COMPARISON OF FOUR MANUAL WHEELCHAIR DESIGNS

by

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ABSTRACT

Musculoskeletal disorders, fatigue and other problems associated with the use of traditional, hand-rim wheelchairs have been documented in several studies. In response to these problems students in the Mechanical Engineering program at the University of Utah have created three alternative propulsion wheelchair prototypes. The three designs are the hand-lever, track-ball, and four-bar design. These wheelchair prototypes were designed to reduce injuries and fatigue, while maintaining safe, ergonomic function. This study tested and compared these prototypes, as well as a traditional hand-rim wheelchair. Each wheelchair propulsion system was evaluated using a wide spectrum of tests. This allowed the evaluation of each system's strengths and weaknesses. These tests included metabolic evaluation, maneuverability, usability and biomechanical modeling. The metabolic testing revealed that the upper body propulsion systems had lower energy demands than the lower body propulsion systems. Maneuverability testing found that the arm lever and hand-rim systems were the two systems which were most maneuverable. Biomechanical modeling noted that the hand-lever had lower force requirements and lowest joint moments than the hand-rim design and the four-bar had lower force requirements and lower joint moments than the trackball.

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First and foremost I want to give my thanks to God. He has given me everything that I have. His patience and never ending love has given me blessings in my life, far greater than anything I could have imagined. I also want to thank my wife. Without her love and support I never would have been able to reach this point. She encouraged me to chase my dream of becoming a mechanical engineer. I would also like to thank my father and mother, who taught me the value of hard work and honesty. I would like to thank Dr. Don Bloswick for being my mentor and guiding me through the Ergonomics and Safety program and Dr. Andrew Merryweather for guiding me through this thesis. I also give thanks to Louise Butler for all her work on the biomechanics portion of the thesis.

1. INTRODUCTION

1.1 Wheelchair history

Using wheeled chairs to transport people dates back to at least the 6th century, as recorded on a stone slate which was found in China [1]. However, these early wheelchairs were essentially slightly modified wheelbarrows, which had to be lifted by an able bodied person. It was not until a thousand years later that there is record of a manual self propelled wheelchair being designed and utilized. The first self-propelled wheelchair was designed by the paraplegic watchmaker Stephan Farfler in 1655 using his knowledge of mechanical systems from his trade.

The next major advancement in wheelchair design was made by Everest and Jennings in 1933. Henry Everest was an engineer who used a wheelchair after a mining accident. He was a close friend to a mechanical engineer named Harry Jennings. Everest desired to take his wheelchair with him when he traveled in a car, but it was too cumbersome. In response to this problem the two discussed improvements that would make wheelchairs lighter and more transportable. Using their ideas Jennings built a lightweight folding wheelchair in his garage. This wheelchair was based on an x-brace design, which allowed the wheelchair to be folded so that it would fit into a car. In addition the use of thin-walled steel tubing greatly reduced the weight. The same x-brace design along with thin-walled steel tubing is still used in the majority of folding wheelchairs manufactured today. After making some slight modifications to their design, the first lightweight foldable wheelchair was patented [2].

Currently the weight of many wheelchairs has been further reduced through the use of aircraft aluminum, titanium, carbon fiber and other lightweight building materials. Use of these lightweight materials allows construction of wheelchairs that weigh as little as 15 pounds. Although currently there is widespread use of lightweight building materials in wheelchair construction, the framework of most modern folding wheelchairs remains the same as Jennings' 1933 design.

Although there has been an increase in the availability of motorized wheelchairs, it is estimated that over 90% of wheelchairs are hand-rim propelled manual wheelchairs [3]. One reason that these wheelchairs remain popular is that they are only a fraction of the cost of motorized units. Also, traditional wheelchairs allow wheelchair users a greater degree of physical activity, to maintain good health. Manual wheelchairs also have greater maneuverability than most motorized wheelchairs and scooters [4]. Apart from these benefits there are also several problems associated with manual wheelchair use.

1.2 Problems associated with manual wheelchair use

There are many problems associated with manual wheelchair use. Research has shown that wheelchair propulsion is energy inefficient due to the biomechanical disadvantage of hand-rim propulsion [5]. A large amount of energy is required to do a small amount of work. In addition many wheelchair users must provide all the effort for propulsion using their arms. This greatly increases fatigue due to the small muscle mass of the arms and the limited physical work capacity of the arms [6].

Studies found that hand-rim wheelchairs are often only 2-10% mechanically efficient [7-8]. Part of this inefficiency is because the preferred direction of applying force to the wheel-rim is not in the optimal direction for power production [9]. A large amount of the force is used to apply friction to the rim rather than contributing to forward motion. This results in overexertion and fatigue of the muscles used for wheelchair propulsion. Overexertion of muscles during manual wheelchair propulsion causes a host of musculoskeletal disorders, such as shoulder, elbow, wrist, and hand pain [10-11]. One study found that 72% of wheelchair users suffered from pain in the wrists and/or shoulders [12]. These injuries often result in a debilitative cycle which leads to inactivity and increases the onset of associated long term health problems [13].

Apart from musculoskeletal disorders and fatigue, there are other problems associated with hand-rim wheelchair use. In order to slow a hand-rim wheelchair the user applies pressure to the wheel-rim with the hands. However, while using a hand-rim wheelchair in inclimate weather, such as in the snow or rain, there is reduced friction between the hand and the rim. The reduction of friction causes two problems. First, the wheelchair user needs to apply greater force to the rims in order to stop. This extra exertion may result in an acute injury to the hands, muscles or joints. However, despite their best efforts wheelchair users may still not be able to apply sufficient friction in order stop or slow the wheelchair. This may result in an accident which may injure the wheelchair user or others.

Physicians encourage wheelchair users with lower body strength, such as many of the elderly, to continue exercising their leg muscles. One of the easiest ways for wheelchair users to exercise their legs is to extend their legs at the knee to propel themselves backwards while sitting in the wheelchair. Forward propulsion using the legs is nearly impossible due to the position of the wheelchair framework. This rearward motion in a wheelchair presents a safety risk because often the elderly and others confined to wheelchairs have reduced range of motion in their necks and cannot easily turn their heads to see where they are going. This places them and pedestrians around them at greater risk of serious injury, especially in a nursing home environment [14].

1.3 Alternative propulsion wheelchairs

In response to the recognized problems with hand-rim wheelchair propulsion, several alternative propulsion wheelchair prototypes have been designed and built by students in the University of Utah's Mechanical Engineering program. These designs consist of one upper body propulsion wheelchair and two lower body propulsion wheelchairs. The upper body propulsion wheelchair which was tested is the hand-lever design. The lower body propulsion wheelchairs are the trackball and the four-bar designs.

1.3.1 Hand-lever propelled wheelchair

The hand-lever propulsion system allows wheelchair users to utilize larger muscle groups, such as the latissimus dorsi, to propel their wheelchairs. Studies have noted that lever propelled wheelchairs produce less physical strain [15-16] and are more mechanically efficient than traditional hand-rim wheelchairs [17-18]. Another benefit of the hand-lever design is that the wheelchair users do not have to grip near the wheel, as with the traditional hand-rim design. This reduces exposure of the hands and clothing to water, snow, dirt, and other foreign matter that may be on the wheel surface. The hand-lever propulsion design is shown in Figure 1.1.

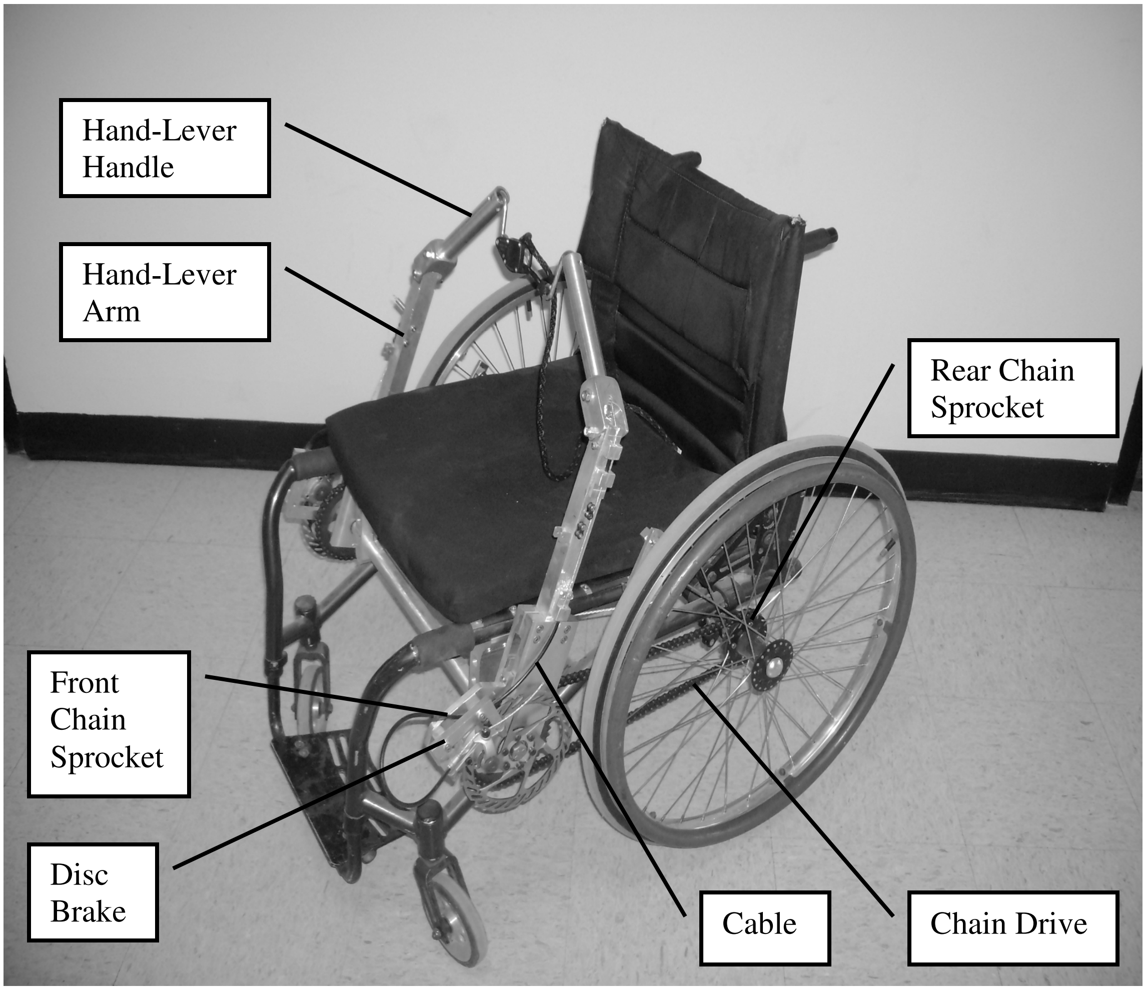

Figure 1.1 Hand-lever Design

The hand-lever design uses two levers connected to a system of disc brakes and chain drives. Each chain drive is connected to a sprocket on a disk brake and another on the rear wheel. To use this system the occupant raises the levers from the sides of the wheelchair and grips the handle at the end of each lever. There is a swivel located below each handle. When the handles are pulled medially towards the occupant, a cable is tightened which causes two brake pads to grip a disk brake. After the disk brake is applied, movement of the levers will cause the rear drive wheels to move forwards or backwards, depending on the direction the levers are actuated. In addition to forward and rearward propulsion the levers can also be used to slow or stop the wheelchair. When the handles are turned inward with the levers stationary, the brakes will be activated. The braking force is proportional to the force used to turn the handles medially.

1.3.2 Track-ball

Many wheelchair users with lower body strength push their feet against the floor in order to exercise their leg muscles. This movement of the legs is often referred to as knee extension. Unfortunately, knee extension causes traditional wheelchairs to roll backwards. This backwards motion may result in an accident due to lack of rearward visibility. The track-ball wheelchair translates the wheelchair user's knee extension into forward wheelchair propulsion. This allows the wheelchair user greater visibility in the direction of travel. Therefore, the risk of accidents is greatly reduced. In a study at an extended care facility, the trackball was preferred by subjects over several other knee extension propelled wheelchairs [12].

The track-ball design (Figure 1.2) consists of an aluminum ring attached to the front of a traditional wheelchair. This aluminum ring is lined with spherical rollers. In the center of this ring is a standard sized, textured rubber basketball to provide a high coefficient of friction. The wheelchair user places one or both feet on top of the basketball surface. As force is applied, the ball is rolled and the wheelchair will travel in the direction that the feet are pushing. Therefore, if the feet are pushing forward the wheelchair will travel forward. This system can also be used to turn the wheelchair and to go in reverse. The basketball is located approximately one foot in front of the wheelchair. This space allows most track-ball users to easily reach the ball with their feet and provides sufficient space for foot movement on and around the ball.

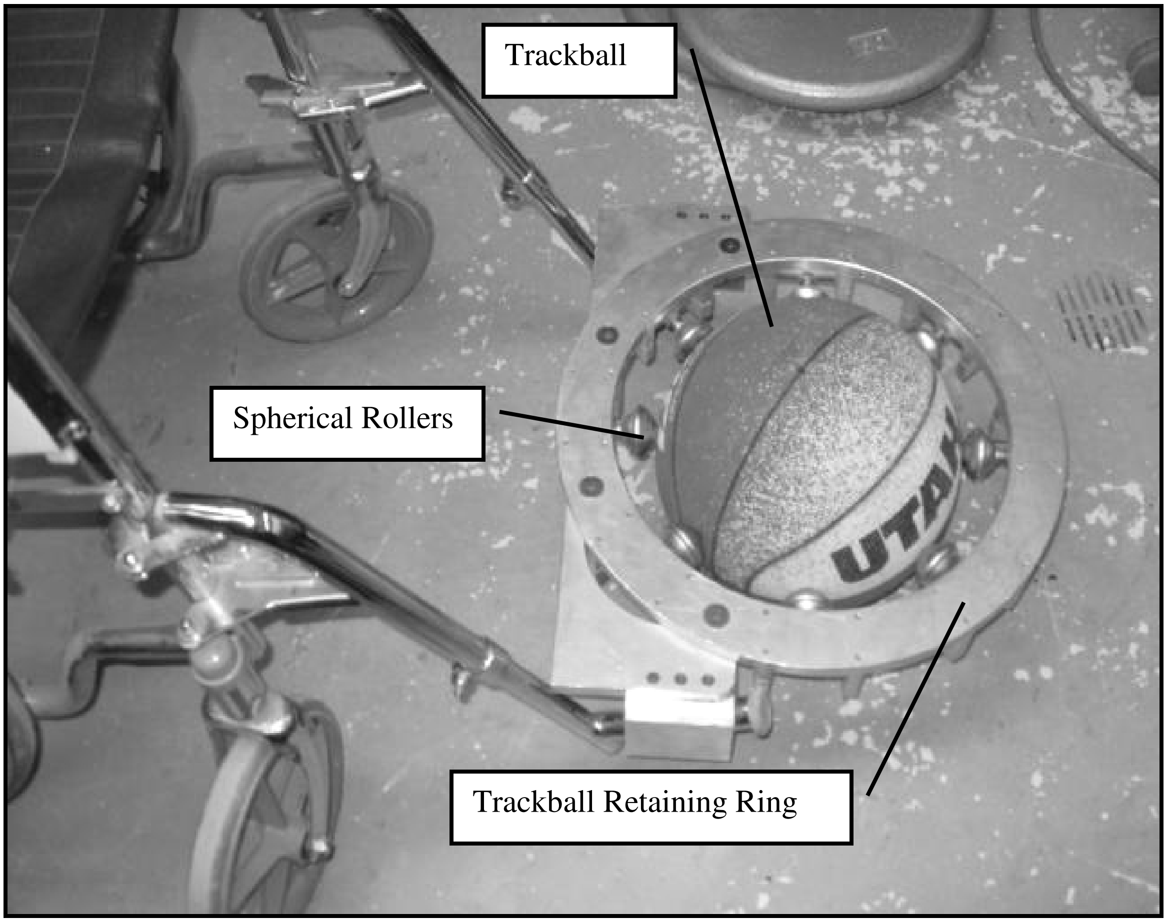

Figure 1.2 Trackball Design

1.3.3 Four-bar linkage design

Much like the track-ball the four-bar wheelchair, also known as the swing design wheelchair, was designed to allow wheelchair users with limited leg strength the ability to exercise their leg muscles while sitting in a wheelchair. The four-bar design is propelled by knee extension while the feet are on the footrests. This motion translates into forward wheelchair propulsion. The four-bar wheelchair was unique among the wheelchair propulsion systems tested due to its lack of reverse. The cam only allows forward wheelchair motion. While ascending a ramp the wheelchair user can stop moving their legs and rest, without the need of manually applying the brakes.

