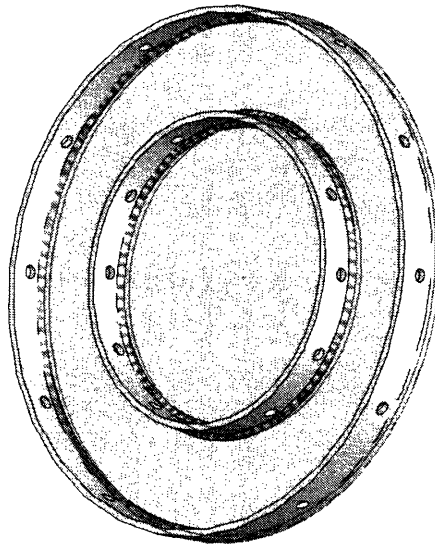


Figure 3-1: Welded wheel base design.

This wheelbase design allowed another possibility for spoke assembly, as well. The reciprocal method to that mentioned above would be to use hollow spokes of appropriate strength and extension springs rather than compression. The extension springs could be placed inside each spoke, thus avoiding possible entanglement and resulting in a more elegant look for the design. However, in order to secure a spring inside a spoke, the spring end would have to be pinned through the spoke. This complicates the assembly process considerably. A pin would obstruct the spoke's motion and additionally would create stress concentrations that could compromise the spoke's strength. It was thus concluded that the compression spring spoke design would suffice.

### 3.1.2 Propulsion

A bench level experiment was done to verify that freely rotating spoked wheels do not provide a significant improvement over ordinary wheels when there is an input force instead of an input torque. Thus, it was decided that it would be necessary to

power the wheels using high torque motors. To preserve steering ability, a separate motor was used for each wheel. Motor specifications are available in Appendix B.

### **3.1.3 Spoke Locking and Release**

While working on the stair-climbing wheelchair prototype (as discussed in Section 1.2) it was observed that while a wheelchair equipped with spoked wheels could function normally along flat ground, the unnecessarily contracting and extending spokes created a great deal of noise. It was thus decided that a method of retracting all the spokes for flat rolling travel should be incorporated into the design.

A simple method of controlling spoke retraction was arrived upon, utilizing the same principle of jamming that allows the spokes to function during climbing. Each spoke was equipped with a small metal plate with a hole punched in the center slightly larger than the spoke. The plate was hinged to the wheel base behind each spoke and preloaded with small springs. By preloading the plate in one direction, the plate would only allow the spoke to move in one direction. In the other, it would jam.

If the plates are allowed to move freely, all the spokes will have a natural tendency to lock inside. It thus became necessary to constrain the locking plates during climbing operation. A beveled clutch was designed to rest on the wheel axle without rotating with it. The clutch can be engaged and disengaged via wire cables, which are controlled by gripping triggers in the cart handle. The angle of the clutch bevel forces the locking plates to change angle as the clutch is engaged, allowing the spokes to slip. When the clutch is not engaged, the locking plates return to their default position. Within one full rotation of the wheel in normal rolling mode, all spokes will be locked in compressed configuration. The clutch is naturally in retracted position, so the triggers must be pressed for spoke release and stair-climbing.

### **3.1.4 Safety Factors**

Since this product is intended to assist users' handling of heavy loads in areas with high potential energy, it was necessary to include several safety features in the design.

Guards were placed over each wheel at a suitable distance to allow the spokes to pass underneath unobstructed while in fully extended position. This prevents payload from being stacked within the operating range of the wheels while the spokes are locked inside, since such an action would prevent the spoked wheels from operating properly.

As mentioned in Section 1.2, the previous design for the Blanco wheel included a ratchet, set either in the hub of the wheel or mounted along the rim. The purpose of this ratchet was to prevent the wheels from rolling back down the stairs during or after ascension. This ratchet could then be disengaged for ordinary rolling use. This ratchet system works well for the stair climbing wheelchair for which it was originally intended, since it prevents possible accidents due to excessive user fatigue.

