ONE-ARM DRIVE MANUAL WHEELCHAIR

A Major Qualifying Project
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by

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Abstract

Traditional manual wheelchairs require considerable use and control of both arms for operation, thus adaptations are required for individuals with asymmetrical use of their arms. Building upon previous projects, the goal of this project was to create an accessory, to be installed on a standard wheelchair, which would allow full control of the wheelchair with only one arm/hand while addressing areas lacking in commercial products and previous designs, such as manufacturability, attendant control, user comfort and ergonomics.

After preliminary testing and analysis of three one-arm propulsion designs (Meyra lever-operated chair, Quickie dual-pushrim chair, and the 2005-06 MQP's prototype), the project team developed a design for a removable, lever-operated accessory which could be adapted to fit a range of the most popular standard wheelchair models. The propulsion system, connected to the main lever by a coupler link, consists of a dual gear-pawl assembly in which the desired direction of motion is chosen by moving a shifter to engage one of the two gears press-fit around clutches, each of which allows motion in only one direction, either forward or reverse. By including a neutral pawl position in which neither clutch is engaged, this design allows an attendant to propel and control the chair. Disc brakes mounted to each of the two wheels are operated via a brake lever attached to the handle of the main propulsion lever. The steering design consists of a cable wrapped around two pulleys. One pulley, attached to the main lever handle, transmits the user's input to the second pulley at the caster wheel, causing the caster to turn. Careful attention was paid to minimizing the number of specialized parts and hardware used in the design in order to improve its manufacturability and ease of installation, and to minimize the need for maintenance. During final testing, the team's prototype was compared to the Meyra lever-operated wheelchair and the prototype from the 2005-06 MQP by Cassidy, et al. The 2008-09 wheelchair showed considerable improvement over the prior MQP in the areas of size, required propulsion force, and user comfort. The 2008-09 MQP was also successful in greatly reducing operational noise and safety hazards due to sharp edges and moving parts. Deficiencies in the 2008-09 design included mechanical disadvantage in the steering system, excessive weight, and failure due to stress concentrations in the accessory mounting spokes.

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1. Problem Statement

There are countless injuries and conditions, including stroke, paralysis, muscular dystrophy, and amputation, that require individuals to depend on a wheelchair as their main means of mobility. The traditional manual wheelchair, which requires use of both arms to operate, is sufficient for most of these individuals. For those with asymmetrical use/control of the arms, or perhaps impaired cognitive ability as a result of their condition, these traditional wheelchairs are not an option. Instead, a manual wheelchair which can be propelled and steered with one arm is required. Though there are some commercially available one-arm manual wheelchairs, they often have poor steering and ergonomic design, and cannot be pushed by an attendant because the modifications that allow one-handed propulsion impede the freedom of the front casters. Additionally, the modifications are a permanent part of the chair's design, meaning a new chair must be purchased if the user's abilities change (i.e. if through therapy they regain use of both arms to the point of being able to use a traditional wheelchair, or a progressing disease leaves them with diminished ability). As such, there is a definite need for an accessory which can convert most traditional, commercially available manual wheelchairs to a one-arm drive manual wheelchair.

2. Introduction

As of 2008, approximately 2.2 million individuals in the United States require the use of wheelchairs for their daily activities. Worldwide, 100-130 million people need wheelchairs, but less than 10% either own or have means of obtaining one because most of these people live in developing countries where wheelchairs are not available (Cooper, Cooper, and Boninger, 2008). It is predicted that these figures will rise by 22% over the next ten years for a number of reasons, including but not limited to the aging baby-boomer generation, ongoing wars, re-habitation of areas infested with land mines from prior conflicts, and other injuries and diseases.

Current wheelchair technology is relatively well-established in that there is not a great deal of variation in the wheelchair market, which can create difficulties for individuals whose needs are not met by currently available models. Wheelchair design and functionality as a whole has been greatly improved over the past several decades, but there is still a need for new technology and innovative designs. The majority of assistive device users are over age 65, with increases expected as the baby boomers age and the average life expectancy increases. For this population, conditions such as stroke, hemiplegia, Parkinson’s disease, and arthritis are some of the more common limitations requiring wheelchair use (Kang, Kaye, and LaPlante, 1995). Among younger individuals, wheelchair use is also increasing due to increased spinal cord injuries and other traumas (Cooper, Cooper, and Boninger, 2008). Many of the conditions that restrict an individual to reliance on a wheelchair also limit control of the upper extremities to the extent that the user can only operate the chair with one hand. Powered wheelchairs serve this need quite well but are expensive and thus inaccessible for many individuals. They are also difficult to transport without a specially-adapted vehicle, meaning additional expense for someone who wishes to remain independent and mobile. Therefore, there is a need for manual one-arm drive wheelchairs. Though some models are currently on the market, they require awkward hand positioning and a degree of dexterity beyond that of much of the potential user population.

There have been two prior MQP projects addressing this topic; namely, to design a more ergonomic one-arm propulsion mechanism for a manual wheelchair that retains all of the functions of a regular manual chair. In 2004-05, the team of Jennifer Cofske, Barrett Franklin, and Darcy Vought created a design that incorporates a lever-driven dual-cam propulsion system, toggle-stick cable steering, and rotary brakes (Cofske, Franklin, and Vought, 2005). In 2005-06, the team of Sean Cassidy, Shawn LeMarbre, and Tiffany Madsen designed a linkage-driven ratchet and pawl propulsion system with cable steering and cantilever brakes (Cassidy et al., 2006). Many of the recommendations both teams had for further improvements on their designs dealt with the areas of manufacturing, steering, and braking. It is therefore the primary aim of this project to design a system that will improve on these areas.

3. Background Research

The following chapter presents background research conducted in order to better understand certain topics related to the project. A large portion of the team's efforts are geared toward designing an accessory that is comfortable and easy to use for as large a population as possible. To do this successfully, the team had to first investigate human factors engineering, especially areas like human factors, testing, and anthropometrics. Human factors helps understand the design processes and considerations that go into creating a consumer product. Anthropometrics will be required for ensuring the accessory properly fits the user. Research into testing of consumer products, particularly industry standards for wheelchairs, will help the team with evaluation of both prior designs and the accessory. In addition, patent benchmarking and market research helped the team become familiar with devices that have already been created and/or put on the market and also provided possible design ideas. Lastly, the team conducted its own preliminary evaluations of three of the chairs available in the Rehab Laboratory in order to determine shortcomings and areas requiring attention during the design process.

3.1 Human Factors Engineering

3.1.1 Human Factors

Human factors engineering is defined as "the application of scientific knowledge of human capabilities and limitations to the design of systems and equipment to produce products with the most safe, effective, and reliable operation" (Fries, 2006). These limitations arise from a variety of factors ranging from physical size to mental capabilities to reaction time. While the designer must take them into consideration, limitations cannot be allowed to affect the integrity or effectiveness of the device. Rather, the device must be designed for use by the least-skilled individual(s) of the intended user population (Fries, 2006). In this sense, user skill plays a large role in determining interface design and is affected to a degree by the operational environment of the device. A design must attempt to address any potential problems the user may have that stem from the operational environment (Fries, 2006). Other goals of human factors engineering include designing devices that fit the user properly, calculating and providing clearances that allow objects plenty of space to move without hindering or hurting others, and eliminating accidental access to dangerous areas (Kroemer, 2006).

There are three main elements to human factors, according to Fries (2006): the human element, the software element, and the hardware element. This project will only deal with the human and hardware elements. The human element addresses topics such as cognition, speech, vision, and user skills (Fries, 2006). A device should not overload the senses or long-term or short-term memory, as this has been shown to reduce user performance. It should be as simple and with as few controls as possible to promote ease of use. A simple design will also require less maintenance and fewer repairs. If maintenance or repairs are necessary, they should be possible for an individual with minimal training to perform in the field, without having to take the device to a special repair shop (Fries, 2006).