The four-bar linkage design is named for the two sets of interconnected parallel steel bars attached to the front of a wheelchair (Figure 1.3). There is a foot rest on each side attached to the lowest bar, parallel to the floor. As the foot is brought forward, a cable attached to the four-bar linkage turns a ratcheting cam attached to the rear wheel. The turning of the cam results in forward propulsion of the rear drive wheel. When the foot returns to the starting position the cam is pulled back to its starting position by a tensioning spring. The rear wheel brake is actuated when either handle is pulled backwards or when the footrest is pulled backwards through knee flexion.

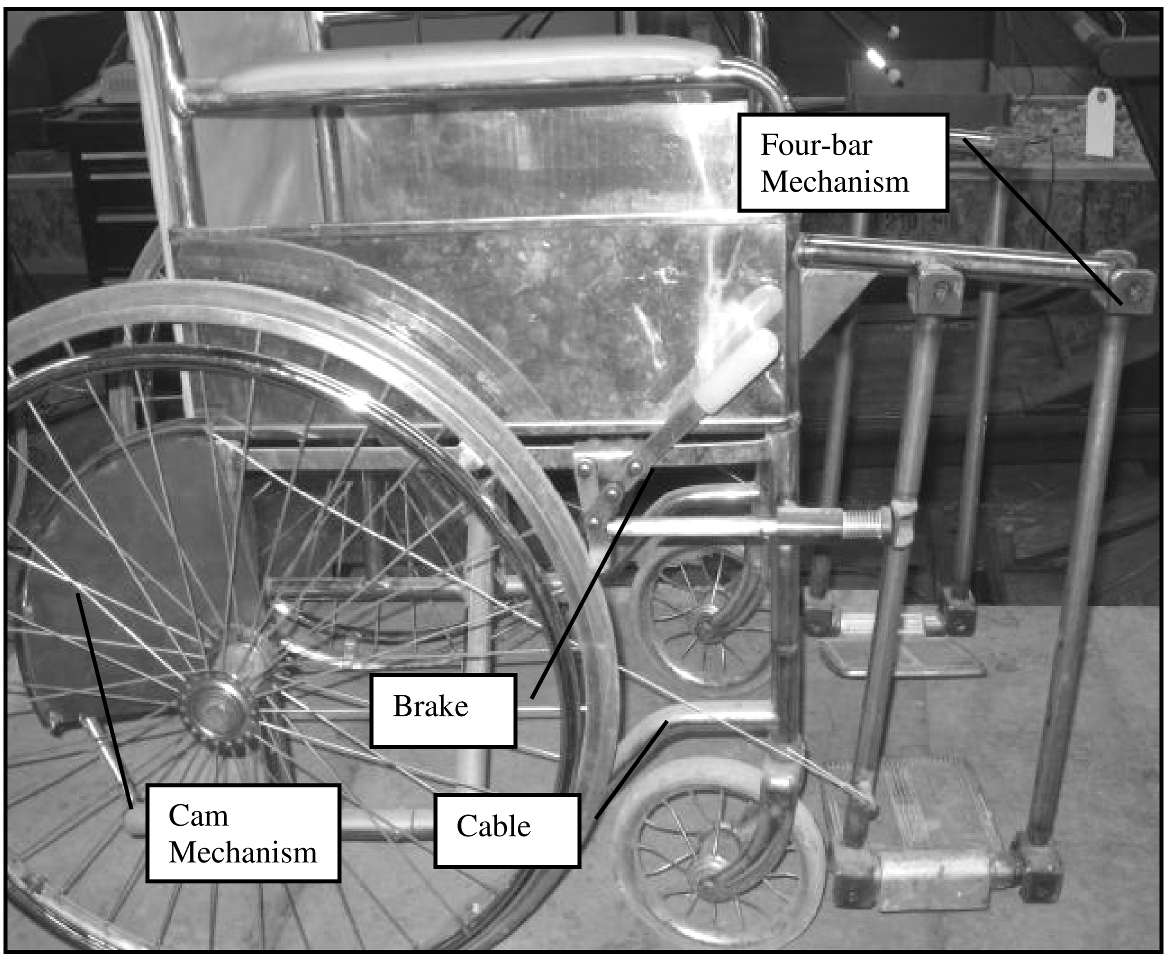

Figure 1.3 Four-bar Design

1.4 Experimental test design

1.4.1 Subject selection criteria

Recruitment of study participants was limited to able bodied individuals between the ages of 18 and 59. Both male and females were recruited. Exclusions were made for those who reported experiencing pain while sitting, or while exercising the arms or legs. Individuals with respiratory and/or heart problems were also excluded from participating in the study. Test subjects anthropometry

The 10 subjects in the study consisted of 5 able bodied males and 5 able bodied females. The age of the females varied between 23 and 30 years of age, with the average female age being 25.6 years. The height of the females varied between 155 and 170 cm. The average female height was 163.6 cm. The weight of the females was between 44 and 69.4 kg. The average female weight was 58.9 kg.

The age of the male subjects varied between 26 and 54 years. Their average age was 33.2 years. The height of the males was between 170 and 191 cm. The average male height was 179.3 cm. The weight of the males varied between 71.3 and 111.2 kg. The average male weight was 88.8 kg.

1.4.2 Test design

The results of all testing procedures were recorded on spreadsheets and other forms. Video imaging and photographs were taken of several subjects. However, not all subjects were recorded because several individuals declined consent to be photographed and/or video recorded. Subjects who declined consent were allowed to continue in the study because video imaging and photography were not an essential part of the data collection process.

1.4.3 Administrative responsibilities

In order to maintain subject confidentiality, each subject was identified by an alphanumeric label. There were 5 subjects of each gender which participated in the study. In order to distinguish between genders, a letter signifying their sex was listed after their subject number, M was used for males and F for females. The numeric portion of their identifying label indicated which subject number they were. For example, the first female subject was 1F, and the first male subject was 1M. These identifying labels were used on all paperwork and forms relating to each subject.

Also, to ensure confidentiality the results of testing and all other documentation were stored either on a secured computer system or within the access restricted Ergonomics and Safety Laboratory at the University of Utah.

1.4.4 Equipment used for testing

1) Wheelchair treadmill
2) Douglas air bag system
3) Hans Rudolph breathing tube, mouth piece and nose clip
4) Ametek TM-1B Oxygen analyzer
5) Collins 3L calibrated syringe
6) Polar heart rate monitoring system
7) Measuring tape
8) Cardboard boxes
9) Weighted pulley experimental setup
10) Chatillon CSD 200 Dynamometer

1.4.5 Equipment and software used for data analysis

1) Toshiba Satellite L555 computer
2) Microsoft Office 2003
3) University of Michigan's 3-D Static Strength Prediction Program (3DSSPP^{TM})
4) JMP 9

1.5 Wheelchair treadmill design and construction

The majority of the equipment used in the study was commercially designed. One exception was the wheelchair treadmill used during metabolic testing. Commercially available wheelchair treadmills typically cost $10,000 to $15,000. However, the allotted funds for this research project were only $750. In order to stay within the budget the researcher designed and built a wheelchair treadmill using used treadmills and parts.

Two used Quinton Club-Track 510 treadmills were purchased from government surplus at Hill Air Force Base for $300. After plans were drawn the steel frames of the two treadmills were modified and interconnected. The new enlarged framework was then reinforced using steel beams. The front and rear rollers of the two treadmills were interconnected using parts custom machined by the researcher. The treadmills were then rewired to allow use as a wheelchair treadmill. After wiring was complete the original control panel from one of the treadmills was attached to the new framework. Next, a guide wire and front and rear limits were added for safety, to prevent the wheelchair from leaving the treadmill surface. The finished wheelchair treadmill is shown in Figure 1.4.

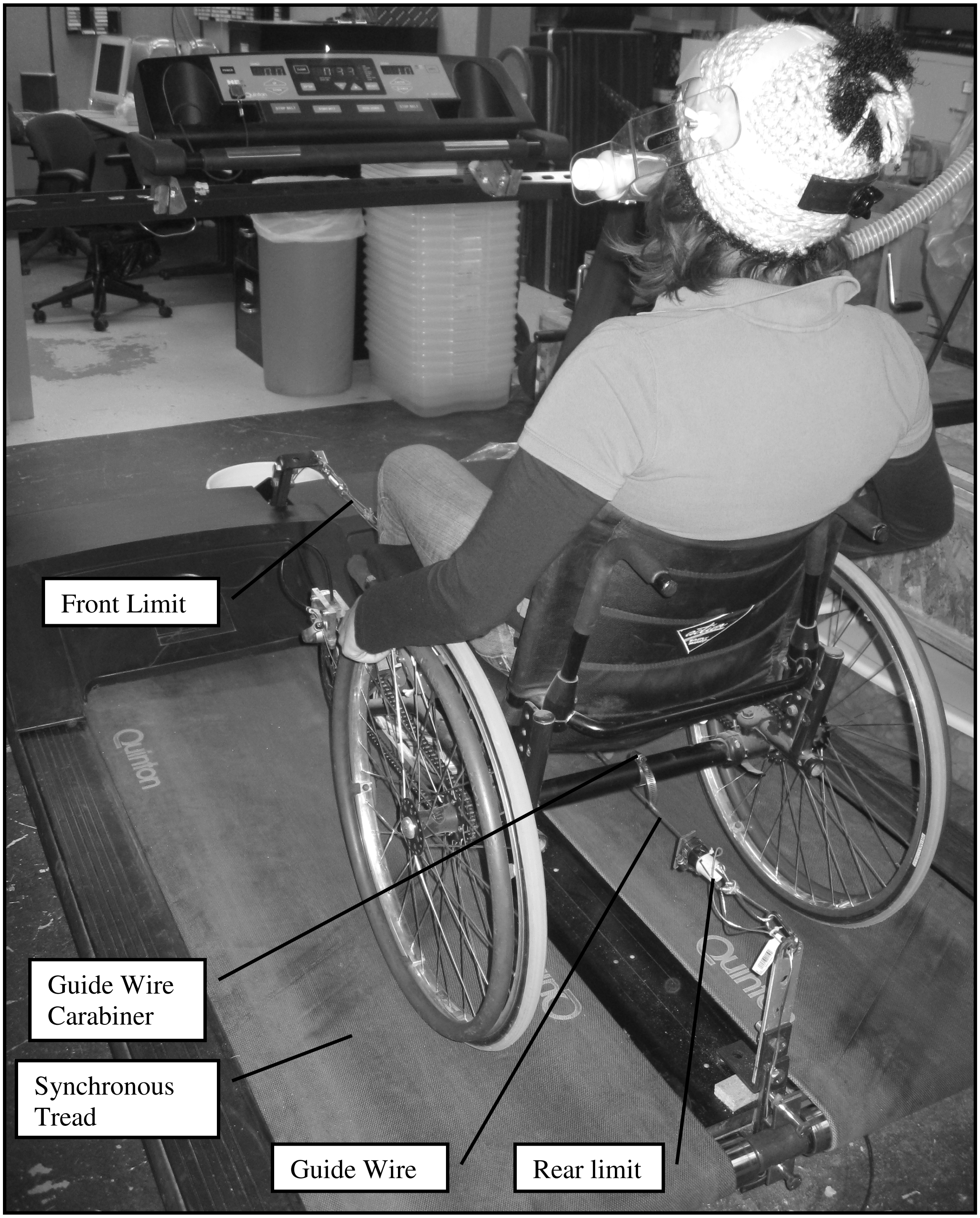

Figure 1.4 Wheelchair Treadmill Assembly

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2. METABOLIC, MANEUVERABILITY AND USABILITY TESTING OF ALTERNATIVE PROPULSION MANUAL WHEELCHAIRS

2.1 Abstract

Research has demonstrated that traditional hand-rim propelled wheelchair use results in musculoskeletal disorders such as carpal tunnel syndrome and shoulder injuries. In response several alternative propulsion wheelchairs have been designed, many of which are available the public. Unfortunately, there is a lack of information regarding the benefits and problems associated with using these wheelchairs. In addition, few studies have compared upper body propulsion systems with lower body propulsion systems. The purpose of this study was to test and compare four unique manual propulsion wheelchairs. Two of these wheelchair propulsion systems operate using upper body propulsion and two used lower body propulsion. The upper body propelled wheelchair used traditional hand-rim propulsion and hand-lever propulsion. The lower body propulsion wheelchairs were the trackball wheelchair and a four-bar linkage wheelchair.

The comprehensive testing procedure involved metabolic testing, maneuverability testing and usability testing. Results of the metabolic testing indicate that the energy cost of upper body propulsion was 45.1% lower than lower propulsion. Also, the VO_2 was 54.5% lower than the lower body propulsion wheelchairs. The duration of the metabolic testing was 5 minutes. It is recommended that further metabolic research be conducted over longer durations of time in order to determine the effects of fatigue on the energy

demands of upper and lower body wheelchair propulsion systems. Maneuverability testing revealed that the hand-rim and hand-lever designs were most maneuverable. The least maneuverable wheelchair system was the four-bar design. The results of usability testing differed between genders. Male subjects preferred the hand-lever design. Females preferred the traditional hand-rim design. All subjects chose the four-bar design as their least favorite. Based on metabolic, maneuverability and usability testing it appears that the hand-lever and hand-rim propulsion systems performed the best overall and were most preferred by users. Likewise the four-bar design was the least preferred and requires several modifications in order to improve its performance.

2.2 Introduction

2.2.1 Introduction to research

Early wheelchair research focused on the mechanical aspects of wheelchairs, such as the materials used, level of safety, and durability [1-4]. However, currently testing is also being performed in other areas of study, such as metabolic demands and maneuverability. Metabolic studies have shown that long term regular wheelchair exercise can results in increased VO2 max [5] and is highly important for those who have a chronic disease or are in rehabilitation [6]. Research has also found that using a hand-rim propelled wheelchair results in musculoskeletal disorders such as carpal tunnel syndrome and shoulder injuries [7-9]. In addition, hand-rim wheelchair propulsion is inefficient and metabolically costly due to the biomechanical disadvantage of hand-rim propulsion [10]. The mechanical efficiency of hand-rim wheelchairs can be as low as 2-10% [11-14]. In order to reduce the fatigue and stress associated with hand-rim wheelchair propulsion wheelchair designers have studied motorized wheelchairs and made modifications to manual propulsion wheelchairs.

Although there has been an increase in the availability of motorized wheelchairs, it is estimated that over 90% of wheelchairs are hand-rim propelled manual wheelchairs [15]. The cost of a manual wheelchair is only a fraction of a motorized unit. Also, manual propulsion wheelchairs allow wheelchair users a greater degree of physical activity. Manual wheelchairs also have greater maneuverability than most motorized wheelchairs and scooters [16].

In an attempt to reduce the fatigue and physical strain associated with manual wheelchair use, designers are now using more lightweight materials. However, a recent study found that lowering the weight by as much as 5 kg appears to have a negligible effect on the energy expenditure (EE), heart rate, and performance [17]. In recognition of the problems associated with hand-rim propulsion wheelchairs several alternative propulsion manual wheelchairs have been designed. The two principal types of alternative propulsion wheelchairs are the upper body propulsion and lower body propulsion systems. Upper body propulsion mechanisms often use levers or cranks. It has been shown that both lever and crank propelled wheelchairs are less physically stressful and more efficient than hand-rim wheelchairs [18]. Lever propulsion wheelchairs have been shown to have greater physical efficiency [19-21] , and produce less physical strain [22,23].