A similar design was attempted for the stair-climbing hand truck, in order to prevent the cart and its payload from tumbling back down the stairs if accidentally released. However, it soon became apparent that in this case such a ratchet would do more harm than good. The location of the center of gravity of a loaded hand truck is much more variable than that of a wheelchair. Also, the angle at which the handtruck is carried up the stairs is greater than  $45^\circ$  and will vary somewhat with the user. Instead of stopping the hand truck on the stairs in the event of accidental release, ratcheting wheels could cause the hand truck to flip over. Flipping the cart is likely to cause more damage than a simple fall.

To eliminate this danger, the wheel ratchet was removed from the design entirely and was replaced with a basic safety stop. This simple stop design consisted of two lengths of steel pipe mounted on either side of the cart. These members can be extended during stairclimbing and retracted for normal use. The end of each pipe is fitted with a rubber tip. If the cart is released during stairclimbing, the cart rolls back a short distance until the rubber tips of the two pipes contact the previous stair. Binding friction between the stair surface and the rubber causes the cart to stop its descent. This safety stop is far less likely to cause the cart to tip over.

## 3.2 Modeling and Construction

Since the intent was to create a device that did not depart too far from an ordinary hand truck in appearance, a standard consumer-grade hand truck was purchased to use as a basis for a first-generation prototype. Solid models of all parts were created using SolidWorks CAD software. From these models, prototype parts were constructed.

As discussed in Section 3.1.1, the proper way to construct the wheel base involves welding two concentric rings to a flat aluminum plate. However, both the materials and welding ability necessary to create this part were beyond the resources of this project. A prototype-level approximation of the wheel base was constructed instead. This design performed the same functions as the original design. The base was created by cutting twenty-four slots into a twelve-inch lexan wheel using an OMAX waterjet. The slots were arranged in two concentric dodecahedrons, and a small sheet metal plate with a hole in the center was pressfit into each slot. The resulting array, shown in Figure 3-2, approximated the circular rings of the welded design. It should be noted that this part design is not intended for use in a production-level machine: it is not nearly as durable as the concentric ring design, and it requires excessive assembly.

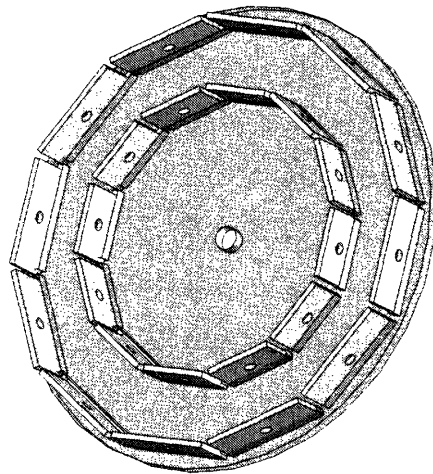


Figure 3-2: Assembled dodecagon wheel base design.



Steel spokes were cut to a length of six inches each, with a .25-inch diameter. A small rubber tip of moderate stiffness was press-fit onto the end of each spoke. The spokes were then assembled in the wheel base, together with the springs and locking plates. A rear lexan plate with identical waterjetted slots was press fit to the free sides of the plates. The rear plate contained a clearance hole to allow the clutch to move in and out. A hub of delrin was attached to each wheel base, thermoformed clutch parts were mounted on each hub, and the hubs was then pinned to half-inch aluminum shafts nine inches long.

After the resulting assembly was secured on the hand truck frame, control grips were mounted on the frame handles. Cables were then run between the clutches and the control grips. A nylon gear was pinned to each shaft at a distance that allowed the clutch sufficient room to move. Motors were then mounted to the frame of the hand truck such that the geared motor shafts engaged the axles.



# Chapter 4

## Results

The figures below show aspects of the completed prototype during operation. The modified hand truck was able to climb stairs while bearing a moderate load. The prototype was not tested with a full 300 pounds, due to the lack of a welded wheel base.