3.1.2 Anthropometrics

Fries (2006) defines anthropometry as "the science of measuring the human body and its parts and functional capacities." These measurements are taken and then statistically analyzed for large sample groups to be used as representative data for a given population. The data can be sorted by the subjects' age, gender, race, occupation, and various other categories. In the United States, the most common and reliable source of anthropometric data is the U.S. military, as it has been taking measurements of its soldiers since the Civil War (Kroemer, 2006). Though this is not the ideal sample population for representing *all* Americans (because soldiers tend to be young, healthy, and average-sized), it is the most comprehensive set of measurements available. Devices can be designed for a certain percentile range of the population, though great care must be taken in doing this so as to avoid excluding too many people.

Anthropometric data can be used in many ways. Engineers and anthropometrists must decide whether they wish to design for the maximal or upper limit of the selected group or for the minimal (lower) limit, though often both limits have an influence on the design (Kroemer, 2006). When looking at strength data, one must determine whether the situation calls for static or dynamic strength measurements. Static measurements can be approximated using isometric strength data, but dynamic measurements must take into consideration factors like the individual's endurance (Kroemer, 2006). The positions in which anthropometric measurements are taken also tends to be quite different from the actual positions an individual assumes during daily activities (i.e. a measurement of leg-to-shoulder length taken in a sitting position may be greater when measured for anthropometric data than when actually sitting, as many people tend to slouch or alter their posture from a straight-backed position) (Kroemer, 2006). As such, slight adjustments to the measurements are required, though the extent is left up to the designer.

The team will need to use anthropometric data to ensure that the accessory is usable by the largest population possible. The accessory will be designed mainly for use by adults and the elderly, which requires anthropometric data for individuals ages 17 to 18 and above. This data is included in Appendix B. More specifically, it includes hand measurement data, mobility data, and general anthropometrics, as well as diagrams showing how measurements are taken.

3.1.3 Testing

The design and production of any consumer product or device requires testing to ensure the product is safe and will not endanger the consumer during normal use. There are several categories of testing, two of which are safety and functional testing. Safety testing, according to Fries (2006), is testing which "verifies that the product performs safely." The goal of safety testing is to minimize and/or eliminate the "potential for human error and minimize its consequences" (Fries, 2006). Functional testing, on the other hand, is done to ensure that the product performs as desired and that all functional requirements have been met. A device that does not perform its intended function (i.e. a walker that cannot support the dynamic weight of its user) is useless and even dangerous, and must be redesigned such that it performs as required.

The ANSI/RESNA Wheelchair Standards cover a broad spectrum of safety and functional testing for wheelchairs, both powered and manual. It is essential that the team adhere to these standards in order for the accessory to be accepted by the rehabilitation technology industry. The tests help to ensure that the accessory is safe for everyday use in a wide variety of environments and situations. Of particular interest to this project are the static stability tests set forth in ANSI/RESNA WC/01 and determination of mass and turning radius (found in ANSI/RESNA WC/05). The accessory should not make the chair more difficult to transport or drive, and so tests for mass and turning radius with the accessory installed are necessary. In addition, the accessory will be installed on the side of the wheelchair, thus the team needs some means of ensuring that the added weight does not significantly alter the chair's center of gravity and make it more likely to tip while on an uneven surface.

Conditions for testing stability are as follows:

- Testing must be carried out on a flat, hard plane with an adjustable slope

- The surface’s coefficient of friction will follow ANSI/RESNA WC/13
- The chair must be fully equipped as for normal use, with tires properly inflated
- Wheels must be locked relative to wheelchair frame
- A dummy of appropriate size will be used, positioned in the chair as far back in the seat as possible, equidistant from the sides, with legs positioned such that the back of the legs coincide with the rear edges of the footrest
- The dummy will be secured so that it does not move from the aforementioned position
- Leg supports will be elevated

For a test of static stability with wheels locked in the forward and aft directions (tip angle with the chair facing up and down the slope, respectively), the wheelchair will be positioned on the test plane with wheels locked, facing in the appropriate direction. The slope of the plane will gradually be increased at a uniform rate until the uphill wheels just begin to lift off the plane. The angle at which this occurs is measured by pulling a piece of paper at right angles from beneath the uphill wheels. If the chair slides during this process, the angle at which this occurred will be noted and straps will be used to prevent the chair from sliding during the retest.

To test the static stability (tip angle) of the chair in the transverse direction, brakes locked, the chair is set up under the same conditions as for the forward and aft tests. It is to be oriented 90° from its previous position, i.e. facing off the side of the plane. The incline of the plane will be gradually increased at a uniform rate until the uphill wheels just begin to lift off the plane, and the angle at which this occurs will be measured and noted. As before, any slipping will be corrected by the use of straps to secure the wheelchair.

ANSI/RESNA WC/05 sets forth procedures for determining the mass and turning radius of a manual wheelchair. The wheelchair’s mass should be measured to the nearest kilogram with all accessories loaded onto the chair. If possible, the mass of each component should also be measured. This standard defines minimum turning radius of the chair as “the smallest cylinder in which the chair can be turned 360°.”

3.2 Patent Investigation

In order to ensure that the team came up with a design not already available and that offered a feature or combination of features that was unique and original, it was necessary to research patents for wheelchair propulsion mechanisms. Additionally, this research provided ideas from which the team based some of its preliminary designs.

3.2.1 Wheelchair Propulsion Systems

There are many patents for wheelchair propulsion systems that use methods other than pushrims to propel and steer the chair. Some of these patents are outlined below. While not all of them are for single-arm propulsion mechanisms, the team felt it was important to investigate dual-arm options as well in order to see if these mechanisms had the potential to be useful in the design process.

U.S. Patent #5007655 (Hanna, 1991) discusses a wheelchair operated using levers on both sides of the chair. It has two forms, in both of which the levers are connected to sprockets on the drive wheels. The difference between the two versions is the manner in which the levers connect to the sprockets. In one, a toothed rack connected to the lever at one end is meshed with the sprocket, and a clutch allows the power stroke of the lever to drive the wheels through this arrangement. It also lets the sprocket rotate freely during the return stroke, rather than engaging the teeth and driving the wheels in the opposite direction. The rack also has a section without any teeth (58), which allows the drive mechanism to be disengaged, i.e. a “neutral” setting, in order for the chair to be propelled by the pushrims or an attendant. Figure 1 shows this version of the wheelchair.

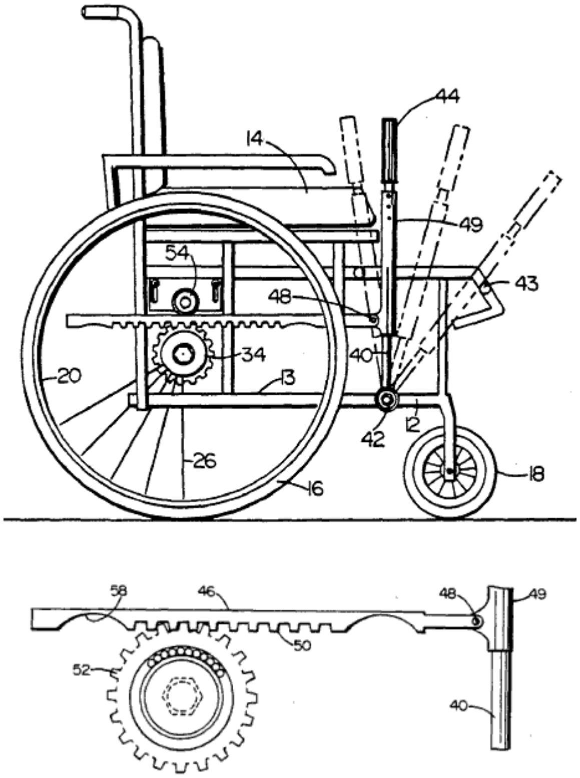


Figure 1: U.S. Patent #5007655 - Sprocket-Rack Arrangement (Hanna, 1991)

In the other form of this design, a chain similar to a bicycle chain connects the lever to the sprocket. The chain is attached at one end to the lever, leads back to and around the sprocket, and at its other end is attached to a return spring anchored on the wheelchair frame. Like the rack, the chain has an area without pins (70) to allow the wheelchair a "neutral" setting (Figure 2).