Although there have been many studies of wheelchair exercise, few have conducted comprehensive testing comparing lower body and upper body propelled wheelchairs. One study involving a prototype wheelchair found that leg propulsion required less than half the effort of upper body hand wheeling [24]. One group that may benefit greatly from leg propulsion wheelchair use is the elderly. Elderly people often do not have sufficient strength in their upper bodies to use a hand-propelled wheelchair. Many of the elderly have sufficient lower body strength but are not comfortable walking on their own due to vestibular dysfunction and/or the potential for slips and falls [25]. A leg propulsion wheelchair would allow them greater mobility and the opportunity to maintain lower body strength.

The lack of available information regarding alternative manual propulsion wheelchairs greatly hinders the ability of wheelchair users knowing which form of wheelchair propulsion would be best for their situation. The purpose of this study was to provide comprehensive testing of four different manual propulsion wheelchair systems. The testing consisted of a metabolic analysis, a maneuverability test and a usability survey. Comprehensive testing allows a better understanding of the strengths and weaknesses of each wheelchair.

There are two general forms of manual wheelchair propulsion depending on which muscle groups are used. Upper body propulsion manual wheelchairs utilize the arm and back muscles. Lower body propulsion manual wheelchairs use the leg muscles. Two upper body propulsion and two lower body propulsion systems were tested. The upper body propulsion systems included traditional hand-rim propulsion and hand-lever propulsion. These two propulsion mechanisms are located on the same wheelchair. The lower body propulsion mechanisms in the study were the trackball and four-bar wheelchairs. The trackball, four-bar and the hand-rim/hand-lever wheelchairs are detailed in Figure 2.1, Figure 2.2 and Figure 2.3, respectively.

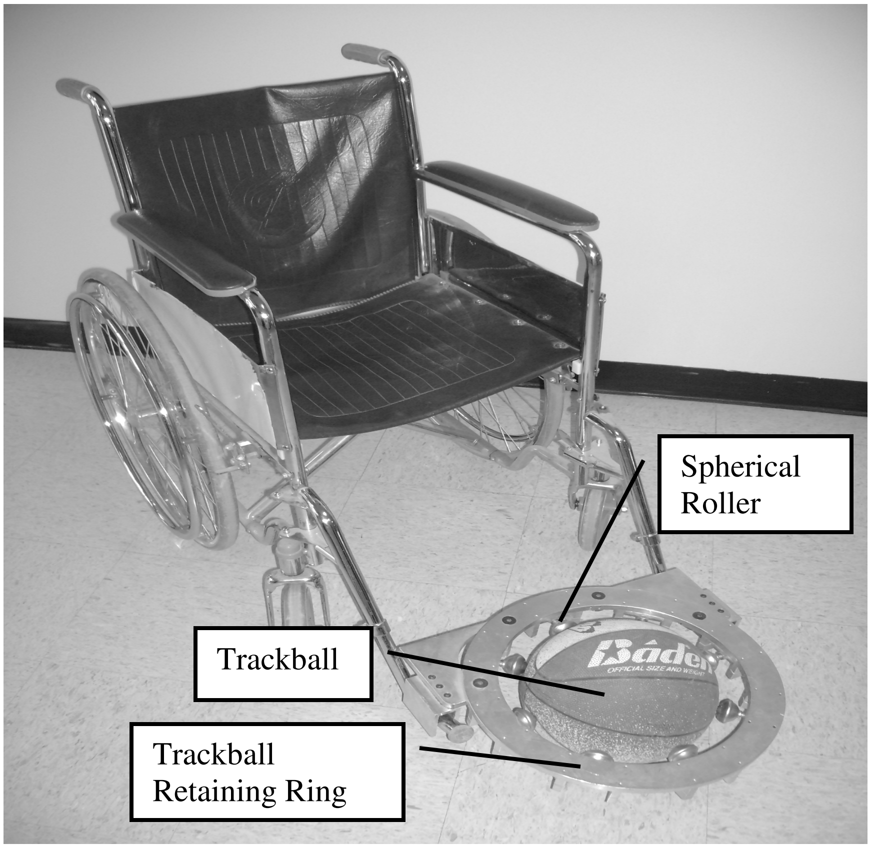

Figure 2.1 Trackball Wheelchair Design

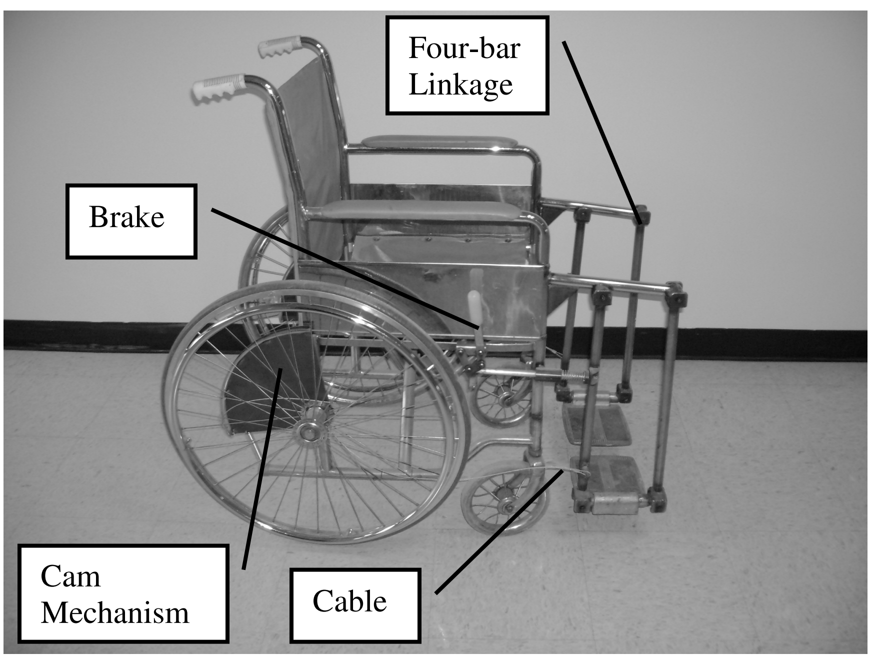

Figure 2.2 Four-bar Wheelchair Design

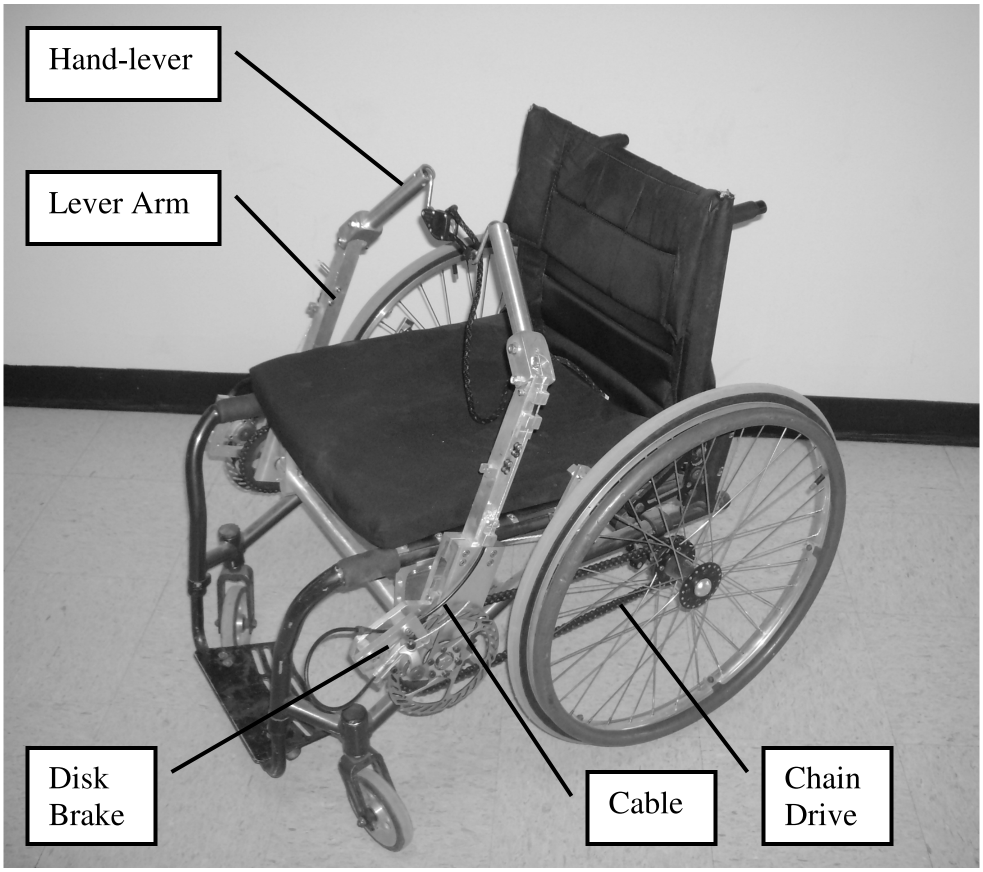

Figure 2.3 Hand-rim and Hand-lever Wheelchair Design

2.2.2 Introduction to metabolic testing

Metabolic studies of wheelchair activity often focus on oxygen consumption and heart rate [29-30]. This information is used to determine the energy demand, which is intrinsically connected to a wheelchair's mechanical efficiency. Metabolic testing is often conducted using a wheelchair ergometer or wheelchair treadmill. Wheelchair simulators are also occasionally used. Apart from testing a wheelchair on a simple track, the most realistic form of metabolic testing is conducted using a wheelchair treadmill [29]. Treadmill propulsion allows use of actual wheelchairs and natural movements in a controlled environment. Using a wheelchair on a treadmill is mechanically realistic [30] and "can be valid surrogate for over-ground studies of wheelchair propulsion" [31]. Also, the rolling friction and inertia are realistic [29]. Another advantage of using a wheelchair treadmill is that standardization is increased due to the lack of drag from air movement [29].

Due to the prohibitive cost of commercially available wheelchair treadmills the researcher designed and constructed a wheelchair treadmill (Figure 2.4). The wheelchair treadmill was made out of two individual treadmills that were purchased from government surplus. These treadmills were disassembled, measured and photographed, for reconstruction purposes. After plans were drawn the steel frames of the two treadmills were modified and interconnected. The front and rear rollers of the two treadmills were interconnected using parts custom machined by the researcher. The treadmills were then rewired to allow use as a wheelchair treadmill. Finally, carabiners were placed on each wheelchair undercarriage and a guide wire with front and rear limits was added to prevent the wheelchair from leaving the treadmill surface.

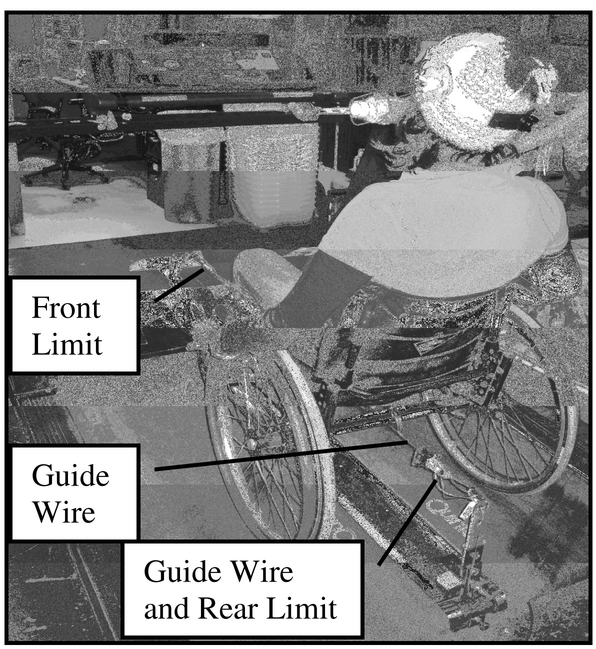

Figure 2.4 Wheelchair Treadmill

2.2.3 Introduction to maneuverability testing

One of the challenges that wheelchair users encounter is the inability to use their wheelchairs within the restricted spaces of rooms and hallways of some buildings and most homes. Although the Americans with Disabilities Act (ADA) specifies that commercial facilities must be "readily accessible to and usable by individuals with disabilities" [33]. Noncommercial buildings and private homes are not affected by the ADA. In effect these disabled individuals, who make up one of the largest minority groups in the United States, have been segregated from mainstream America by their inability to access the same facilities as able-bodied persons.

The easiest method for wheelchair users to increase their accessibility is to use wheelchairs with a large degree of maneuverability. Unfortunately, information is not readily available regarding a wheelchair's maneuverability. Often wheelchair users can not tell how well a wheelchair maneuvers until after it is purchased. The purpose of this research was to determine which wheelchair designs are most maneuverable. This information may help wheelchair users know which wheelchair is right for them, based on their maneuverability needs.

2.2.4 Introduction to usability testing

Another factor that is very important for wheelchair users is the usability of a wheelchair. Usability is a subjective quality referring to how well a wheelchair handles, the level of comfort, and any design improvements which would make the wheelchair better and easier to use. Usability is one of the most important qualities of a wheelchair. Although a wheelchair may be highly maneuverable or mechanically efficient it is not practical if it is uncomfortable, complicated or difficult to use.

3. METHODS

3.1 Approach

The metabolic, maneuverability and usability tests were conducted using 10 able-bodied subjects. Recently studies have shown that the several physiological and metabolic responses of wheelchair users are similar to able bodied person during wheelchair exercise [33, 34]. Studies often use able-bodied subjects during metabolic wheelchair testing [23, 28, 35, 36]. Using able-bodied subjects to test several different wheelchairs allowed results which were not biased by long term experience to a certain wheelchair type. Another advantage of using able bodied subjects is that each subject could use both upper and lower body propulsion systems, which allows comparisons between the two types during all testing procedures. Another reason that able-bodied subjects are often used in metabolic wheelchair research is the consistently high test/retest reliability for heart rate and VO_2 during wheelchair treadmill exercise. [37-40].

3.2 Experimental design

3.2.1 Research hypothesis

1. There is a significant difference in the metabolic energy requirements between upper and lower body propulsion wheelchairs and that difference can be determined by VO_2 testing on a wheelchair treadmill.
2. Maneuverability testing will reveal that wheelchairs with smaller frame "footprints" (length x width) will be more easily maneuvered. Maneuverability

will be determined by observation and measurement of space requirements to conduct five different maneuvers.

3.2.2 Metabolic testing experimental design

Metabolic testing consisted of four separate trials with each subject using each of the four different wheelchair propulsion systems. Each trial was 5 minutes in length. In order to ensure that subjects would be able to complete all four trials, the researcher conducted pretesting trials to establish the testing criteria. These pretesting trials were performed using all four wheelchairs' propulsion systems at different speeds. Based on the lower cardiopulmonary demands experienced during testing, a speed of 1 mph was selected. Also, 1 mph is the speed usually preferred by indoor wheelchair users [15].

During metabolic testing, each subject wore a heart rate monitor. Initially, one of the four wheelchair propulsion systems was assigned to them and placed on the wheelchair treadmill. Assignments were based on a preselected randomized order. After the wheelchair was placed on the treadmill, the wheelchair frame was fastened to the treadmill guide wire. The guide wire was placed in the center of the treadmill between the two treads. This safety wire prevented the wheelchair from coming off the treadmill by limiting the direction of travel. At the front and rear of the guide wire were mechanical limits. A green light on the control panel was provided to verify correct wheelchair position on the treadmill. The light turned off when the wheelchair contacted either the front or rear limit on the guide wire. Subjects were advised to ensure the light was on while using the wheelchair.

The treadmill surface was level and an electronic speedometer was used to monitor the treadmill velocity. The velocity was maintained at 1 mph. Use of a constant velocity, rather than self-selected velocity ensured standardization during statistical comparisons between wheelchair systems. During the first 3 minutes of wheelchair locomotion, a steady state heart rate was established. Also, this time allowed each subject to become familiarized with using each wheelchair propulsion system on the treadmill.

During the last 2 minutes of wheelchair exercise, the exhaled air was collected using a Douglas air bag. Measuring VO_2 after 3 minutes is important to ensure steady state condition has been reached. At the end of the trial the treadmill was stopped and the subject then rested for 5 minutes before the next trial. While the subject was resting the researcher measured the oxygen content of the room air and the air in the Douglas air bag, using the oxygen analyzer. The volume of the exhaled air was also measured using the calibrated syringe. Next, the Douglas air bag was completely evacuated and attached to the breathing tube in preparation for the next trial. The first wheelchair was then removed from the treadmill and the next wheelchair was placed on the treadmill. The final three metabolic tests were then completed using the same procedure.