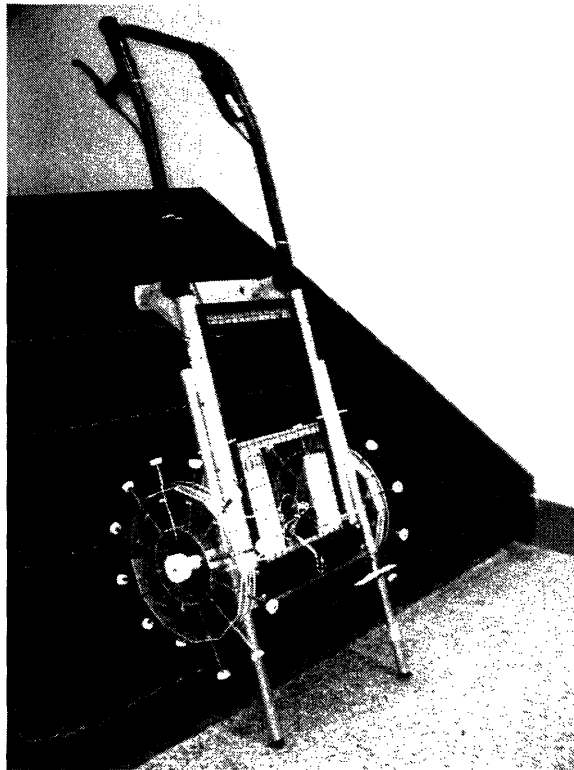
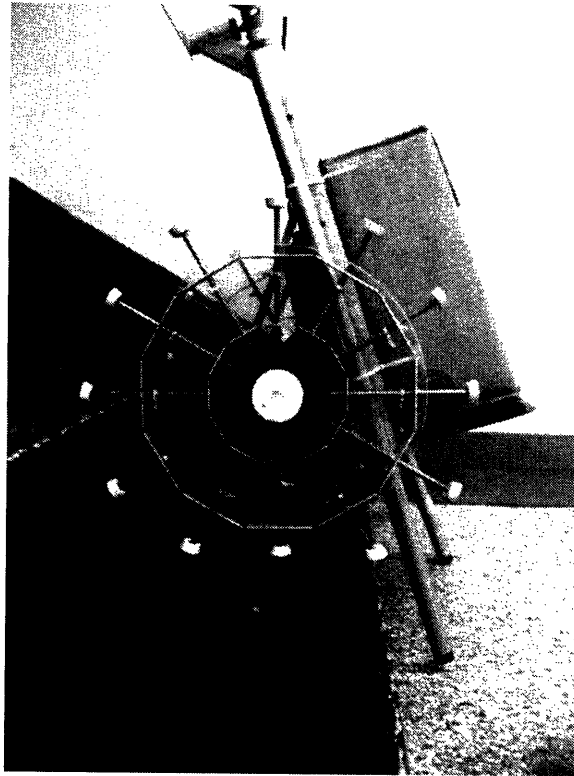
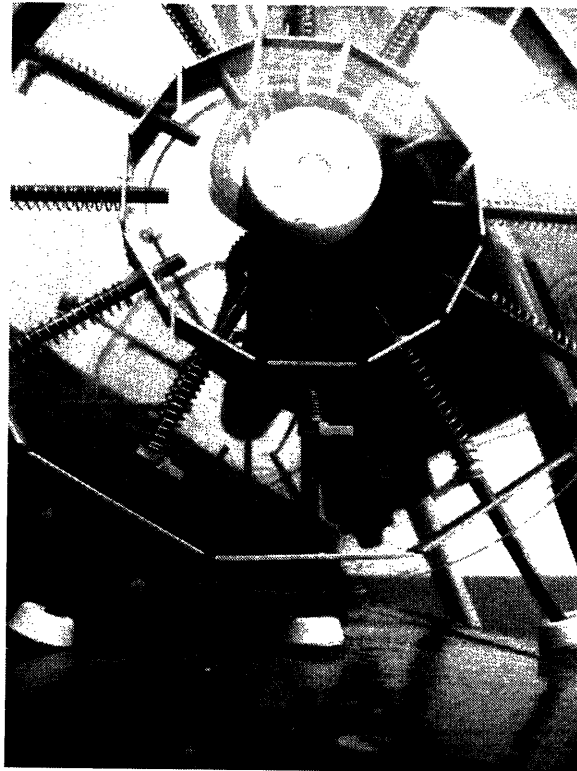