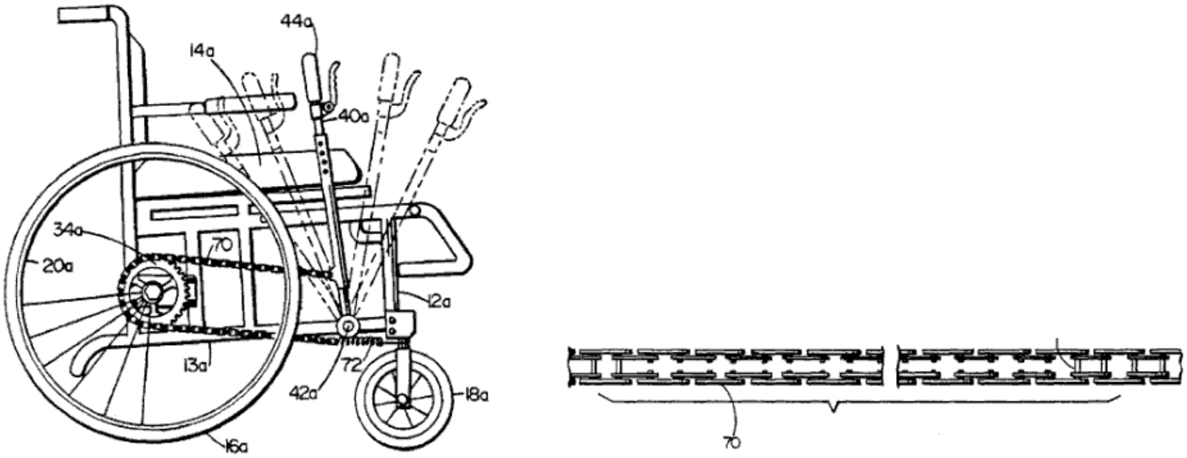


Figure 2: U.S. Patent #5007655 - Sprocket-Chain Arrangement (Hanna, 1991)

In addition, the wheelchair drive mechanism will not engage when the wheels are moving faster than the drive speed, such as when the chair is rolling down an incline. This ensures that the lever will not be moving back and forth at dangerous speeds, posing the risk of injury to the user. Both models have a speed change mechanism which allows the user to vary the torque that is applied to the sprocket, and thus the force with which the wheels are driven. Lastly, in order to propel the chair backward, this design requires that the drive mechanism be disengaged and the wheels propelled backward by hand, i.e. using the pushrims.

The next relevant patent is US Patent #5020815 (Harris et al., 1991), which details an after-market accessory that can be installed on a manual wheelchair to convert it into a one-arm-propelled chair. This patent (Figure 3) was of particular interest to the team because developing such a device is the team's primary design goal. The attachment consists of a drive attachment (5) installed on one of the rear wheels of the chair, connected to the wheel by a hub arrangement. There is also an elongated arm (1) that attaches to the front caster via a gearbox (13) mounted to the chair, and extends vertically upward to become the handle for the entire mechanism. Finally, a connecting link (9) between the arm and drive attachment links the pieces of the accessory together. The drive arm is attached to the rear wheel using a hub attachment coupled with a reversible ratcheting mechanism. The hub attachment has several arms that fit between the spokes of the rear wheel, making it adaptable to the various spoke arrangements found on wheelchairs. The ratchet mechanism allows the lever to be returned to its starting position after the power stroke without driving the wheels. A control lever (84) on the handle (23) determines the direction in which the power stroke drives the chair, i.e. forward or reverse, by activating a cable (90) to adjust the ratchet accordingly. The lever arm itself has an outer drive arm portion and an inner steering arm portion. Both are mounted such that they can pivot on a common horizontal axis (11) to engage the drive mechanism. The steering arm portion can also be rotated about a separate longitudinal vertical axis to steer the front caster to which it is attached.

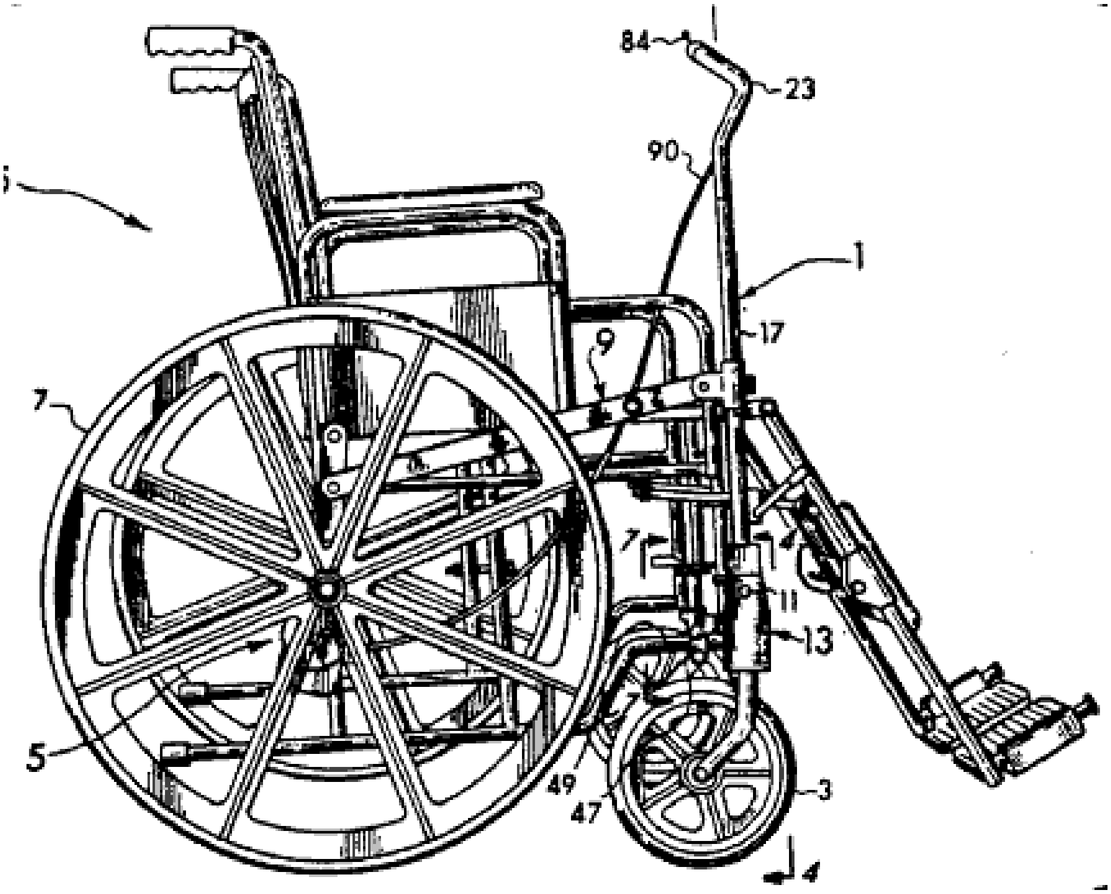


Figure 3: US Patent #5020815 - One-Arm Lever Propulsion Accessory (Harris et al., 1991)

Another two-arm lever design is described in US Patent #4453729. The levers are pushed away from the user for the power stroke, and dual ratcheting mechanisms on either side transfer the motion to the wheel to drive the chair forward. The wheels are not driven during the return stroke. A cable provides the connection between the lever and wheel, running from the lever, around the wheel and ratcheting mechanism, back to a return spring on the wheelchair frame (Figure 4).