3.2.3 Maneuverability testing experimental design

Before maneuverability testing was performed, each wheelchair was measured and weighed. Measurements were taken of the wheelchair frame's length and width. These measurements were used to calculate the "footprint" of the wheelchair, the footprint being equal to the width times the length of the wheelchair. The length that the propulsion mechanism extends beyond the frame during movement was also recorded. This extended length was then used to calculate the "footprint during movement." Also, the thickness of the back cushioning, and seat cushioning were recorded. These measurements are presented in Table 3.1.

Table 3.1 Wheelchair Measurement Index

	Length	Width	Length of propulsion mechanism beyond frame during use	Footprint of wheelchair during movement	Width of seat cushion	Width of back cushion	Weight
Hand-rim	91.4 cm (36.0”)	68.6 cm (27.0”)	0 cm (0”)	6,270 cm^2 (972 $in.^2$)	5.08 cm (2.00”)	2.54 cm (1.00”)	20.6 kg (45.5 lbs)
Hand-lever	91.4 cm (36.0”)	68.6 cm (27.0”)	0 cm (0”)	6,270 cm^2 (972 $in.^2$)	5.08 cm (2.00”)	2.54 cm (1.00”)	20.6 kg (45.5 lbs)
Trackball	130 cm (51.0”)	61.0 cm (24.0”)	0 cm (0”)	7,890 cm^2 (1,220 $in.^2$)	.640 cm (.250”)	.640 cm (.250”)	23.1 kg (51.0 lbs)
Four-bar	97.8 cm (38.5”)	64.8 cm (25.5”)	38.1 cm (15.0”)	8,800 cm^2 (1,360 $in.^2$)	.640 cm (.250”)	.640 cm (.250”)	24.0 kg (53.0 lbs)

Testing was performed in accordance with the wheelchair maneuverability testing protocol developed by Bloswick [14]. This protocol involves a controlled test, representing five standard wheelchair activities. During testing the subjects perform five different maneuvers. The maneuvers include a 360° rotation (Figure 3.1), a forward 90° turn (Figure 3.2), a reverse 90° degree turn (Figure 3.3), a three-point turn (Figure 3.4) and a 180° turn (Figure 3.5). These maneuvers and the recommended areas were taken from *Designing for the Disabled* [41]. The recommended areas were established as guidelines to help builders understand the minimum required areas that wheelchair occupants need to allow access within buildings.

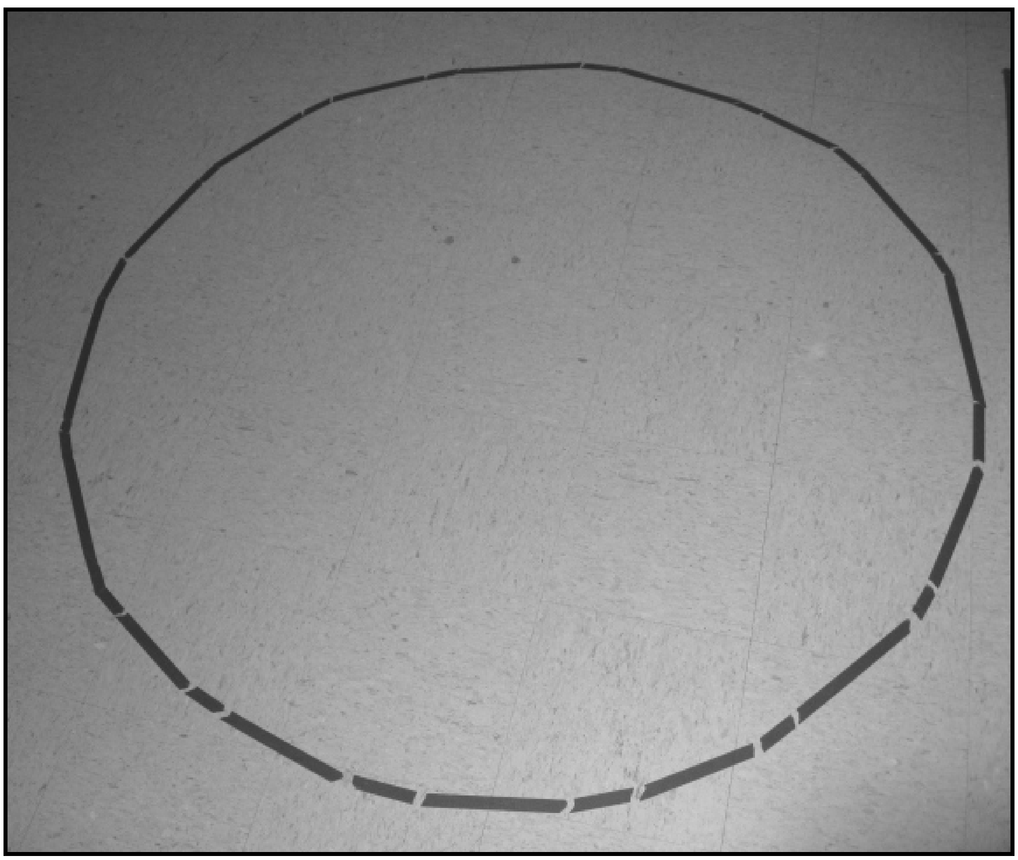

Figure 3.1 360° Rotation

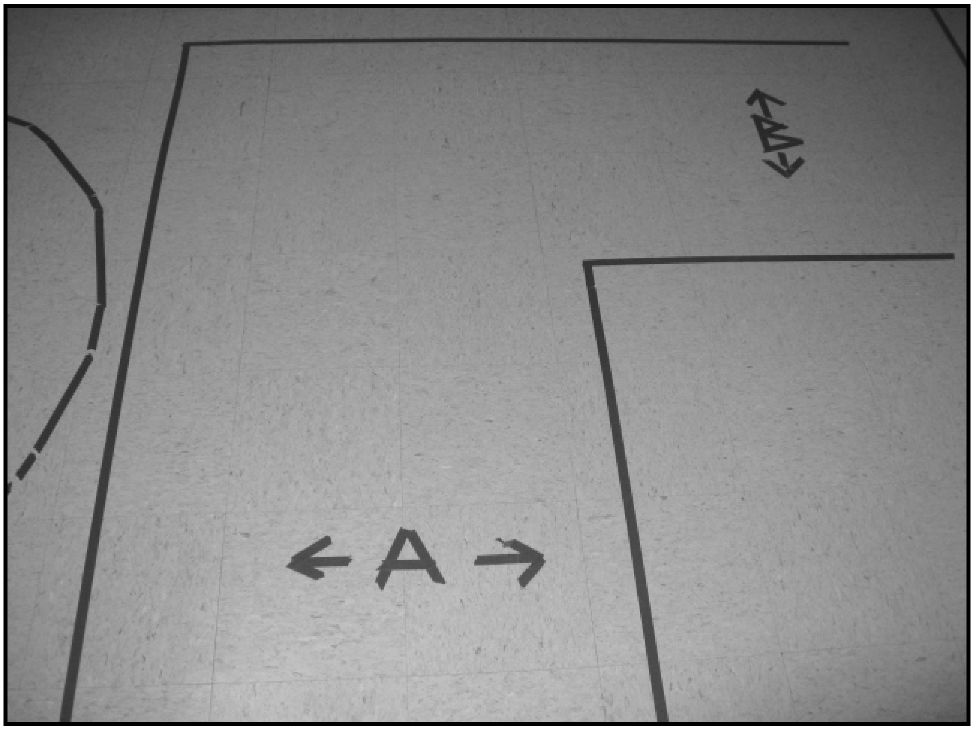

Figure 3.2 Forward 90° Turn

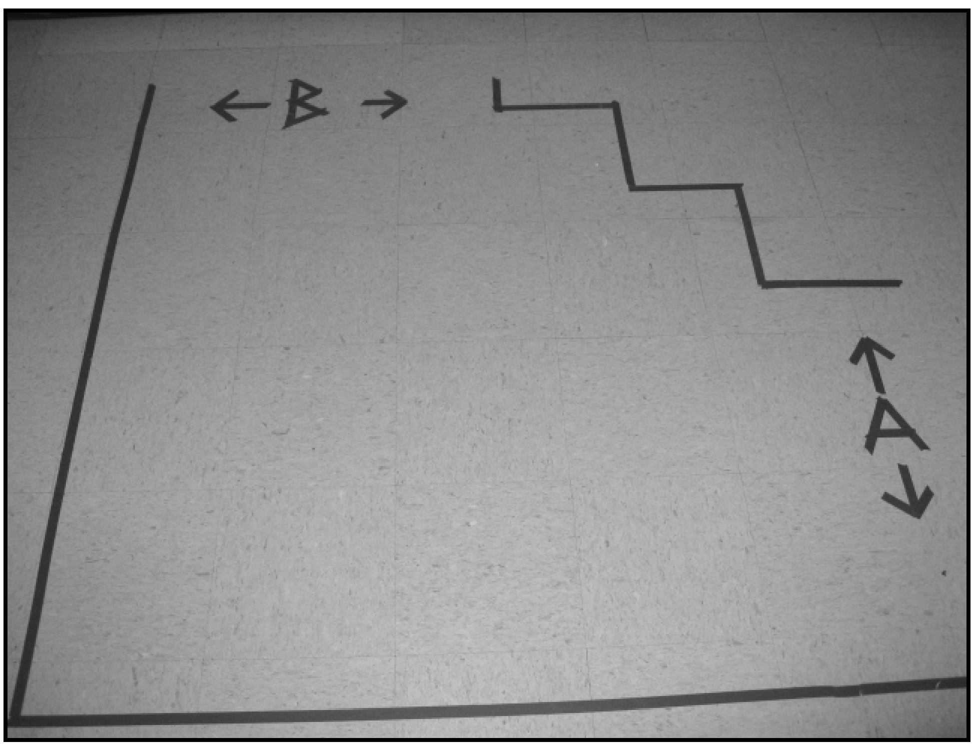

Figure 3.3 Reverse 90° Turn Area

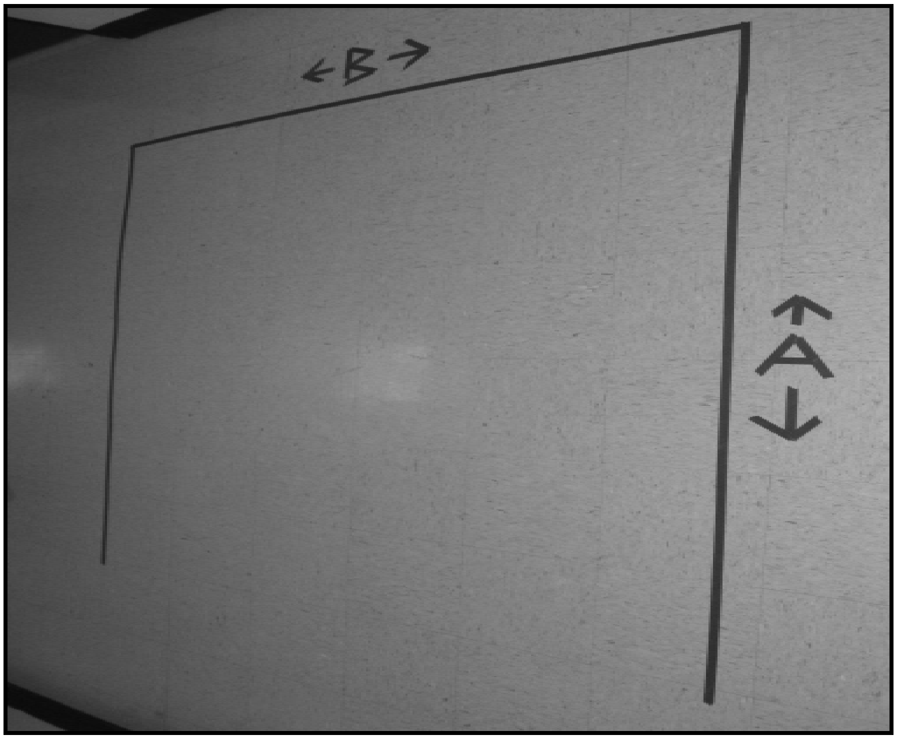

Figure 3.4 Three-point Turn Area

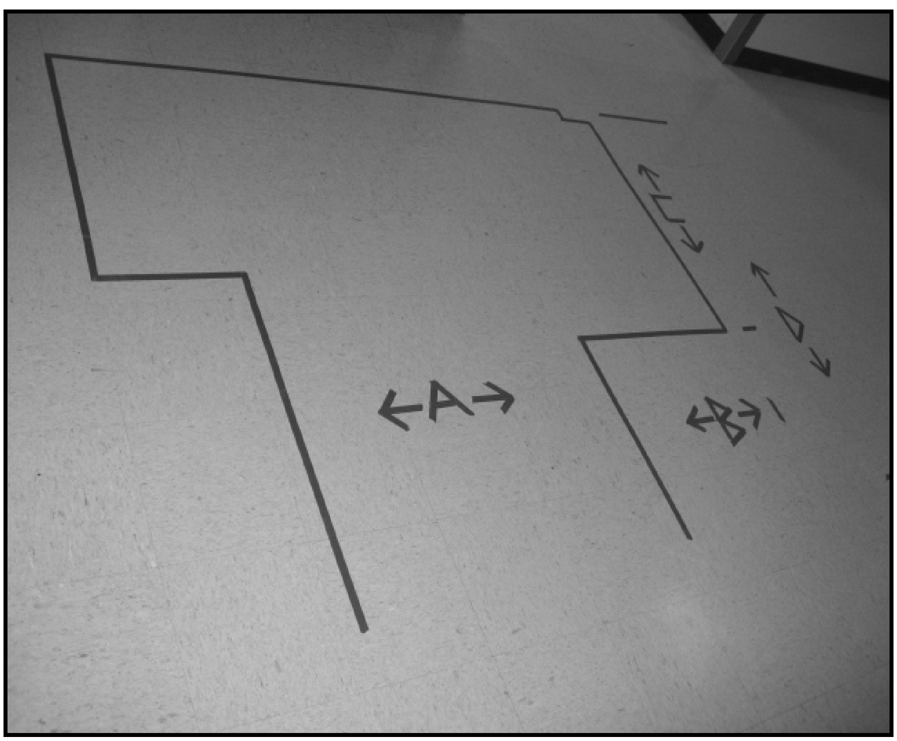

Figure 3.5 180° Turn Area

During maneuverability testing all four manual wheelchair systems were independently tested. The recommended areas for each maneuver were marked with blue tape on a hard level surface. Cardboard boxes were then placed parallel with the lines. Measurements were taken along specific lengths in order to determine each wheelchair design's maneuverability. These lengths were marked with blue arrows and letters for identification.

During testing when a subject contacted a cardboard box, the wheelchair pushed it away from the blue line. After the subject completed the maneuver, the distance from the blue line to the cardboard box was measured with a tape measure and recorded on a form. The subjects were advised to repeat the maneuver until they felt that they could not perform it in a smaller area. If the subject was able to perform the maneuver within the recommended space without moving any cardboard boxes, it was noted and they proceeded to the next maneuvering area. After all five maneuvers were completed using the first wheelchair propulsion system the procedure was repeated until all four manual propulsion wheelchair systems had been tested.

3.3 Statistics

The metabolic testing data were divided into four groups based on the four manual wheelchair propulsion systems used. Means, standard deviations, and powers were calculated using the physiological variables. Dependent variables included oxygen uptake ($V0_2$, L/min), pulmonary ventilation (VE, L/min), heart rate (beats/min), and energy cost (EC, (ml/kg)/min). Independent variables included the form of wheelchair propulsion used, body mass index (BMI), and gender. The sample size was limited to the data collected from the 10 subjects using the four wheelchair designs. All modeling was performed using JMP® statistical software.