Figure 4-1: Hand truck standing on safety stops.



(a) Side view of hand truck.



(b) Close view of spoke compliance.

Figure 4-2: Stair-spoke compliance.

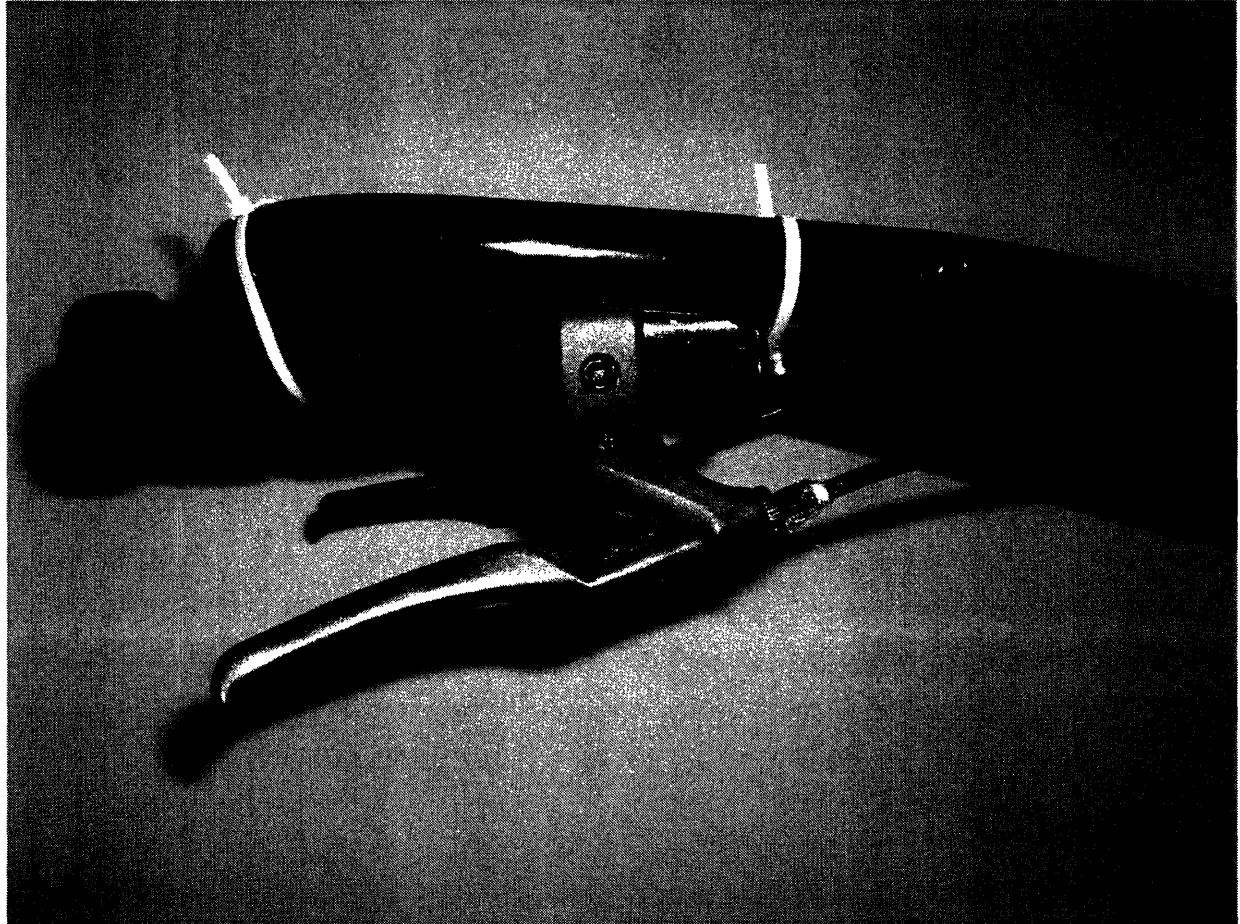


Figure 4-3: Close view of clutch control handles and cables.

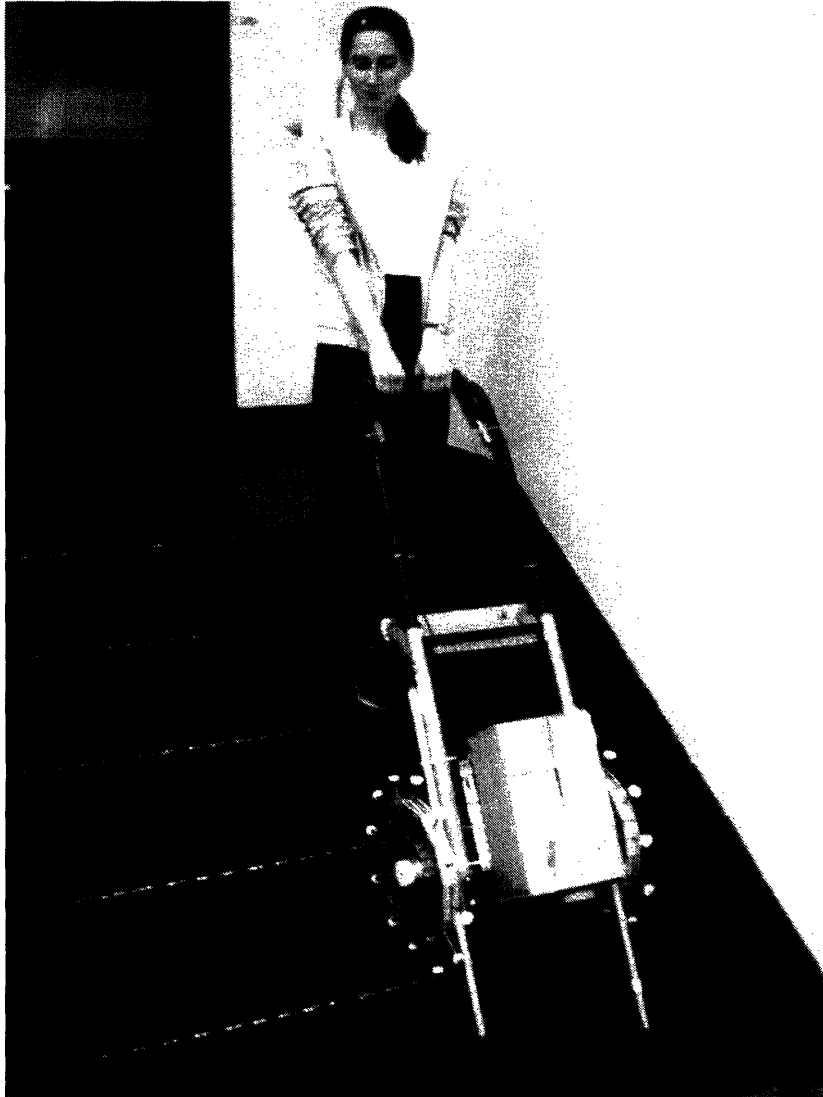


Figure 4-4: Hand truck during climbing operation.