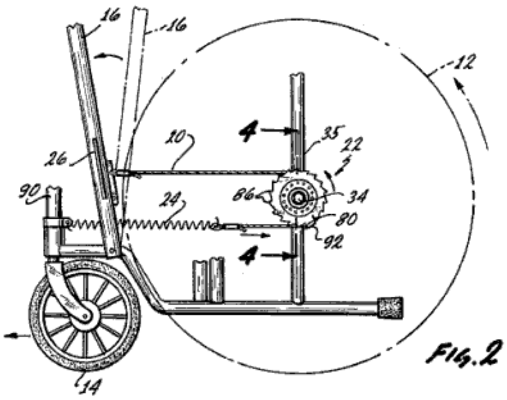


Figure 4: US Patent #4453729 - Dual Lever/Ratchet Propulsion Mechanism (Lucken, 1984)

The ratcheting mechanisms have two parts, the first of which also allows the driving wheel to always freewheel in the forward direction, and the second of which allows the driving wheel to freewheel in both the forward and reverse directions when the levers are in the neutral position, i.e. towards the user. This means that, similar to the design described in US Patent #5007655, the levers will not move back and forth at dangerous rates when the wheels are spinning quickly. In order to simply propel the chair forward, both levers are pushed away at the same time, whereas to turn the chair only one lever is driven. However, to propel the chair backward, the levers must be in their neutral position and the wheels driven backward via the pushrims.

Similarly, US Patent #5941547 discusses another two-arm lever design. The designers of this particular device wanted to use pushing and pulling motions because they observed that the traditional pushrim propulsion sometimes required users to inadvertently lift themselves out of the chair during the downward stroke motion, thereby shifting the center of gravity of the chair and making it unstable. In this design (Figure 5), the levers are connected to wheel pulleys by a drive cable (18 and 25).

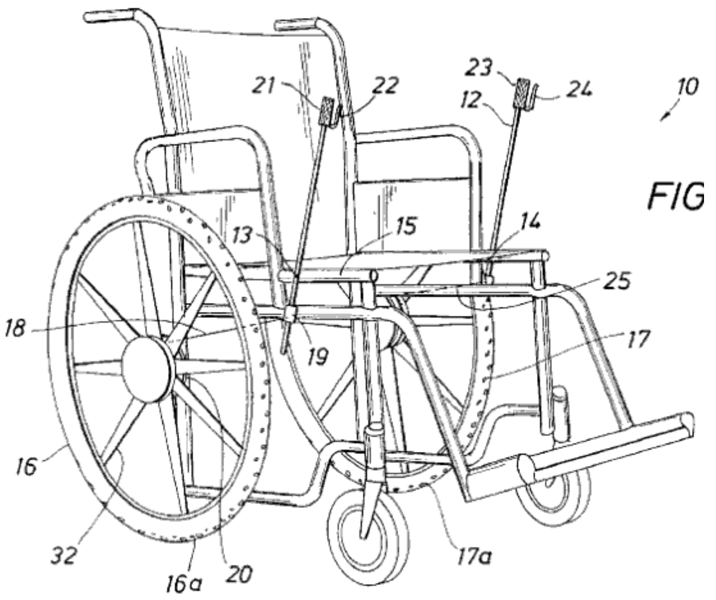


Figure 5: US Patent #5941547- Dual Lever Drive Cable Propulsion Mechanism (Drake, 1999)

When the levers are pushed away from the body during the power stroke, one-way clutches allow the wheel pulleys to propel the wheels. In all other situations the clutches allow the wheels to rotate freely. The cable is wound back onto the pulleys by recoil springs during the return stroke. To change the mechanical advantage (i.e. the attachment point of the cable on the drive lever), the handle on the lever arm is rotated in a clockwise or counter-clockwise direction. This causes a pin in the connector to move through a helical groove in the lever (Figure 6), thereby moving the connector up or down depending on the direction of rotation of the lever. When the connector is moved below the pivot point, the chair will be driven in the reverse direction by the power stroke.

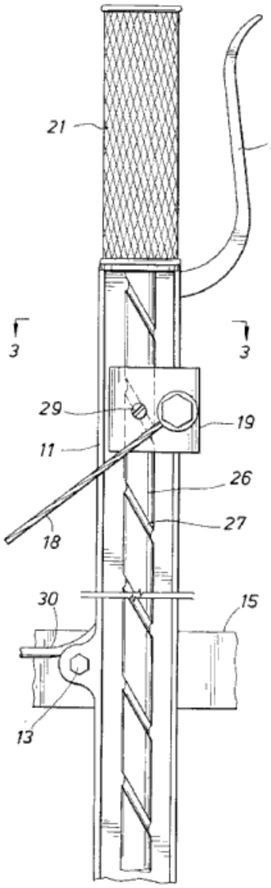


Figure 6: US Patent #5941547 - Means of Changing Mechanical Advantage (Drake, 1999)

The steering is not directly controlled by rotating the levers like in previously mentioned designs. Rather, the user must steer either by using the brakes (levers for which are located on each of the propulsion levers) or varying the power applied to each wheel. This design is also adaptable for one-handed operation, in which a single lever powers both wheels via a common axle and steering is accomplished by applying the brakes. Levers to control the brakes for each of the two drive wheels are located on the single lever arm in this case.

One of the most popular commercially-available one-arm drive wheelchairs is the Quickie dual pushrim manual wheelchair. This chair was designed specifically for triplegics or individuals with use of only one arm. US Patent #5306035 describes the Quickie chair. The chair (Figure 7) has a manual pushrim assembly consisting of two rims, one slightly smaller than and concentric to the other, which are mounted proximally onto one of the drive wheels (22) of the chair. Both are mounted on the same side, coaxial to the axle of the drive wheel (24). This hand rim assembly also has a drive axle component (55) that can be attached to both the rim assembly and the second drive wheel on the opposite side of the chair. The outermost rim (26) controls the second drive wheel (23) through this connection. Rotation of the inner rim (25) controls the first drive wheel (22) only, as it is a normal hand rim connected directly to that wheel. When set up in this way, grasping both rims and rotating them simultaneously will cause both drive wheels to rotate, propelling the chair in a straight line. To steer the chair, only the inner or outer rim is used, based on the desired turn direction. The drive axle can also be detached to allow the chair to be collapsed for storage or travel purposes.

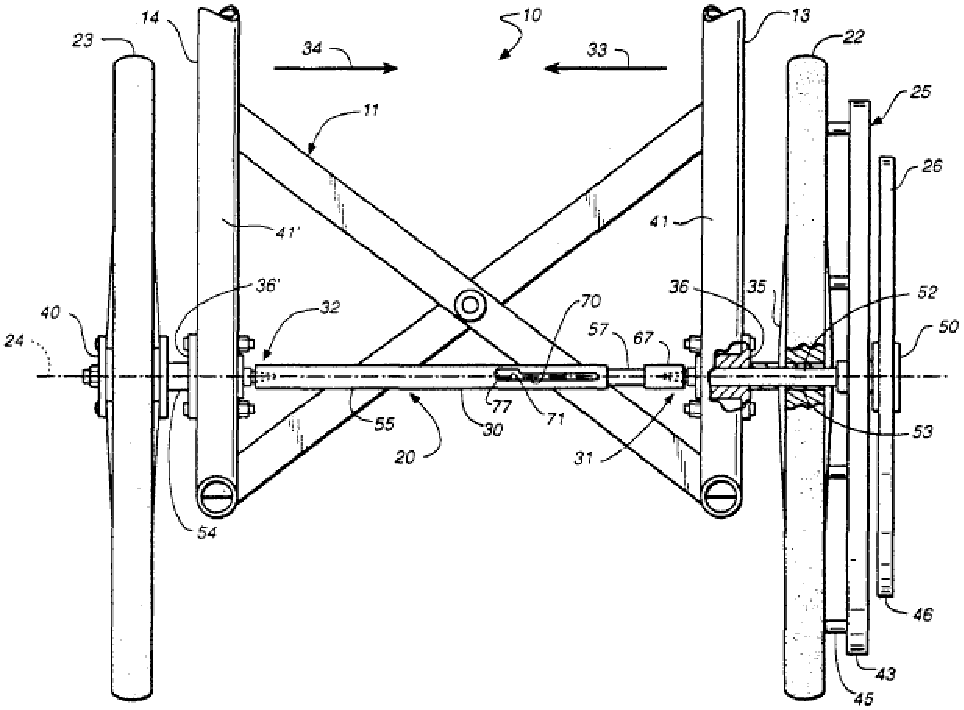


Figure 7: US Patent #5306035 - Quickie Dual Pushrim Drive System (Counts, 1994)