Statistical significance was tested at the $p < 0.05$ level. The null hypothesis is normally rejected when the *p*-value is less than 0.05. This value corresponds to a 5% chance of rejecting the null hypothesis when it is true. The P-value for the multivariate model which included the energy cost and oxygen uptake was $P < .0001$ for the type of wheelchair propulsion. All other independent variables, such as BMI and gender were insignificant. A power analysis was also performed. Powers of .8 are considered adequate to reduce the probability of a Type II error. Type II errors accept the null hypothesis, although the alternative hypothesis is the true state. For the energy cost and oxygen uptake the only independent variable with a power greater than .8 was the form of wheelchair propulsion, which power was .99 for both dependent variables. A means comparison using Tukey-Kramer HSD revealed that statistical significance exists between the upper and lower body propulsion systems but not within the upper or lower body propulsion groups.

3.4 Results

3.4.1 Metabolic results

Figure 3.6 details the VO_2 (standardized by body weight) while using the wheelchair propulsion systems. This value, referred to as the energy cost (EC), facilitates comparison of energy consumption between people with different body masses.

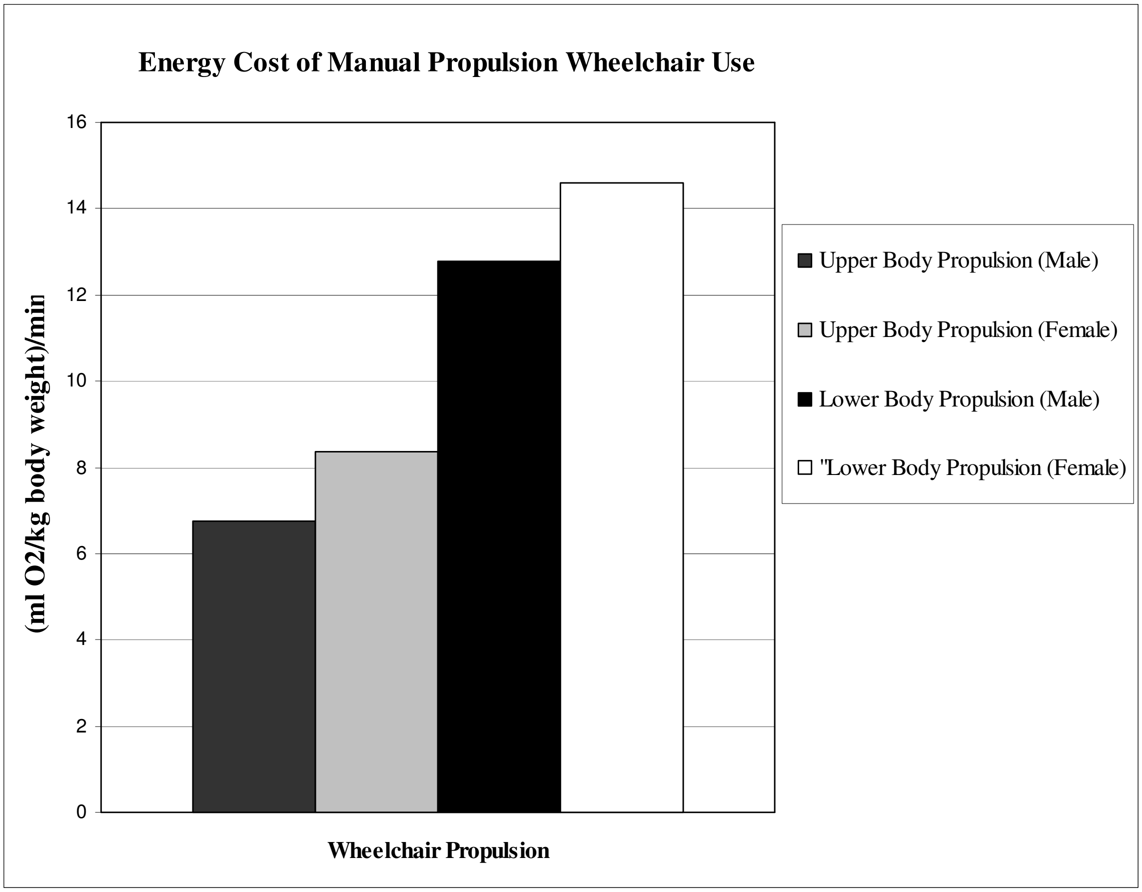

Figure 3.6 Energy Cost of Upper and Lower Body Propulsion Wheelchairs

Table 3.2 contains a summary of the all the metabolic results. This table lists the data for all the metabolic indicators which were recorded during wheelchair treadmill propulsion. The steady state heart rate (HR) is the heart rate per minute during the cardiovascular steady state. The cardiovascular steady state occured during the last two minutes of wheelchair treadmill exercise. The ventilatory exhalation is the volume of air exhaled during the last two minute of wheelchair exercise. The VO_2 is the volume of oxygen that was consumed per minute during the last two minutes on the wheelchair treadmill.

Table 3.2 Results Summary Table

Wheelchair Type	**Mean Steady State HR (Beats/min)**	**Ventilitory Exhalation (Liters)**	**VO_2 (Liters of O_2/min)**	**Energy Cost (ml O_2/kg)/min**
Hand-rim (Male)	77.9	29.5	1.16	6.64
Hand-rim (Female)	91.0	24.4	.940	8.22
Hand-rim (Both sexes)	***84.4***	***27.0***	***1.05***	***7.43***
Hand-lever (Male)	78.2	31.2	1.21	6.68
Hand-lever (Female)	94.0	23.8	.980	8.52
Hand-lever (Both sexes)	***86.1***	***27.5***	***1.10***	***7.60***
Trackball (Male)	90.1	46.9	2.04	11.5
Trackball (Female)	116	38.2	1.60	13.9
Trackball (Both sexes)	***103***	***42.6***	***1.82***	***12.7***
Four-bar (Male)	96.2	56.1	2.42	14.1
Four-bar (Female)	118	38.8	1.80	15.3
Four-bar (Both sexes)	***107***	***47.5***	***2.11***	***14.7***

Table 3.3 contains the areas recommended for each maneuver and the areas that were required by each of the four manual propulsion wheelchair designs to perform each maneuver. The maneuverability areas were calculated by multiplying the width and length of each area. The area that each wheelchair required to perform a maneuver was calculated by how far the cardboard limits were moved beyond the recommended areas. The distance between limits was then measured to calculate the required area.

Table 3.3 Maneuverability Areas

	Recommended area	**Smallest area - Hand-rim**	**Smallest area - Hand-lever**	**Smallest area -Track-ball**	**Smallest area - Four-bar**
360° Rotation	19,500 cm^2 (3,020 in^2)	19,500 cm^2 (3,020 in^2)	19,500 cm^2 (3,020 in^2)	27,000 cm^2 (4,180 in^2)	34,100 cm^2 (5,280 in^2)
180° Turn	32,500 cm^2 (5,030 in^2)	32,500 cm^2 (5,030 in^2)	32,500 cm^2 (5,030 in^2)	32,500 cm^2 (5,030 in^2)	32,500 cm^2 (5,030 in^2)
Forward turn through 90°	24,700 cm^2 (3,830 in^2)	24,700 cm^2 (3,830 in^2)	24,700 cm^2 (3,830 in^2)	24,700 cm^2 (3,830 in^2)	26,000 cm^2 (4,030 in^2)
Reverse turn through 90°	17,200 cm^2 (2,670 in^2)	17,200 cm^2 (2,670 in^2)	17,200 cm^2 (2,670 in^2)	17,400 cm^2 (2,690 in^2)	Four-bar wheelchair could not perform this maneuver (No reverse)
Three-point turn	24,200 cm^2 (3,750 in^2)	24,200 cm^2 (3,750 in^2)	24,200 cm^2 (3,750 in^2)	27,900 cm^2 (4,320 in^2)	Four-bar wheelchair could not perform this maneuver (No reverse)

3.4.2 Usability results

The responses to the usability questionnaire indicated that the manual wheelchair propulsion system which was most preferred by the males was the hand-lever followed by the hand-rim. The females generally preferred the hand-rim followed by the hand-lever. The least desired wheelchair propulsion system, chosen by both sexes, was the four-bar. Subjects noted that the four-bar was difficult to use and the mechanism did not always work consistently. Whereas subjects noted that both the hand-rim and the hand-lever were "easy to control" and "comfortable." A summary of recommended design improvements is shown in Table 3.4.

Table 3.4 Recommended Design Modifications

Hand-rim

1. Make the hand rim more ergonomic.
2. Allow more adjustability of the seat for people of different heights.

Hand-lever

1. Modify the levers so that they don't go too far forward.
2. Change the handle shape so that they don't get caught on clothes.

Trackball

1. Use a ball with a higher coefficient of friction.
2. Shorten the front to back length of the wheelchair.
3. Widen the seat.

Four-bar

1. Change the gearing design so that reverse motion is possible.
2. Adjust the cable so that there is never any slack, so that it retracts smoothly and completely.

3.5 Discussion

3.5.1 Metabolic discussion

The EC of wheelchair propulsion varied between 7.43 and 14.67 (ml O_2/kg)/min. The upper body propulsion systems had EC and VO_2 that were, respectively, 45.1% and 54.5% lower than the lower body propulsion wheelchairs. Although this study found that lower body wheelchair propulsion had higher metabolic demands during 5 minutes of wheelchair exercise, it is important to realize that over longer time periods larger muscle groups, such as the quadriceps in the legs, would have longer endurance time according to the Rohmert curve. The metabolic demand greatly increases during fatigue in order to meet the increased oxygen demand of the mitochondria [42].

The Rohmert curve illustrates that endurance time is a hyperbolic function of the muscular force level. This force level can be measured using electromyography (EMG). The endurance time is increased as the force level is decreased. Larger muscle groups will have to exert less force than smaller muscle groups for a given task, and therefore will have greater endurance. It is expected that over long time periods the large muscle groups used in lower body wheelchair propulsion would have greater endurance than the smaller, more easily fatigued upper body musculature used in upper body propulsion wheelchairs.

In addition to muscle size, muscle type is also important. Posture providing muscles such as the quadriceps, have a higher ratio of fatigue resistant Type 1 muscles fibers [43]. These fibers have a high potential for storing and using oxygen and are surrounded by a plentitude of capillaries which provide oxygen rich blood [44]. Muscles which are used in upper body wheelchair propulsion, such as the pectoralis and biceps muscles, have a greater percentage of Type 2A muscles which are more easily fatigued [43]. As the smaller muscles used in upper body propulsion are fatigued their EC and VO2 will increase. It is unknown if this increase will be greater then the energy demand of lower body propulsion. It is recommended that future study investigates the effect of fatigue on the energy demands of upper and lower body wheelchair propulsion systems by using a longer testing period.

3.5.2 Maneuverability discussion

Participants with all the wheelchairs designs were able to complete the 180° turn within the recommended space. The most maneuverable wheelchair propulsion systems, as shown in Table 3.3 are the hand-rim and the hand-lever designs. Both of these propulsion systems are on the same wheelchair, which has the smallest operational 'footprint' (Table 3.1). Both of these designs were able to complete all five maneuvers within the recommended areas. Due to its inability to go in reverse the four-bar wheelchair was unable to complete two of the maneuvers. However, in the other maneuvers the four-bar wheelchair was always the least maneuverable of all four designs. The four-bar wheelchair also had the largest 'footprint' while it was being used (Table 3.3). The trackball had a 'footprint' which was smaller than the four-bar, but larger than the hand-lever and hand-rim (Table 3.3). Likewise, the area it required to maneuver was also between the four-bar and the other two designs.

One limitation of the maneuverability testing was that it was all conducted on a hard level surface. It would be beneficial to conduct future maneuverability studies on uneven surfaces and unlevel terrain to determine the effect on a wheelchair's maneuverability.

3.5.3 Usability discussion

The subjective results of the usability survey differed slightly between the sexes. Males preferred the hand-lever, followed by the hand-rim, trackball, and four-bar designs. Females preferred the hand-rim followed by the hand-lever, trackball, and four-bar designs. One of the reasons stated by subjects that the hand-lever and hand-rim were preferred over the other two designs was the increased padding. The padding on the upper body propulsion wheelchair was eight times thicker in the seat and four times thicker in the back cushion, as compared to the other two wheelchair designs. Although the weight of the hand-lever/hand-rim wheelchair was 10-14% lighter than the other two wheelchair designs it was not cited by subjects as a factor in determining their favorite wheelchair propulsion system. Based on comments, it appears that the four-bar was least favored due to its lack of reverse, difficulty in controlling, and a cable mechanism which sometimes would bind up, hindering propulsion.

3.6 Conclusions and recommendations for further research

This study found that during 5 minutes of wheelchair exercise on a level treadmill at 1 mph the lower body propulsion manual wheelchairs have statistically significant higher energy demands than upper body propulsion systems. Apart from the energy demands other aspects of a wheelchair function should be considered.

Wheelchair propulsion systems which are highly maneuverable, such as the hand-lever, allow wheelchair users greater accessibility. Also, the hand-lever wheelchair's braking system is advantageous because the wheelchair user does not have to brake using direct friction from their hand, as in hand-rim wheelchairs. Friction is applied by brake pads on the disk brakes. The leverage provided by the lever-arms should also reduce the force required to ascend a slope, in comparison to a hand-rim wheelchair. Despite the higher energy demands found in this study, lower body propulsion wheelchairs may actually have lower energy demands during longer periods of wheelchair exercise, due to the effects of fatigue on upper body musculature. Future research comparing upper and lower body propulsion systems over longer time periods would be beneficial in order to determine the effects of fatigue on EC, HR and VO_2.

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4. BIOMECHANICAL TESTING

4.1 Abstract

Biomechanical testing of wheelchairs has recently become more popular. The study of the forces acting on wheelchair users facilitates the design of wheelchairs that are less stressful to the musculoskeletal system. Effective designs result in fewer musculoskeletal disorders. With regard to the current biomechanical knowledge of manual wheelchair propulsion there needs to be further work evaluating designs of both upper and lower body propulsion systems. The purpose of this study was to determine the stresses placed on a wheelchair user's body during use of four different manual propulsion wheelchair designs on an ADA approved ramp. The results indicate that hand-lever propulsion, followed by four-bar propulsion require the least amount of force to ascend a ramp. Joint moments were also lowest for the hand-lever and four-bar propulsion designs.

4.2 Introduction

Studies of manual propulsion wheelchairs have identified several concerns. It has been found that traditional wheelchairs, also known as hand-rim wheelchairs, are often 2-10% mechanically efficient [1-4]. In addition many wheelchair users must provide all the effort for propulsion using only their arms. Reliance on the relatively small muscle mass located in the arms results in increased local levels of fatigue [5, 6] because of the limited physical work capacity (PWC) of the arms [7-9]. The PWC is reduced due to low levels of oxygen uptake by upper body musculature. The peak oxygen uptake of upper body propulsion is only 60-85% of leg propulsion [10]. In addition low cardiopulmonary fitness and reduced musculature caused by a physical disability may further reduce PWC [11-13]. Overexertion of upper body musculature and joints during hand-rim wheelchair propulsion causes a host of musculoskeletal disorders (MSD), such as shoulder, elbow, wrist, and hand pain [14-16]. Biomechanical research has found that shoulder joint forces and moments depend strongly on the propulsion speed, increasing in magnitude when speed is increased by as little as 1 km/h [17]. These increased joint forces increase the risk of injury, MSDs and pain. The incidents of pain experienced by users of manual propulsion wheelchairs are high. One study found that 72% of wheelchair users suffered from pain in the wrists and/or shoulders [18].

In order to reduce the fatigue and stress associated with hand-rim wheelchair propulsion wheelchair designers have made several modifications. Wheelchair designers have tried changing the gearing and rim size of traditional wheelchairs [19-21] and have added projections to the wheel rims [22, 23]. Alternative propulsion wheelchairs which rely on upper and lower body propulsion have also been introduced. Metabolic testing has shown that the upper body propelled hand-crank and hand-lever systems are less metabolically stressful and more efficient than traditional hand-rim wheelchairs [24-27]. In addition, these systems have been found to create less physical strain than the hand-rim design [28, 29].

The availability of lower body propulsion wheelchair systems is limited and likewise they are rarely studied. These wheelchairs are ideal for elderly wheelchair users who do not have sufficient strength in their arms to propel a traditional wheelchair. Also, many of these elderly wheelchair users do not have sufficient lower body strength to walk unassisted. In order to propel themselves while seated in a traditional wheelchair they "frequently use the strength of the quadriceps muscles in their upper legs to push themselves while sitting in the wheelchair" [30]. Seated knee extension results in backwards motion of the wheelchair and occupant [31, 32]. This rearward propulsion results in reduced visibility in the direction of travel and therefore an increase in accident risk. Lower body propulsion wheelchairs correct this problem by translating knee extension into provide forward propulsion. In addition leg propulsion wheelchairs have been found to be beneficial in other areas.