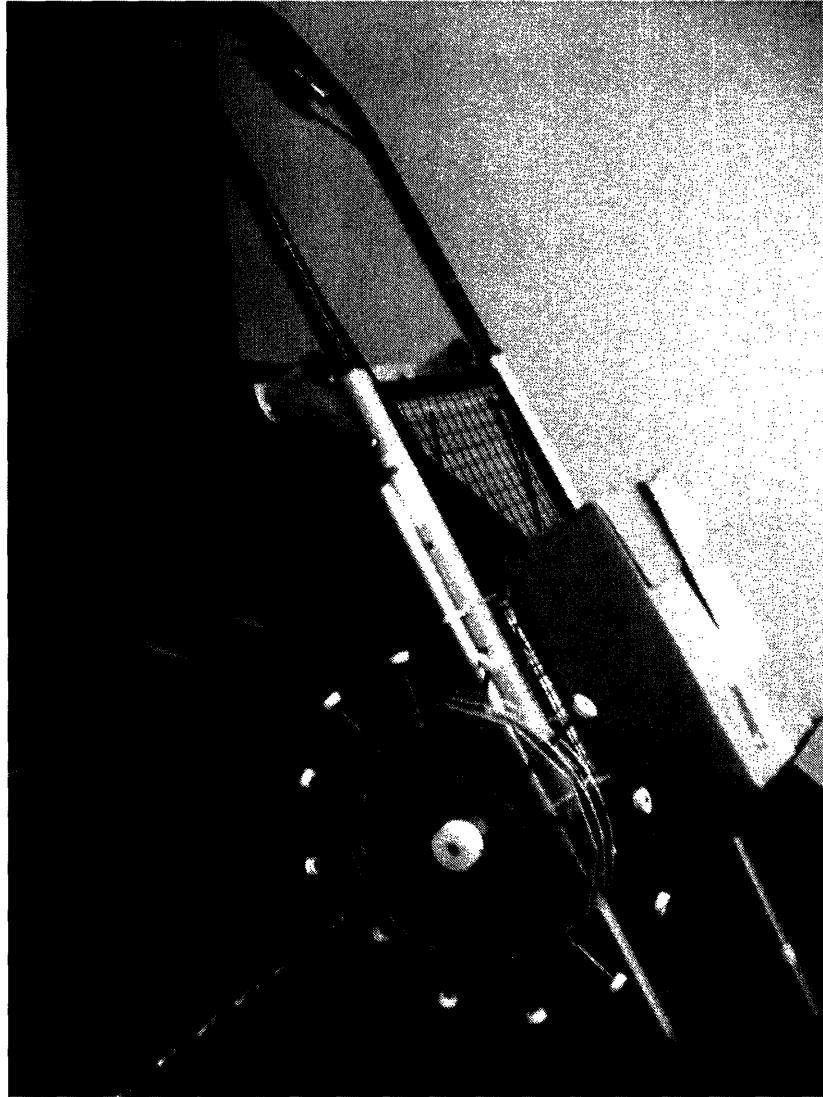


Figure 4-5: Hand truck climbing with jammed spoke.





# Chapter 5

## Discussion and Conclusion

The results of the prototype testing are encouraging, and the stair-climbing hand truck may yet become a commercial product. However, this first-generation prototype is far from perfect, and many design questions still remain.

### 5.1 Design Problems

The stairclimbing hand truck has been proven as a feasible solution to lifting heavy weights up stairs with reduced risk of injury. However, this design is not without its flaws. One principal concern is that wear and fatigue will result from cyclic spoke loading inherent in the Blanco mechanism. Also, the current power system of this design adds considerable weight and cost to the product.

#### 5.1.1 Wear and Fatigue

The Blanco mechanism relies on the jamming effect to function. However, after repeated use the contact surfaces that cause this frictional binding will begin to wear down. As that happens, the holes through which the spokes slide will become larger. In addition, the surface finish of the components will become slightly smoother. The resulting decrease in friction and increase in binding angle will cause the binding efficiency to drop and increase the probability of slip.