3.2.2 Other Devices

While propulsion is the main function of the group's design, there are other features that must be investigated and fully understood in order to develop a fully functional, safe accessory. In addition, the group realized that devices other than wheelchairs had features that were potentially valuable design ideas. Patents for these features and devices are described below.

In any wheelchair, it is important to provide a means of locking the wheels to prevent any rotation whatsoever. This allows the wheelchair to serve as a steady support base against which users may brace themselves when needed and also prevents any undesired motion. US Patent

#6929100 describes a simple wheel locking mechanism that can be added to a wheelchair. The wheel locks themselves are mounted to either side of the wheelchair frame, between the wheel and the frame. One lock has an actuating lever which is connected to the lock on the opposite side via a flexible link. Because of this link, activation of the first stop causes automatic activation of the second, meaning the mechanism is operable with one hand. Should the link break, the first stop can still be used to lock the wheel to which it is adjacent. The portion of the lock that comes into contact with the wheel has a cutout that fits the wheel to better engage it and prevent slipping while locked. Another version of this design has actuating levers on both sides of the chair for two-handed operation. Figure 8 shows the single actuating lever design in its approximate location on the chair.

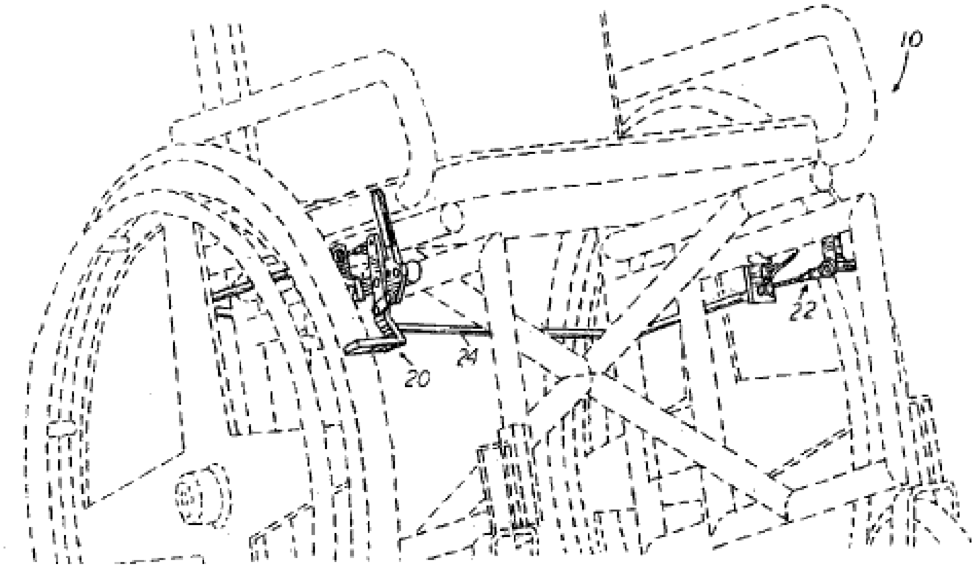


Figure 8: US Patent #6929100 - Single-Lever Wheel Lock Mechanism (Tanksley & Donaldson, 2005)

Another potential wheel-locking mechanism is described in US Patent #6298949. This system is designed to prevent strollers from being able to roll away or move while an operator is not present, but could easily be adapted to a wheelchair. Many strollers, including the one described in this patent, have a bar-type handle grasped with both hands to push the stroller. In this mechanism, the handle has two parts connected by a hinge (Figure 9).

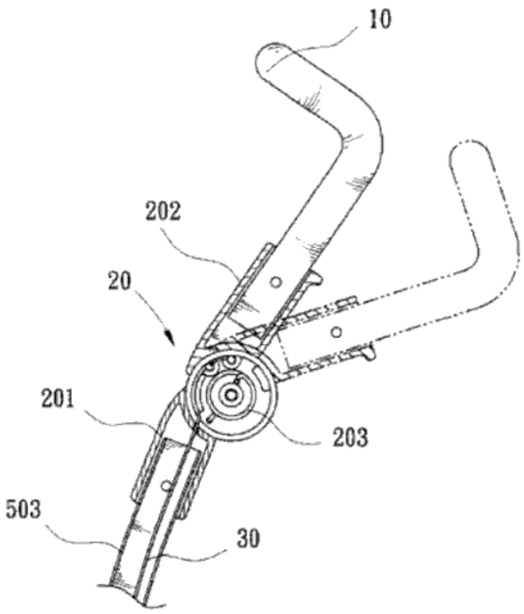


Figure 9: US Patent #6298949 - Stroller Handle (Yang & Cheng, 2001)

A wire, designated by the number 30 in Figure 9, runs from the handle down to the brake assembly on the rear wheels of the stroller. When the handle is depressed (Figure 9, dashed lines) the brakes are released and the wheel is free to rotate. Whenever this pressure is not applied, a spring in the wheel assembly pulls the wire back down and engages the brakes, thus the "default" state is one in which the brakes are engaged and the wheels cannot move. Figure 10 shows the rear wheel brake assembly. A small gear (5052) is attached proximally to the wheel (505) on the same axle (5052). A pin (403) attached to the wire running to the handle is also attached to a spring (402) that is connected to the axle such that it pulls the pin toward the axle. The pin protrudes from a slot in the stroller frame in order to engage the gear. When the handle is in the upward position and the spring is at rest, it holds the pin in one of the grooves of the gear and thus preventing the wheel from turning. When the stroller handle is pushed down, the wire stretches the spring by pulling the pin out of the groove far enough that the wheel can rotate. Releasing pressure on the handle allows the spring to pull the pin back into a groove, re-activating the brake.