One study found that leg propulsion requires only half of the effort of arm propulsion [33]. However, studies like this that compare both arm and leg propelled manual wheelchairs are few. The purpose of this study was to expand research in the area of biomechanics by determining and comparing the force requirements and joint moments of several alternative propulsion wheelchair systems, along with a traditional hand-rim wheelchair.

The biomechanics of wheelchair propulsion should to be carefully studied to account for real world conditions. Asymmetrical motion exists during both laboratory and indoor wheelchair activity and may result in erroneous results due to misinterpretation of data [34]. In addition subjects tend to change their stroke patterns while pushing uphill as opposed to wheelchair use on a level surface [35]. This difference needs to be recognized during wheelchair research. Also, increased power is required to propel a wheelchair on a surface that is slanting to one side [36], commonly referred to as a cross slope. In addition "biomechanics researchers may need to standardize kinetic reporting methods to achieve a cohesive comprehension of wheelchair biomechanics" [37]. In order to address these issues testing for this study was conducted by simulating the forces of an ADA approved ramp using an experimental setup on a level surface.

4.3 Approach

Initially hand calculations were performed using free body diagrams of each wheelchair propulsion system. Next empirical testing was conducted to determine the biomechanical forces of manual wheelchair propulsion. These forces were determined through biomechanical modeling using 3DSSPP. The simulated testing environment was two ADA approved ramps. ADA ramps were used because wheelchair propulsion forces are maximized on these inclined environments. The elevated propulsion forces result in increased joint moments. Determination of the joint moments and the required propulsion forces allows areas of greatest musculoskeletal risk for each form of wheelchair propulsion to be identified.

4.4 Experimental Design

This was a two-part biomechanical study which determined the forces acting on a wheelchair user's body during manual wheelchair propulsion on ADA approved ramps. The two ADA approved ramps that were simulated were a 1:8 (height: length) curb ramp and 1:12 (height: length) standard ramp. Two lower and two upper body propulsion wheelchair systems were tested. These systems included traditional hand-rim and hand-lever propulsion (Figure 4.1) mechanisms which were both located on the same wheelchair frame. In addition the trackball propulsion system (Figure 4.2) and the four-bar system (Figure 4.3) were tested.

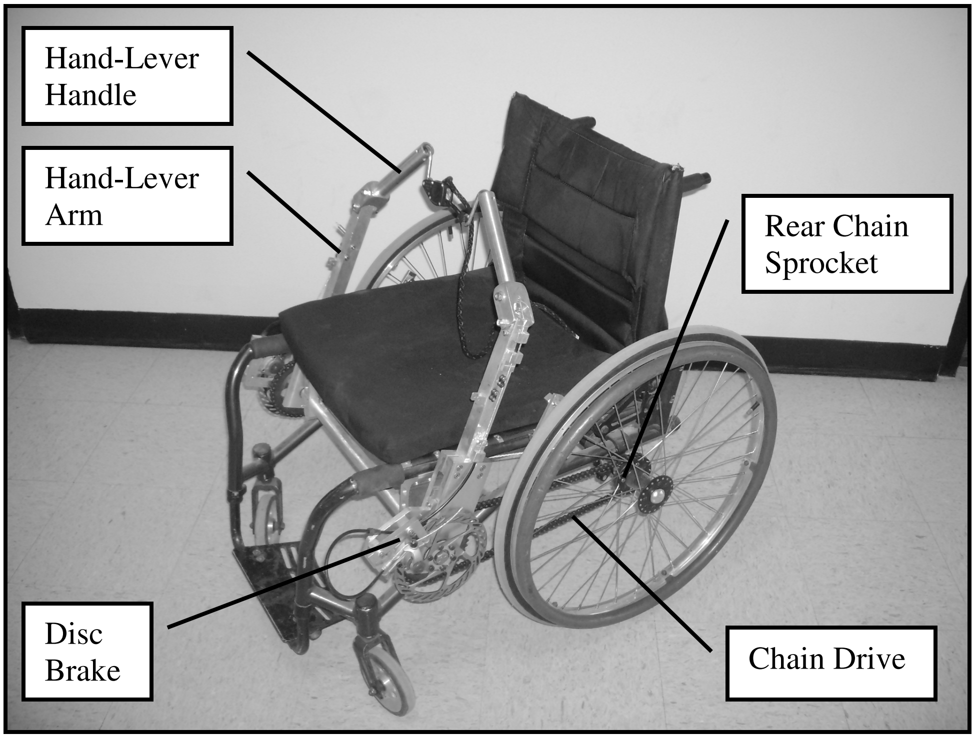


Figure 4.1Hand-rim and Hand lever Wheelchair

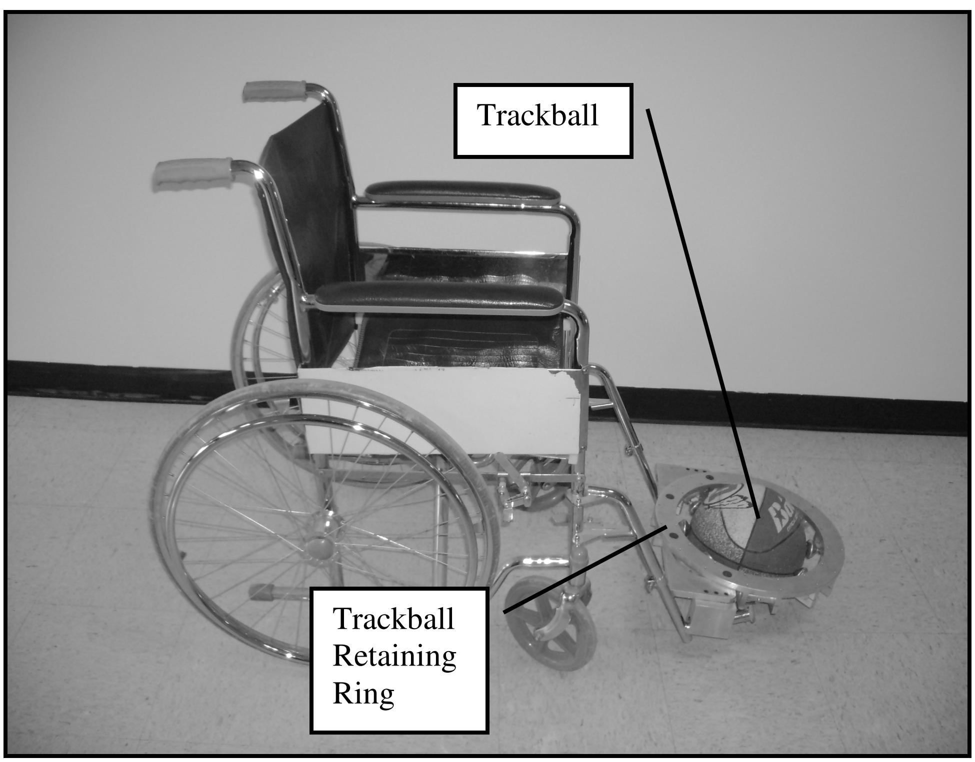


Figure 4.2 Trackball Wheelchair

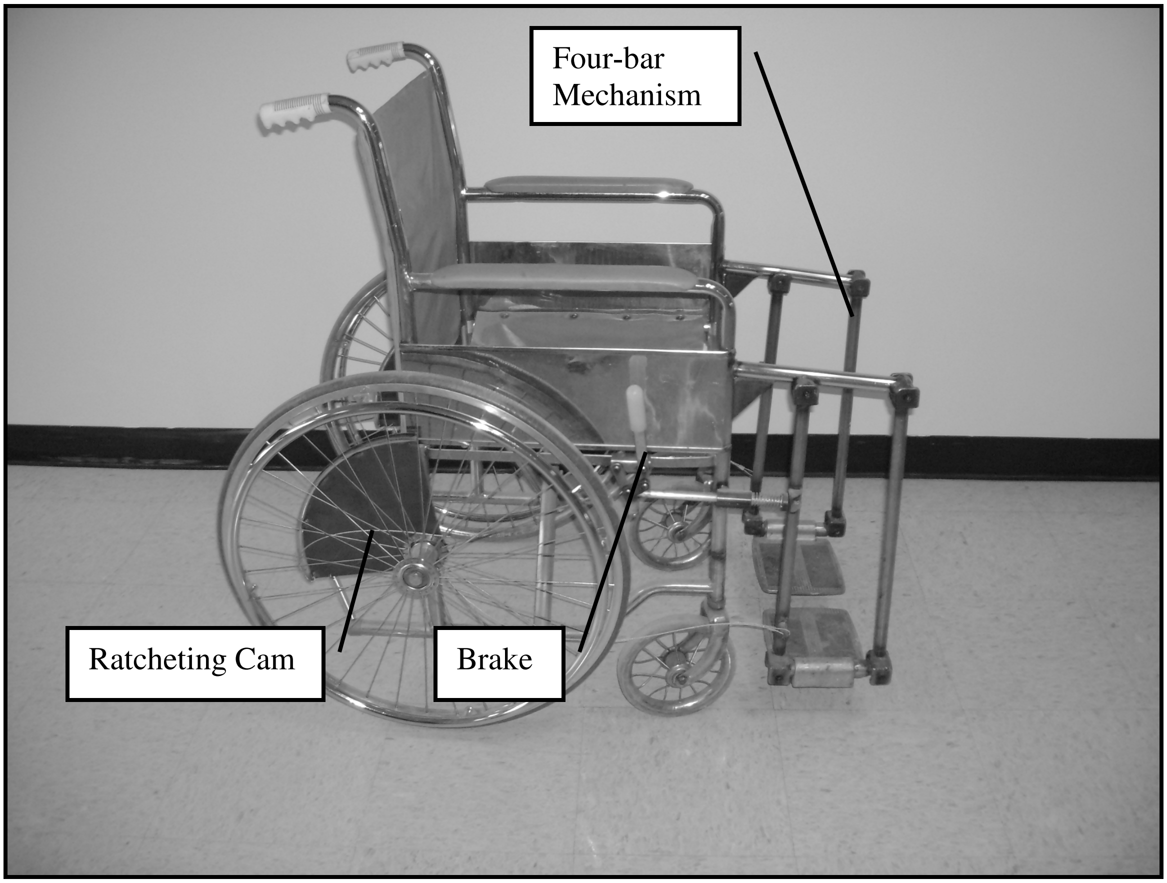
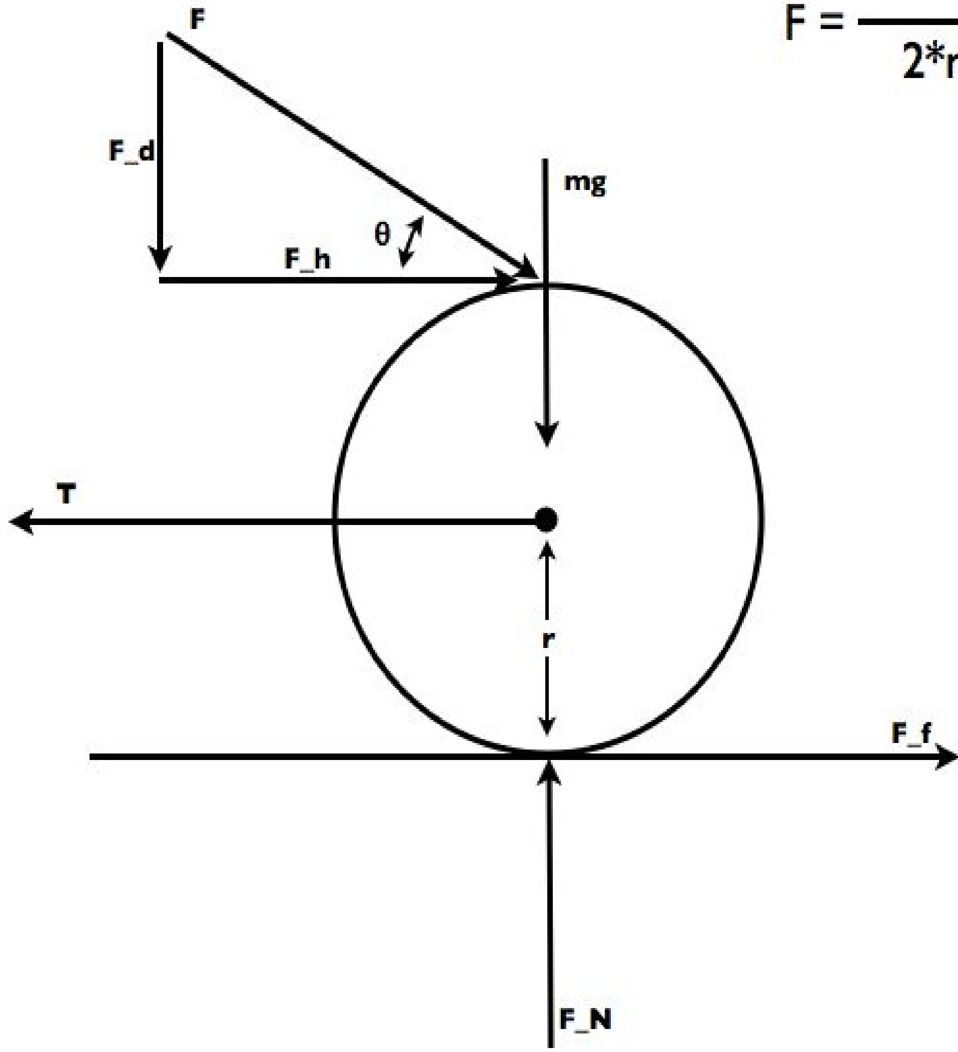


Figure 4.3 Four-bar Wheelchair

The first part of the study used hand calculations to determine the forces generated by the hands or feet in order to manually propel each wheelchair up the two ADA approved ramps. Calculations were based on free-body diagrams of the four unique manual wheelchair propulsion systems. An example of one of the free body diagrams is shown in Figure 4.4. Resultant forces were based on the contact angle between the hands or feet and the point of contact (rim, lever, ball, or foot rest) of each wheelchair propulsion system. This angle differs dependent on the position of the hands and feet during manual wheelchair propulsion. For example, during hand-lever propulsion the contact angle between the hand and the lever changes as the lever is rotated forward during propulsion.



$$F = \frac{T*r}{2*r*\cos(\theta)}$$

Figure 4.4 Hand-lever Wheelchair Free Body Diagram

An experimental setup was designed to simulate the forces acting on a wheelchair located on an ADA approved ramp. This setup consisted of the weighted pulley system shown in Figure 4.5. One end of the cable was attached to the rear of the wheelchair frame. The tension in the cable simulated the force of gravity acting on a wheelchair which is located on an ADA approved ramp. The tension was based on the on the mass of the person using the wheelchair, the mass of the wheelchair, and the angle of the ramp.

Figure 4.5 Experimental Weighted Pulley Setup

For three of the propulsion systems a coupling system was rigged between a digital dynamometer and the point of interest of the propulsion system. The point of interest was the location where force is applied to the manual propulsion wheelchair systems during movement. This location was the two hand-levers of the hand-lever design (Figure 4.6), the two wheels of the hand-rim design (Figure 4.7), and the two foot rests of the four-bar wheelchair (Figure 4.8). The trackball wheelchair required the use of a specialized concave foot attachment on the dynamometer (Figure 4.9). This attachment allowed the measurement of force on the curved ball surface.