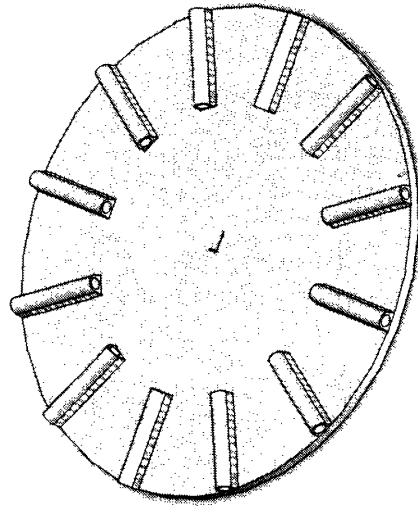


Figure 5-1: Welded tubing wheel base design.

One possibility is to replace the two bearing plates that each spoke passes through with a single tube, as shown in Figure 5-1. This approach produces the same binding effect as the two plates, since the spoke will jam with the ends of the tube. Wear against the jamming points will not have nearly as pronounced an effect, since as the tube edges wear the binding surface area will increase.

### 5.1.2 Weight and Cost

Since the Blanco mechanism wheels do not function effectively without an input torque, two high-torque DC motors were incorporated into the design. As a power source, a rechargeable lead acid battery was also added to the design. Together, these components add considerable mass to the design. These components also add complexity to the design, since measures must be taken to protect the motors and battery from incurring damage during operation. The presence of a battery also creates a inconvenience for the user, since by the user's responsibility the battery must remain charged.

The ideal case, of course, would be a design that relies only on human power to function. The challenge of this design is to require as little upward force as possible. As previously discussed, the Blanco mechanism in its current form requires an input torque to function; either a motor must power the wheels or the user must drive the cart by turning the wheels rather than pulling the entire device. It is possible that the desired effect could be achieved by including a ratchet driver in the design. Several designs for a ratchet driver have been developed for the Blanco stair-climbing wheelchair as a more ergonomic method of propulsion. [3] It is conceivable that the same concept could be applied to the hand truck; however, the ergonomic value and safety of using such a propulsion mechanism must be studied. Of course, the input torque necessary for the Blanco wheel to function may not be needed for other alternative designs. There is some question about the benefit of unpowered tri-star wheels; further analysis and experimentation must be done before a design is created.

Another way to avoid the inconvenience of rechargeable batteries is to create an alternative energy powering mechanism. A design could be created in which energy from the turning wheel axles is stored while the hand truck is rolling on flat ground. This energy might then be used to power the cart when in stair-climbing mode.

## 5.2 Conclusion and Recommendations

A stair-climbing hand truck using the Blanco mechanism has been proven a feasible design. However, it may not be the best design for a device whose goal is to climb stairs bearing a heavy payload. Although preliminary analysis suggested that both the tri-star and the dynamic ramp designs could potentially be incorporated into hand trucks, there was insufficient time and resources available to develop all three designs. To produce a successful product, these other design options must be examined more closely. Future work on this product should involve design and construction of other prototypes which use different stair-climbing strategies. Also, the possibility of a design that does not rely on an electrical power source should be investigated thoroughly. When several prototypes are available, focus groups should

be exposed to each design. User feedback from these focus groups will determine the most important product features from a consumer perspective. Following this process and repeating it as necessary will yield an optimal product.