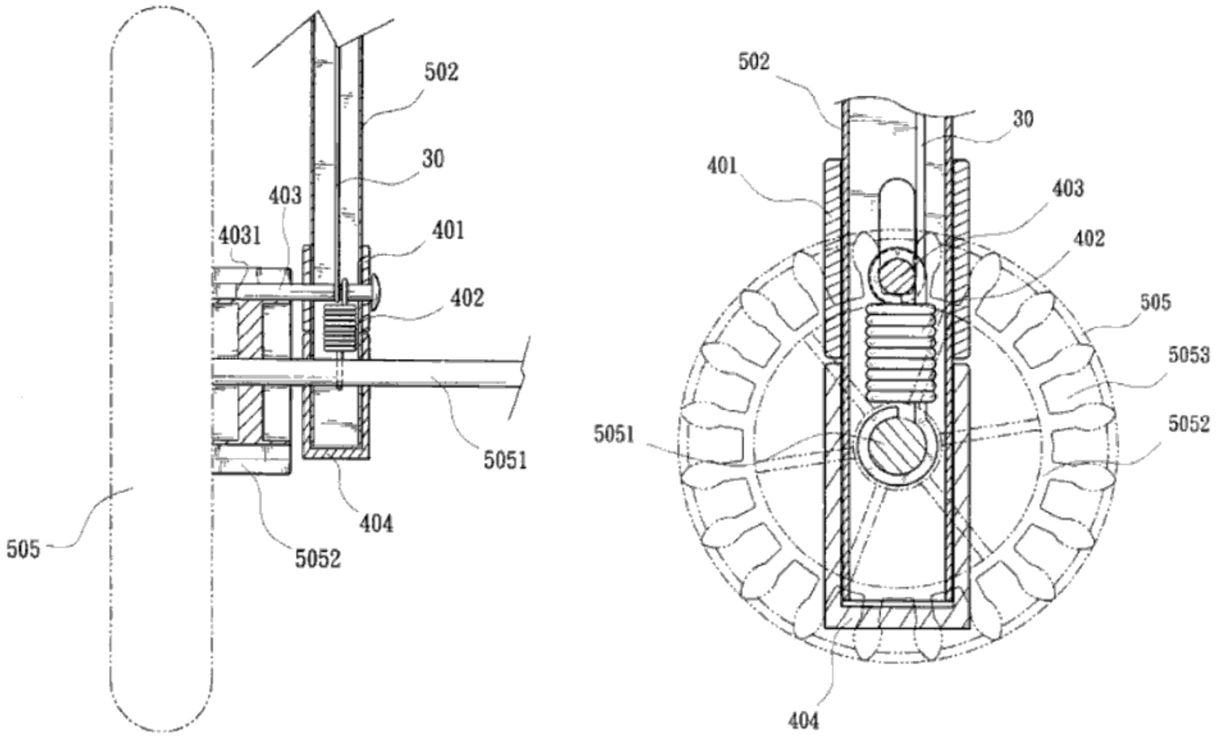


Figure 10: US Patent #6298949 - Stroller Brake Assembly (Yang & Cheng, 2001)

3.3 Market Research

It is essential to conduct background market research in order to determine which users should be targeted for marketing of the team's product. As well, it is a crucial part of the determination of the best types of wheelchair models for which the single arm wheelchair propulsion accessory will be designed and manufactured. The first step in conducting the market research was to determine a set of questions which were to be answered. The research should include demographics of wheelchair users to determine the market for the product, major manual wheelchair manufacturers, different manual wheelchair types, the most popular models, similar existing products, and the price range the users might be willing to pay for a product of this type.

The results of this research will help focus the team's efforts of creating the accessory for a certain user-base and wheelchair models. The team wants to create a product for a user-base who needs it and will purchase it.

3.3.1 Determining the User-Base

Past MQP groups have investigated the need for a one-arm propelled wheelchair and determined the types of individuals who would benefit from such a device (Cassidy et al., 2006). Individuals who have suffered from amputations or stroke and only have use of one arm would comprise part of the user base. Others, such as elderly people with limited strength, users with limited dexterity, patients who suffer from muscular dystrophy or cerebral palsy, as well as wheelchair users with weak upper body strength and those searching for alternative ways of wheelchair propulsion also comprise part of the user base.

In *Demographics of Wheeled Mobility Device Users,* LaPlante (2003) states that the use of assistive devices increases with age, and because the U.S. population is aging, the use of assistive devices is of ever-increasing importance. In the National Health Interview Survey on Disability (NHIS-D), 55.2 percent of wheelchair users are ages 65 and over (Russell, et al., 1997). The advance of the 76 million baby boomers into the older ranks will propel use of wheeled mobility devices even faster than it has grown in the past. It is estimated that by the year 2010 there will be approximately 4.3 million wheeled mobility device users (LaPlante, 2003).

The most prevalent conditions cited as causing mobility limitations among wheelchair and scooter users are arthritis (13%), stroke (11%), and multiple sclerosis (5%). Paralysis and orthopedic impairments are also common. MS and paralysis are most prevalent among nonelderly wheelchair users, whereas arthritis and stroke are most prevalent in elderly wheelchair users (LaPlante, 2003). According to the 2006 Disability Status Report persons between the ages of 45 to 64 years comprise 23.4% of wheelchair users (*Disability Status Report*). Given the wheelchair user statistics on elderly and non-elderly persons, the user base for wheelchairs is very extensive and any design would have to take into consideration the large age range of users.

Users needing a single-arm propulsion device could cover their need by purchasing an electric wheelchair. However, considerations such as the user's preferences, function, and cost also come into play. According to the *Demographics of Wheeled Mobility Device Users* study, lightweight manual wheelchairs usually cost at least $1500 while electric wheelchairs can cost up to $20,000 (LaPlante, 2003). In addition to the high price of electric wheelchairs, one can also look at the unemployment rates of wheeled mobility users. Among those 18-64 years old, only 17-18% are employed. This may be part of the reason why only 17% of wheeled mobility device users have electric wheelchairs or scooters (LaPlante, 2003). With this is mind, it is important to consider price in the development of the team's product. However, price is not necessarily the most important consideration in choosing a manual wheelchair over an electric wheelchair; rather, it is convenience. Manual wheelchairs have the advantage of being built out of light materials for quick folding and easy storage. Electric wheelchairs have the added weight of battery packs, need to be re-charged, and are not foldable or easily stored. Unlike electric chairs, manual wheelchairs do not require lifts or special devices to place the chair in an automobile. The manual wheelchair user can simply make the transfer from the wheelchair to the automobile seat and the wheelchair can be folded and placed in the trunk or back seat. Manual wheelchair users can therefore ride in virtually any automobile without having to worry about storage for their chair. Some experienced users can make the transfer and store the wheelchair themselves but other less-experienced individuals or those suffering from severe conditions may require personal assistance. Additional benefits of manual wheelchairs are daily exercise to promote muscle growth and good health. Considering price, storage, functional independence, health, versatility, and convenience manual wheelchairs seem to be a good focus for the user-base for the product.

3.3.2 Different Types of Wheelchairs

In developing a single-arm propulsion accessory for wheelchairs, one must establish the type(s) of wheelchair that the user base will be utilizing. With an established wheelchair type it becomes easier to focus efforts on designing the accessory for that particular type of wheelchair. There are five main types of manual wheelchairs, which are described below. The following information comes from ABLEDATA's factsheet on manual wheelchairs, a source for information on assistive technology and rehabilitation equipment sponsored by the National Institute on Disability and Rehabilitation Research. Where available, figures showing examples of each type of chair follow the description.

Lightweight/Sports Chairs

The most popular type of wheelchair for everyday use for a person with good upper body mobility is a lightweight manual wheelchair (Figure 11). Lightweight chairs provide maximum independence of movement with a minimum of effort. Many active wheelchair users also prefer the sportier look of the lightweights compared with the more standard-looking everyday chair. It should be noted, however, that heavy or obese persons may be unable to use these types of chairs because the lighter weight of the frame results in a reduced user capacity as compared to standard everyday chairs. Once used primarily by wheelchair athletes, the lightweight chair today is used by people in virtually all walks of life as a preferred mode of assisted mobility. Three-wheeled chairs, developed for such sports as tennis and basketball, are also an everyday chair alternative (ABLEDATA).

Figure 11: Lightweight Wheelchair (ABLEDATA 1994)

Standard/Everyday Chairs

Some wheelchair users still prefer or require a standard wheelchair (Figure 12), which is characterized by a cross-brace frame, built-in or removable arm rests, swing-away footrests, a mid- to high-level back, and push handles to allow non-occupants to propel the chair (ABLEDATA).