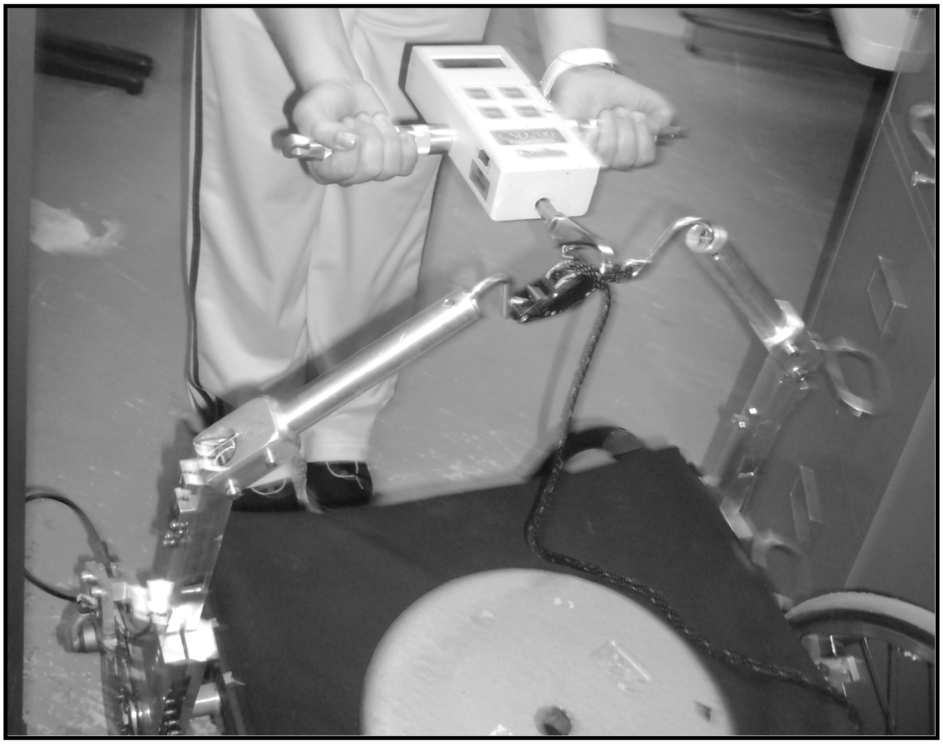


Figure 4.6 Hand-lever Force Coupling Assembly

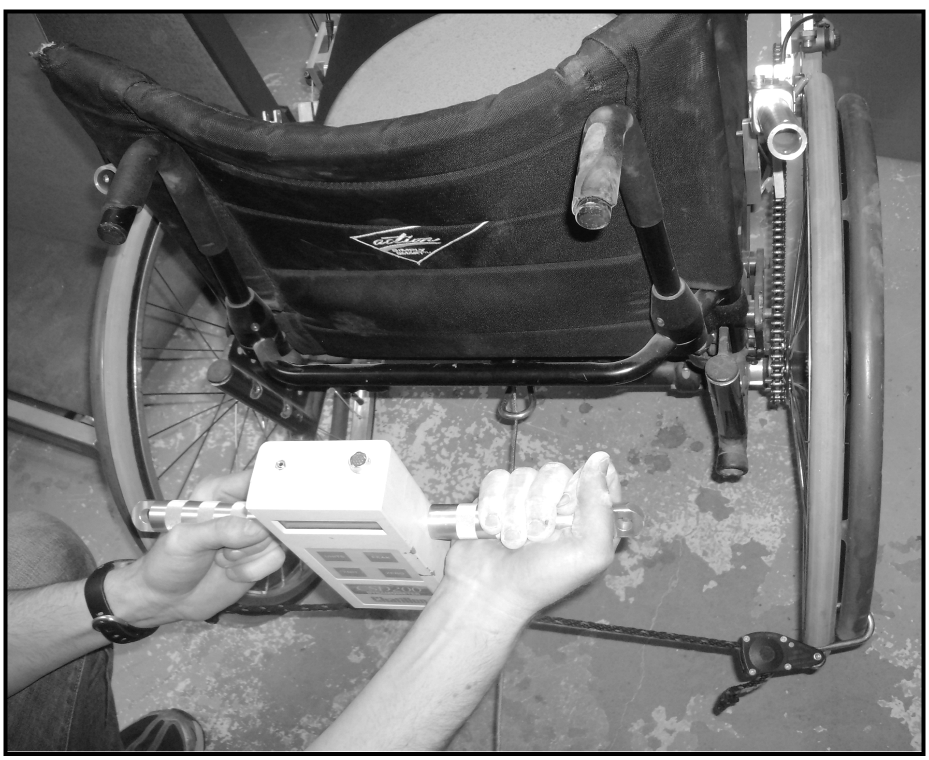


Figure 4.7 Hand-rim Force Coupling Assembly

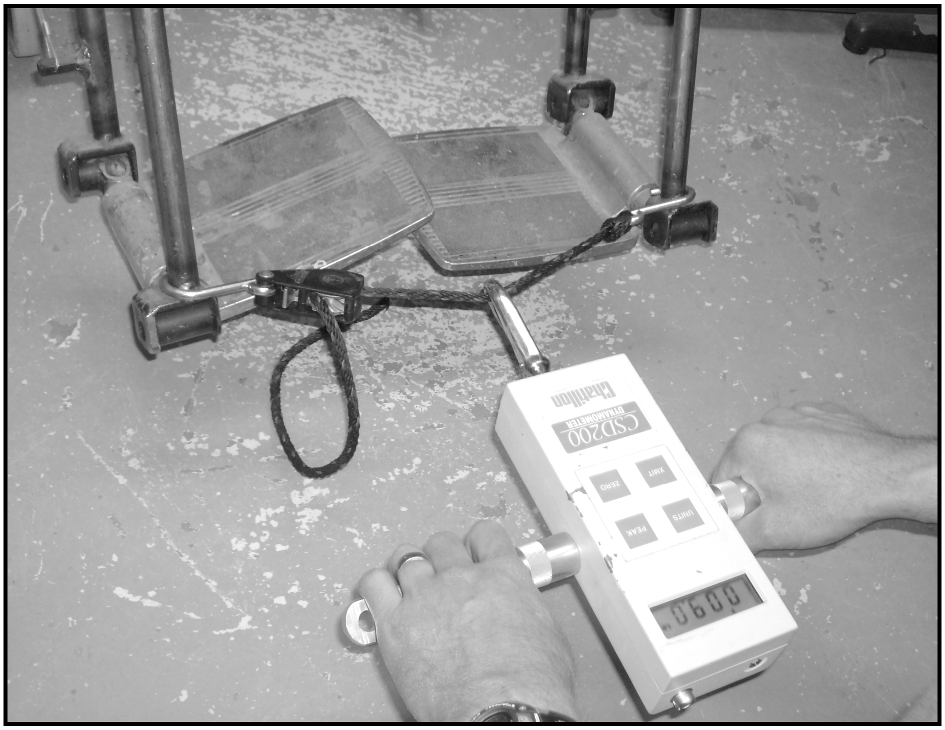


Figure 4.8 Four-bar Force Coupling Assembly

Figure 4.9 Dynamometer Pressure Foot Attachment on Trackball

All force measurements were taken using a Chatillon digital dynamometer. The dynamometer displayed the total force required to maintain static equilibrium in the wheelchair. This value was divided in half in order to input separate hand and foot forces into the 3DSSPP™ software.

Data were entered into the 3DSSPP™ program and models were created for each wheelchair propulsion system (Figures 4.10 – 4.13). These models were adjusted based on gender and anthropometry. The 3DSSPP™ provided a three dimensional human graphical interface. Information related to static biomechanics such as joint moments and population strength capabilities were determined. 3DSSPP™ was ideal for analyzing this study's static force data because during very slow movements, such as ascending an ADA approved ramp, the biomechanical calculations can assume that the effects of acceleration and momentum are negligible [38].