# Appendix A

## Diagram of the Blanco Stair-Climbing Wheelchair [2]

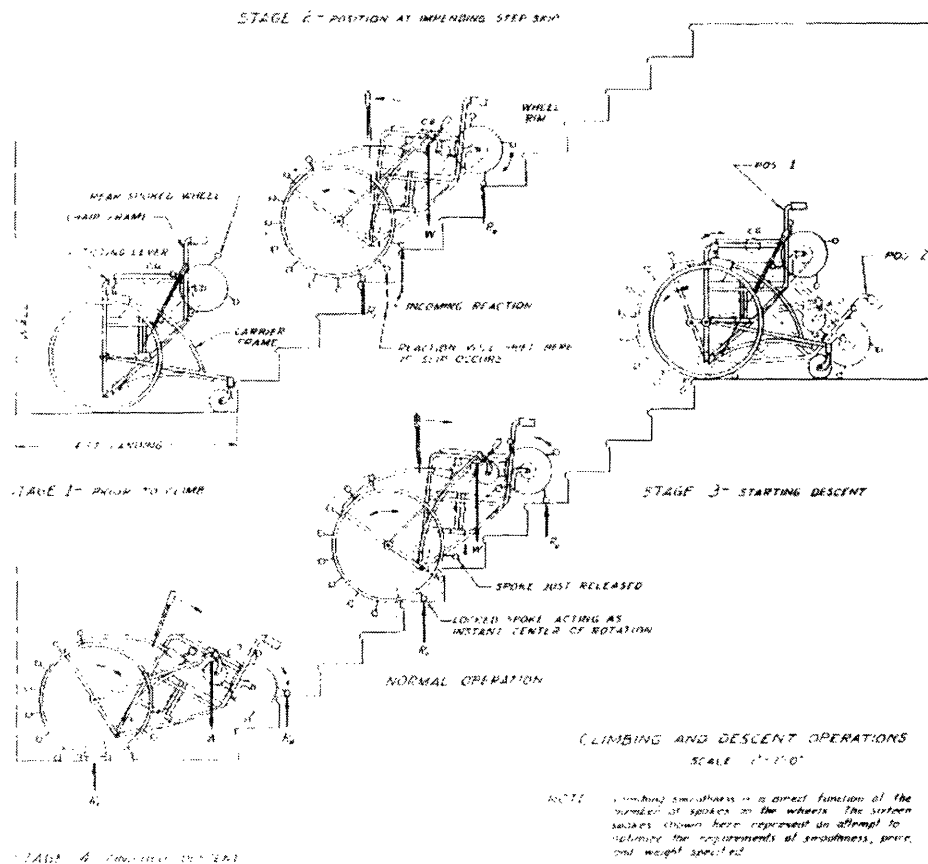


Figure A-1: Diagram of the Blanco wheelchair during the climbing process. [2]



# Appendix B

## Motor Specifications [1]

Table B.1: Specifications for Ford Windshield Wiper Motor

Nominal Voltage	13.8V
No Load Speed (@ 13.8V)	50 rpm
Stall Torque	123.9 in-lbf
Length	7.75 in
Height	4.0 in
Body Diameter	2.4 in
Weight	3.13 lbs
Shaft and Mounting Holes	M6 x 1.0





# Bibliography

- [1] Ford windshield wiper motor. <http://pergatory.mit.edu/2.007/kit/actuator/fordmtr/fordmtr.html>.
- [2] E. E. Blanco. Stair-climbing wheelchair: A case study in creative design. Department of Mechanical Engineering, Massachusetts Institute of Technology.
- [3] J. Choi. A re-redesigned frictional ratchet for wheelchair propulsion. Department of Mechanical Engineering, Massachusetts Institute of Technology, June 1995.
- [4] F. W. Crimson. *U.S. Military Wheeled Vehicles*. Crestline Publishing Co. Inc., 1983.
- [5] A. F. Hoermann. Feasibility analysis of a design for a stair-climbing wheelchair. Department of Mechanical Engineering, Massachusetts Institute of Technology, June 1997.
- [6] A. Slocum. 2.007: Introduction 2 design. 2000.
- [7] R. W. and J. P. Forsyth. Amphibious star-wheeled vehicle, October 1967. US Patent No. 3,348,518.
- [8] M. B. Weinstein. *Android Design*. Hayden Books, 1981.
- [9] W. C. Young and R. G. Budynas. *Roark's Formulas for Stress and Strain*, chapter 8-9, pages 230, 309. McGraw-Hill, 7 edition, 2002.