Figure 12: Standard Manual Wheelchair (ABLEDATA 1994)

Child/Junior Chairs

Children and young adults need chairs that can accommodate their changing needs as they grow. In addition, it is important that wheelchairs for children or teens be adaptable to classroom environments and be "friendly-looking" to help the user fit more readily into social situations. Manufacturers today are becoming increasingly sensitive to these market demands and are attempting to address them with innovative chair designs and a variety of "kid-oriented" colors and styles (Figure 13) (ABLEDATA).

Figure 13: Child/Junior Chair (Mona Medical Supplies)

Specialty Chairs

Wheelchairs have been designed to accommodate many lifestyles because of the diverse needs of wheelchair users. Hemi chairs, which are lower to the floor than standard chairs, allow the user to propel the chair using leg strength. Chairs that can be propelled by one hand are available for people who have paralysis on one side. Oversized chairs and chairs designed to accommodate the weight of obese people are also offered. Rugged, specially equipped chairs are available for outdoor activities. Aerodynamic three-wheeled racing chairs are used in marathons and other racing events. Manual chairs that raise the user to a standing position are available for people who need to be able to stand at their jobs, or who want to stand as part of their physical conditioning routine. These and other specialized chair designs are generally manufactured by independent wheelchair manufacturers who are trying to meet the needs of specific target markets (ABLEDATA). Figure 14 shows an example of a specialty chair.

Figure 14: Specialty Wheelchair (Medline Corporation, 2008)

Institutional/Nursing Home/Depot Chair

The least expensive type of chair available, an institutional chair (Figure 15), is designed for institutional usage only, such as transporting patients in hospitals or nursing homes. It is not an appropriate alternative for anyone who requires independent movement, as the institutional chair is not fitted for a specific individual. These types of chairs are now also used as rental chairs and by commercial enterprises (such as grocery stores and airports) for temporary use (ABLEDATA).

Figure 15: Depot Chair (Drive Medical 2008)

Choice for Project

Of these five different types of wheelchairs, the most appropriate manual wheelchair type for the team's intended user base is the standard/everyday use wheelchair. Lightweight and sports wheelchairs are designed for individuals with good upper body mobility, which is not the case for the chosen user base. Child and junior chairs are not appropriate given the fact that the user base established for the accessory is mostly adults and elderly persons. However, because child and junior chairs are smaller versions of adult chairs, it may be possible to have a scaled-down version of the accessory adaptable to these types of wheelchairs. It is possible that some of the individuals in the established user base may be using specialty chairs. However, these chairs are usually customized depending on the individual's needs and it may not be possible to adapt the accessory to this type of chair. Adapting the one-arm drive accessory to standard every-day use chairs will make the user base more independent by increasing their mobility capabilities for everyday use.

3.3.3 Wheelchair Manufacturers and Models

Some of the top manual wheelchair manufacturers in the market are Invacare, Sunrise Medical, and Drive Medical. There are many other smaller manual wheelchair manufacturers and distributers but the focus will remain on these three main companies given that they are the most common results when searching for manual wheelchair searches. In this section, each company's most popular standard everyday use manual wheelchair model will be examined in order to fully understand the wheelchair type for which the one-arm drive accessory will be developed. Given the user base preferences the wheelchairs in this section are foldable, with pushrims, and front casters in order to be able to implement the one arm drive accessory.

Invacare

Invacare Corporation is one of the leading manufacturers and distributors in the market for medical equipment used in the home. The company designs, manufactures, and distributes an extensive line of health care products for the non-acute care environment, including the home health care, retail, and extended care markets (Invacare Corporation).

Sunrise Medical

Sunrise Medical is one of the largest manufacturers of home care and extended care products. The Sunrise Medical family of products includes many brands in the home care industry including Quickie, Sopur, Jay, DeVilbiss, Hoyer, Guardian, Coopers, Oxford and Joerns (Sunrise Medical Corporation). Sunrise Medical's most popular standard everyday use wheelchair is the Quickie 2 model (Figure 16), with a base price of $1,995.

Figure 16: Quickie 2 Wheelchair (Sunrise Medical Corporation, 2008)

Product Weight: Approx. 27 lbs. w/o footrests
Product Width: 11 in. - 22 in. seat width
Product Length/Depth: 10 in. - 20 in. seat depth
Product Height: 16.75 in. - 22.75 in. seat to floor
Product Weight Capacity: 250 lbs. - standard, 350 lbs.- heavy duty
Caster Options 3 in., 4 in., 5 in., 5X 1.5in, 5 X 2 in., 6in, 6 X 1.5 in., 8 in., 8 in. x 2 in.,
Rear Wheel Options 20 in., 22 in., 24 in., 26 in.
Hemi seat-to-floor height 14.75 in. - 20.75 in.

Drive Medical

Drive Medical's most popular standard everyday use manual wheelchair is the Cruiser III model (Figure 17) (Drive Medical, 2008).

Figure 17: Cruiser III Wheelchair (Drive Medical, 2008)

Product Weight: 35 – 38 lbs
Product Width: 16 in. - 20 in. seat width
Product Length/Depth: 16 in. seat depth
Product Height: 19.5 in. seat to floor
Product Weight Capacity: 300 lbs.

3.3.4 Commercially Available Single-Arm Propulsion Mechanisms

There are a number of single-arm propulsion mechanisms available in the market for manual wheelchair users. However most of these mechanisms are an option that comes permanently attached to the wheelchair when it is ordered. The permanently-attached mechanism may become undesirable if the user no longer needs the device. If this were the case, the user would have to purchase another wheelchair. Other single-arm propulsion accessories available in the market are dual pushrim accessories with which the user can control both wheels with two pushrims on one side. However, this product requires a significant amount of upper body strength and dexterity to grab and control both pushrims for propulsion. Some of these products are detailed below.

The Invacare IVC CLD (Cyclical Lever Drive) (Figure 18; from the Invacare manual wheelchair series brochure) includes a front-caster steering mechanism, simple rowing motion design and adjustability in height and stroke length of the lever. The price of adding the cyclical lever drive to an Invacare wheelchair, which is only an option at the time of ordering, is $797.00 (Invacare Corporation).

Figure 18: Invacare IVC CLD (Invacare Corporation 2008)

Drive Medical's one-arm drive product is an accessory that can be adapted to two of their wheelchair models; the Viper and the Sentra EC. It is a dual pushrim accessory which includes an axle to connect both wheelchair wheels (Figure 19). The accessory is adaptable to both the right and left side of the wheelchair (Drive Medical, 2008).

Figure 19: Drive Medical Dual-Pushrim Design (Drive Medical, 2008)

Meyra's Model 1.409-14-93 wheelchair (Figure 20) is propelled by a hand lever fitted with steering and braking on the handgrip. The model can be ordered with the hand lever on either side and with small or large wheels in the front depending on the terrain on which the wheelchair will be used. Information on the pricing of this model is unavailable (Meyra, 1990).

Figure 20: Meyra Model 1.409-14-93 (Meyra 1990)

A similar hand lever propelled wheelchair model by Meyra is the Model 3.400-885 "Mono-Drive" wheelchair (Figure 21). The design of this product is simpler than that of the previous wheelchair but still operates similarly with steering on the handgrip. Braking, however, is accomplished by positioning the lever at the extreme forward and backward position. This model has been discontinued (Meyra, 1990).

Figure 21: Meyra Model 3.400-885 "Mono-Drive" (Meyra 1990)

Sunrise Medical has a one-arm drive system which includes a dual pushrim on one side for steering and propulsion, connected to the other wheel by a special axle (Figure 22). This accessory can be ordered for, and is only adaptable to, a few of Sunrise Medical's wheelchair models. It comes as an option on their order form and the price for adding this accessory to the wheelchair is $850 (Sunrise Medical Corporation, 2008).

Figure 22: Breezy Dual Pushrim Accessory (Sunrise Medical Corporation, 2008)

In addition to the specific one-arm drive products, many manual wheelchair manufacturers offer the option of adding one-arm drive accessories to a wheelchair when it is ordered. The price for this addition can be anywhere between $500 and $1,000; a considerable added cost given that the price range of a standard manual wheelchair can range from $1,000 to $5,000.