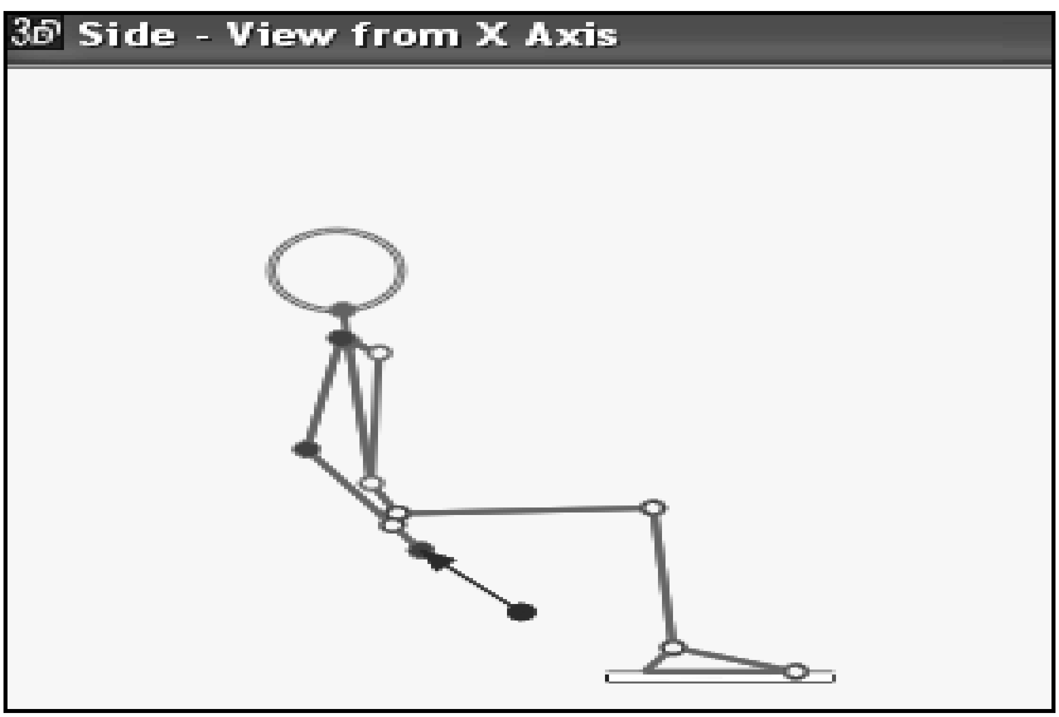


Figure 4.10 Hand-rim Wheelchair 3DSSPP Model

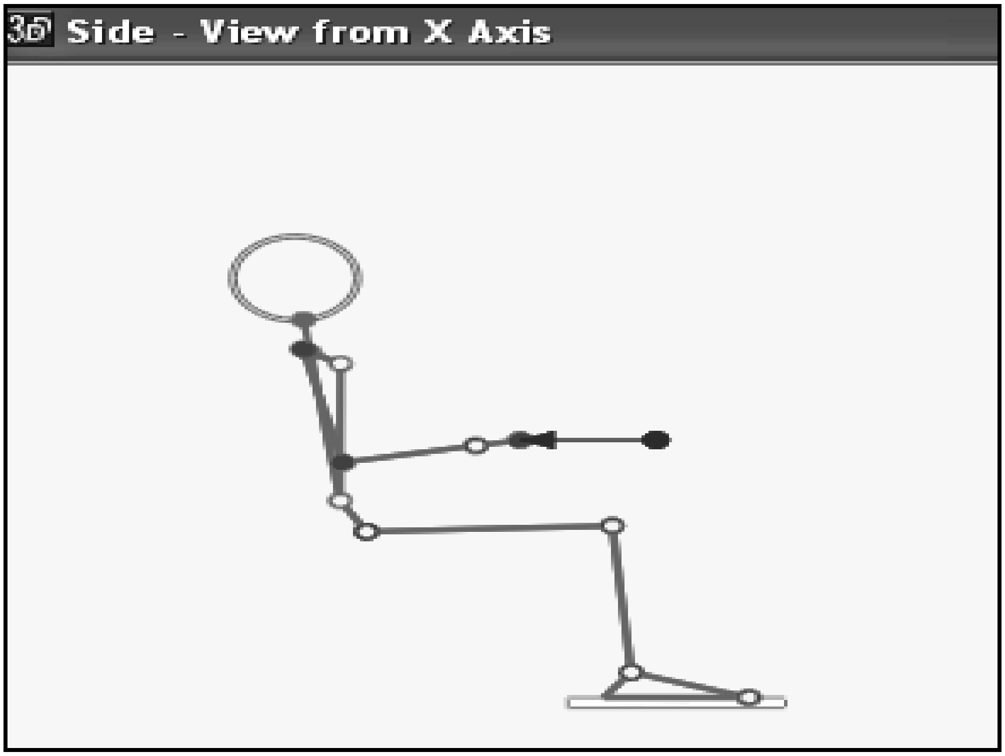


Figure 4.11 Hand-lever Wheelchair 3DSSPP Model

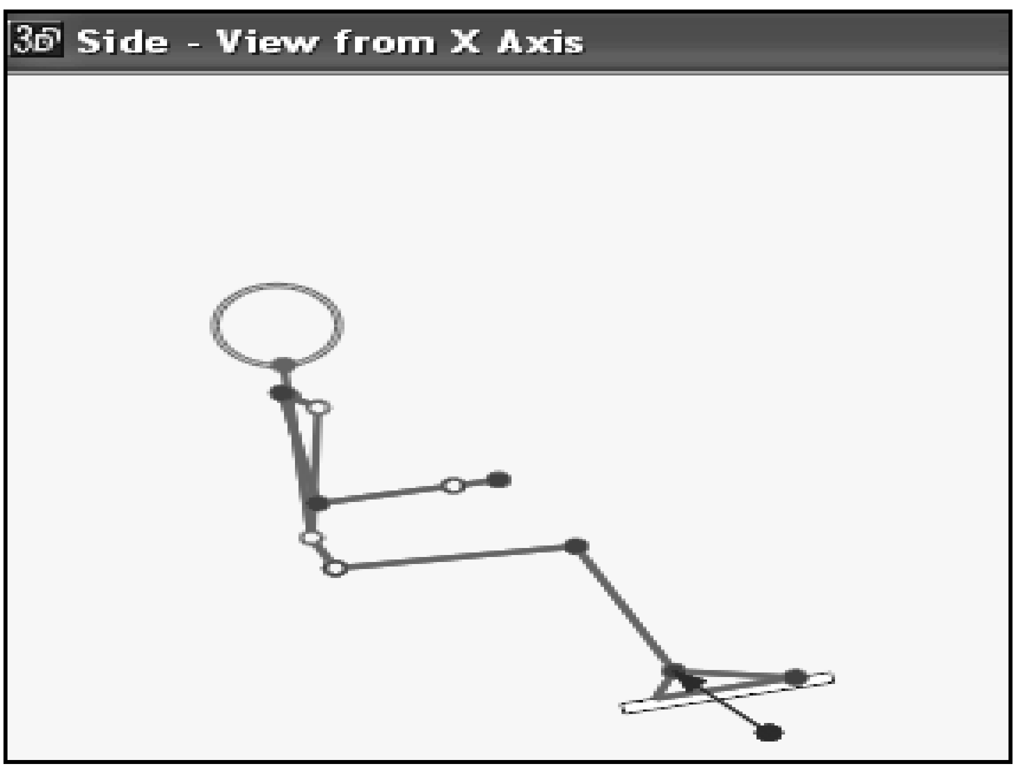


Figure 4.12 Trackball Wheelchair 3DSSPP Model

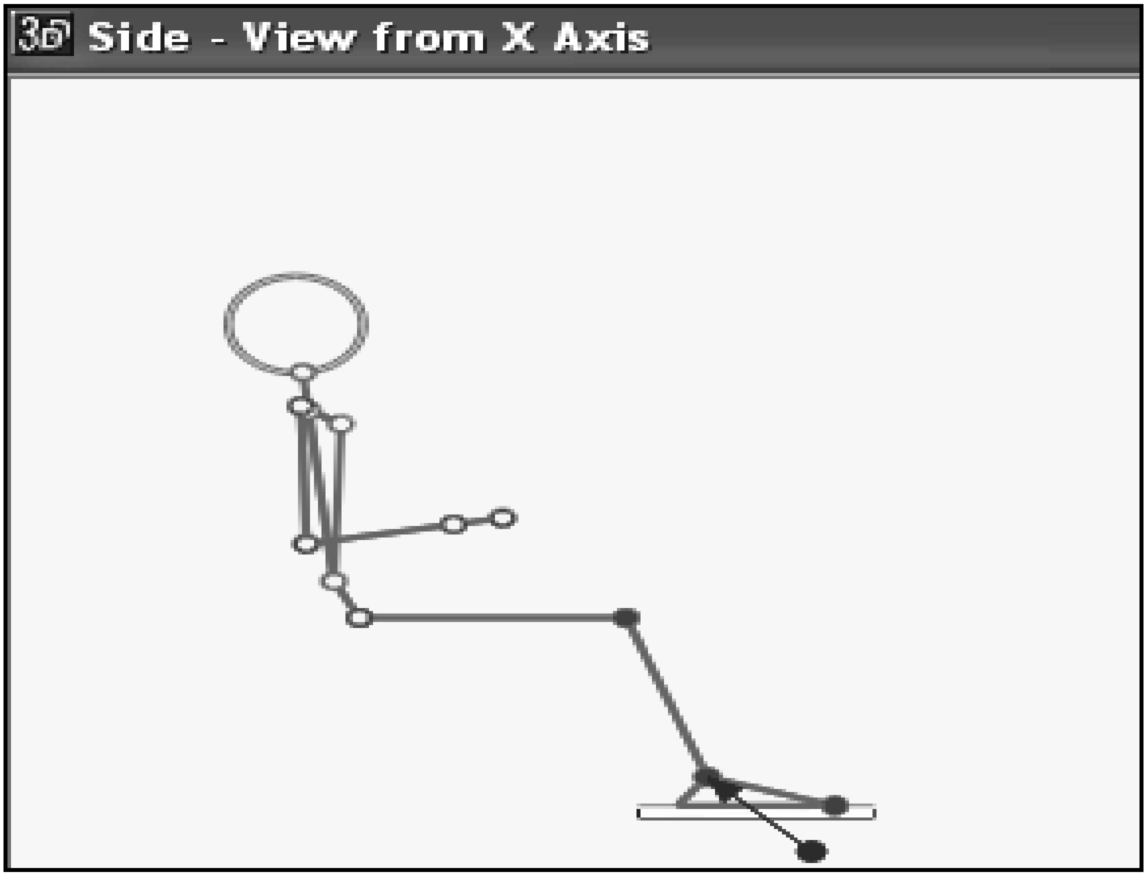


Figure 4.13 Four-bar Wheelchair 3DSSPP Model

4.5 Results

The first part of the biomechanical analysis used the hand calculations from the free body diagrams. These results were plotted, in order to determine the trend of each manual wheelchair propulsion system and to provide a visual comparison of force requirements. These results are illustrated in Figures 4.14-4.17. Before 3DSSPP modeling was performed empirical and hand calculations force results were compared. The force requirements, as determined by the free body diagrams and hand calculations appear to be overestimated. Due to this difference only the empirical data were used in 3DSSPP analysis. The results of 3DSPSS are shown in Table 4.1

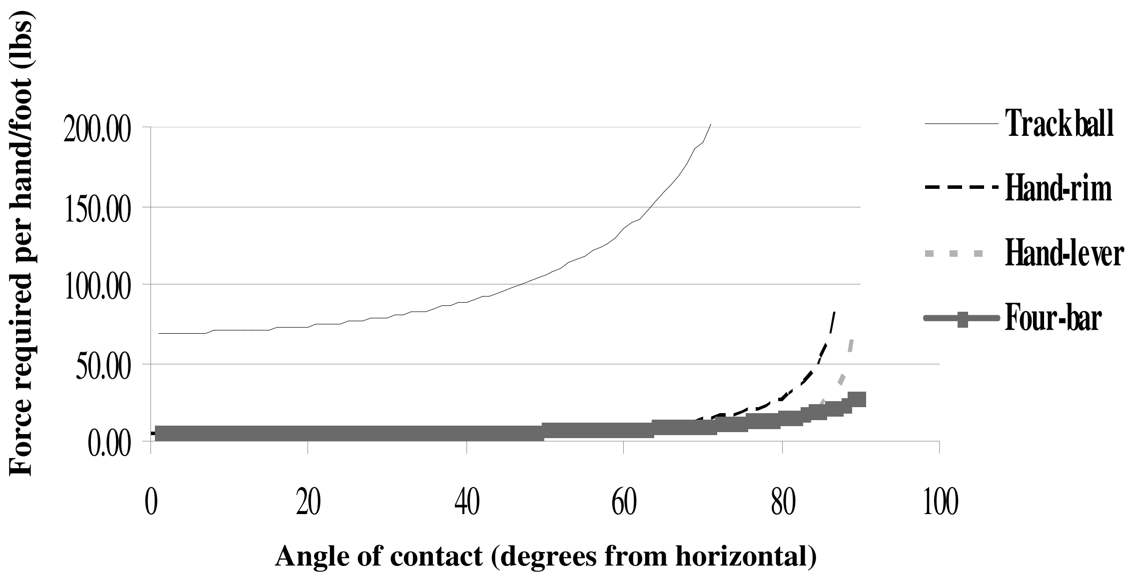


Figure 4.14 Male ADA Ramp (1:12) Required Propulsion Force

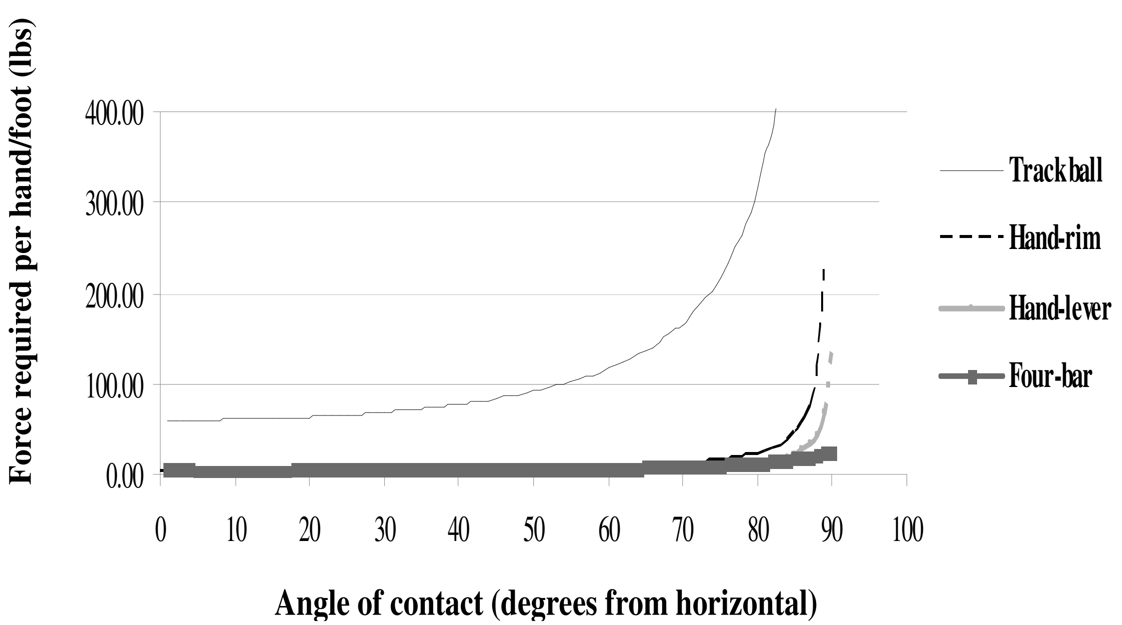


Figure 4.15 Female ADA Ramp (1:12) Required Propulsion Force

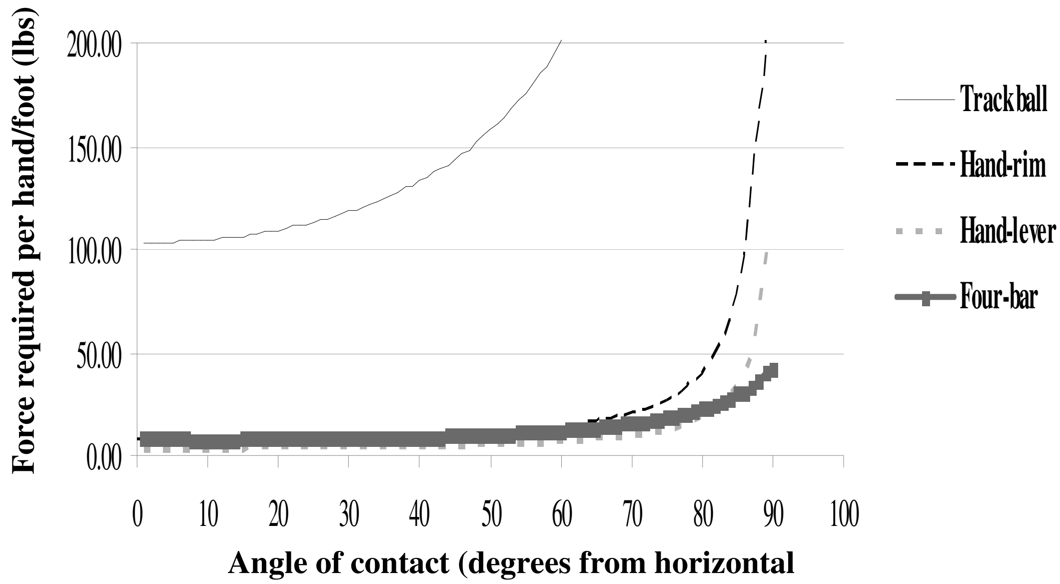


Figure 4.16 Male ADA Ramp (1:8) Required Propulsion Force

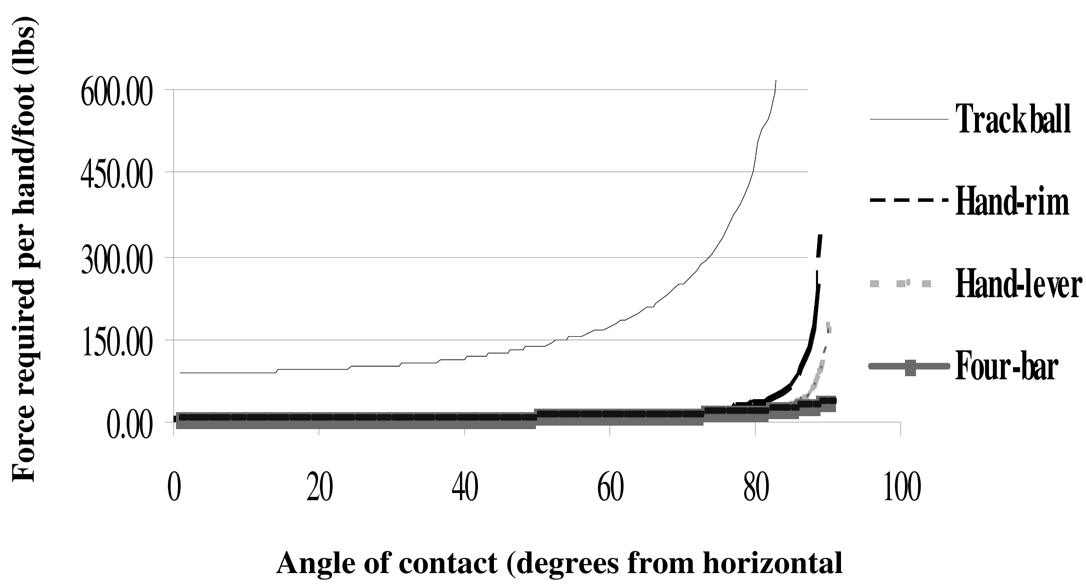


Figure 4.17 Female ADA Ramp (1:8) Required Propulsion Force

Table 4.1 3DSSPP Joint Moments

Wheelchair	Wrist	Elbow	Shoulder	Hip	Knee
Hand-rim	7.10 in-lbs	37.4 in-lbs	115 in-lbs	not applicable	not applicable
Hand-lever	0.600 in-lbs	12.3 in-lbs	98.8 in-lbs	not applicable	not applicable
Trackball	not applicable	not applicable	not applicable	34.5 in-lbs	164 in-lbs
Four-bar	not applicable	not applicable	not applicable	12.5 in-lbs	41.8 in-lbs

4.6 Discussion

Earlier studies have shown that hand-lever propelled wheelchairs are more efficient and less metabolically stressful than hand-rim wheelchair propulsion [7]. The calculations revealed that the hand-lever propulsion system had the lowest force requirements, followed by the four-bar wheelchair. The leverage provided by the hand-lever greatly reduces the force requirements. Also, it appears that the large cam mechanism on the four-bar wheelchair greatly reduced the force requirements on these inclined surfaces. The hand-rim propulsion had the next highest force requirements, followed by the trackball wheelchair. The hand rim and trackball which do not have any cams or reduced gearing were found to have the highest force requirements. Due to the high force requirement results that were found for the trackball, the researchers decided to conduct real world testing to determine if it was possible to maintain these forces in a static position on an ADA approved ramp.

In order to determine if the trackball force requirements could be produced during ADA ramp use the trackball wheelchair was tested on a 1:12 ramp. While trying to move up the ramp, the high friction basketball used in the trackball slipped under the metal retaining ring, rendering it unusable. In order to be functional on an ADA approved ramp the trackball frame would need to be heavily weighted on the front edge, to prevent this from occurring. Another possible solution would be locating the trackball retaining ring closer to the wheelchair so that the location where force is applied to the floor is closer to the wheelchair's center of balance. However this would also increase the force/moment relationship.

Empirical testing results from the experimental set-up and 3DSSPP™ found that shoulder, elbow and wrist moments were greater for hand-rim propulsion then the hand-lever system. The added leverage and gearing of hand-lever propulsion reduced the wrist moment by 91.5%, the elbow moment by 67.1% and the shoulder moment by 13.9%., when compared to hand-rim propulsion. The four-bar propulsion wheelchair had much smaller moments than the trackball. Knee moment was reduced by 74.4%, and the hip moment by 63.8% when compared to track-ball propulsion.

4.7 Conclusion

The biomechanics of alternative propulsion wheelchairs is generally advantageous over traditional hand-rim wheelchair propulsion. The one exception was the trackball wheelchair. Due to its tendency to "wheelie" it is incapable of ascending an ADA ramp. Weight could be added to the front of the wheelchair frame, to prevent it from rising from the ground or the trackball retaining ring could be brought closer to the wheelchair frame to prevent this problem.

Joint moments of hand-lever propulsion on an ADA approved ramp were much lower than the hand-rim wheelchair. While comparing joint moments of lower body propulsion systems the four-bar had much lower knee, and hip moments than the trackball. These lower joint stresses reduce the risk of musculoskeletal disorders.

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5. CONCLUSION

5.1 Discussion

Comprehensive testing of the four manual wheelchairs propulsion systems in this research provides information about the overall strengths and weaknesses of each propulsion system's design. Each design has various strengths and weaknesses.

The information gathered through this research can be used by wheelchair designers to improve the designs of these four forms of manual propulsion wheelchairs. Future manual propulsion wheelchairs may be designed that exploit the strengths, such as comfort or ease of use. Likewise, designers may implement changes that eliminate recognized weak areas of each manual wheelchair propulsion system. Thereby, the recognized strengths may be duplicated in design while the weak areas may be corrected, so that they are also made strong. This information may also be helpful to wheelchair users so that they will be able to find the manual wheelchair propulsion system that works best for them. Their decision can be based on the areas covered in this research. Those areas were metabolic demands, biomechanical modeling to determine UEMSD risk, maneuverability, and usability.

Comprehensive testing of the wheelchair propulsion system found that overall the two upper body propulsion wheelchair had the most favorable test results. The results of metabolic testing found that the upper-body propulsion wheelchairs were less metabolically demanding during the 5 minutes of wheelchair exercise on the wheelchair treadmill. The upper-body wheelchairs were also found to be more easily maneuverable than the lower body wheelchairs. In addition, subjects indicated that they preferred the upper body wheelchairs due to the "ease of use" and the "comfort" that they provided. Empirical testing using biomechanical modeling within each wheelchair group (lower or upper body propulsion), found that joint moments were lower for the hand-lever design than the hand-rim system. Also, biomechanical modeling found the four-bar system to result in lower joint moments than the trackball.

5.2 Further work and recommendations

Additional work needs to be conducted with metabolic testing to determine the metabolic demands of each manual wheelchair propulsion system during longer periods of exercise. During longer durations of wheelchair exercise fatigue is greatly increased. The large muscle groups of the legs, which are more fatigue resistant, may have lower metabolic demands than the smaller muscle groups of the arms. Research may also be conducted in the future to explore the effect of slopes and uneven terrain on the maneuverability of different manual wheelchair propulsion systems.