3.4 Preliminary Testing

In order to determine the effectiveness of each design's user interface, the team brought ten able-bodied individuals to the WPI Rehab Laboratory in Higgins Labs to test and rate the different wheelchair models. The test subjects rated the Meyra chair, a commercialized one-arm drive lever-propelled wheelchair; the Quickie, a one arm drive dual pushrim accessory attached to a wheelchair; and the WPI prototype (developed by Cassidy, LeMarbre, and Madsen in 2005-06), a non-commercialized one-arm drive lever-propelled prototype. The test subjects were males between the ages of 19 to 23 years. They rated the Meyra, Quickie, and WPI 05-06 MQP prototype on a scale from 1 to 5 across fourteen different categories. The rating system was based on 1 being "poor" and 5 being "good" so that the highest score a design could obtain was 70 points. The fourteen categories covered by the evaluation included forward/ backward propulsion, turning, braking, device usage comfort, intuitiveness of use, and aesthetics. The test subjects were also asked to provide additional comments on their experience.

The test subjects rated the Meyra chair higher than the other two, with an average of 56 out of 70 possible points. The Quickie dual pushrim followed with 49 out of 70 points, and finally the WPI 05-06 MQP prototype with 41 out of 70 points. Seven out of ten test subjects rated the Meyra higher than the other two chairs and three out of ten rated the Quickie highest. The average results for each individual category resulting from the ten evaluations are tabulated below.

Categories	Meyra Chair (average)	Quickie Dual Pushrim (average)	WPI MQP Prototype (average)
Forward Propulsion	4	3.44	3.11
Backward Propulsion	3.66	3.44	3.22
Turning Right Forward	4.44	3.66	3.33
Turning Left Forward	4.22	3.44	3.33
Turning Right Backward	4	3.33	3.44
Turning Left Backward	4.11	3.44	3.11
Forward to Backward Switch	4.33	4.55	2
Braking	3.77	3.33	2.66
Device Usage Comfort	3.55	2.88	2.77
Intuitiveness of Use	4.11	4	3
Aesthetics	4.66	4.55	2
Overall Propulsion Mechanism	3.6	3.44	3.05
Overall Turning Mechanism	4.33	3.33	3.44
Overall Braking Mechanism	3.9	3.22	3.11
Totals:	**56/70**	**49/70**	**41/70**

Table 1: Preliminary Quantitative Evaluation Results (1 = Poor, 5 = Excellent; n = 10)

Additional comments were also provided by the test subjects and are quoted below.

- *"The Meyra chair was by far the easiest to use and had best comfort. Something that didn't help the other two was that they were on right side and I am left-handed. The Quickie was very painful and not enjoyable. The WPI MQP (prototype) was very unstable and loud. The device would continue to hit the armrest and get stuck."*

- *"Meyra was great and easy to use mostly all around. Quickie was a bit hard to turn. It turned left a lot when going straight while pushing both wheels. MQP was harder to use than Meyra. Turning was very sensitive. Braking was tough. Reverse was hard to get to."*

- *"Quickie very little effort required compared to other two. Turning on Meyra chair is awesome. Turning on WPI MQP prototype is horrible, can't go straight."*

- *Referring to the MQP prototype: "Angle of steering is more extreme turning right compared to left. Occasionally forward/reverse slipped into neutral. Feels like* *momentum is lost too fast. Braking is poor. When going straight, the handle is angled at 45° which feels weird as I expect 90° would go straight."*

- *"Quickie- I had trouble going straight for an extended period of time greater than 2 seconds. MQP-A bit bulky, the arm gets in the way while going through doors. Meyra-Easy to learn and use. Braking is a bit difficult."*

- *"Switching between back/forward on MQP prototype is dangerous. You could totally cut yourself. Pushing the lever thing is a pain. The brake on MQP prototype is way too tight. On Quickie, it's easier to turn right than left."*

- *"Quickie: My fingers were getting caught. It was very fatiguing. Prototype: Physically taxing, switch from front to back is dangerous because of a lot of sharp edges and location of switch. Steering was hard; the chair wouldn't stay straight and brakes were hard. Meyra: Too much pumping for so little propulsion, steering was by far the best and most easy to use."*

- *"For a person that has been in a wheelchair before it seems really hard to propel forward in a straight line. If I were to go into a supermarket I would hit everything." (Referring to MQP prototype)*

These evaluations provided the team with extremely valuable information and feedback. In developing a one-arm wheelchair propulsion accessory, the team needs to make it versatile and take into consideration both right-handed and left-handed individuals. Safety is also an important consideration. There are many sharp edges on the WPI MQP prototype that could pose a safety threat in combination with the risks involved in switching the direction of propulsion because of the lever's location. Some test subjects mentioned that the propulsion mechanism of the WPI prototype kept hitting the armrest and getting stuck, and that it was unstable. The instability and wobbling of the mechanism could pose a safety threat for the user if it hits the arm or hands. Some of the test subjects complained about the noise of the MQP prototype and were observed to have great difficulty getting through the door of the laboratory (the WPI prototype propulsion mechanism protrudes 6.75 inches from the side of the wheelchair, meaning larger clearances are required for unobstructed travel). It was also observed that it took a great deal of effort and frustration for a few of the test subjects to use the Quickie dual pushrim.

It is understandable that the MQP prototype had lower ratings than the other two devices in most categories because it is not a commercially-streamlined product and did not have good material selection and manufacturing processes. The design concept of the MQP prototype works; however, many of the problems found through the evaluations can be solved by better addressing manufacturing, selection of materials, and assembly of the device. The sharp edges on the device can be reduced or eliminated through better manufacturing. The device can be further stabilized by selecting better materials and using proper assembly practices to ensure that the final product is sturdy and robust.

Other issues found through the evaluations must be addressed in the design process of developing the one-arm wheelchair propulsion accessory. These issues include the location of the bi-directional propulsion switch, the noise coming from the ratcheting mechanism, the loss of momentum during the propulsive stroke, and the need for reducing profile of the mechanism to eliminate interference with doors and other objects in the environment. Important consideration must be given to those categories in which the WPI prototype scored poorly (less than a three). Those categories are aesthetics, device usage comfort, braking, and forward-to-reverse shifting.

In developing a one-arm wheelchair propulsion accessory, the team must take into consideration the results, comments, and recommendations that resulted from these evaluations to develop a working, streamlined, and marketable product.

3.5 Materials

The most common material for wheelchair frame construction is metal, namely steel and aluminum. These two metals have high strength-to-weight ratios, and are easily worked into pipes and other shapes required for a standard wheelchair. Steel alloys commonly used for wheelchairs are AISI 1040, 1060, or mild steel, AISI 4130, or chromium-molybdenum alloy steel, and ANSI 4340, 8620, or chromium-nickel-molybdenum alloy steel. SAE 6061, or aircraft aluminum, is lightweight and provides good structural support for a standard wheelchair. SAE 7075 is known as high-performance aluminum, and is gaining ground in the manufacture of ultra lightweight wheelchairs for sports and racing. This market is also beginning to make use of titanium and titanium alloys, but the cost makes it a prohibitive option (DiGiovine, 2008). Due to cost and availability restrictions, the team will likely use a combination of aluminum and steel to construct the accessory.

Plastics and composites are useful for the manufacture of smaller wheelchair parts or components because they can be so easily molded into a variety of shapes. These parts are typically non-structural in nature, such as hand grips or footrests. Choice of plastics is based on the individual bulk mechanical properties and the role the component will fulfill. While the team has not ruled out plastics completely, it is unlikely that they will be one of the chief components of the accessory simply because of workability difficulties (i.e. it is difficult to get the plastic machined, etc.).

4. Design Specifications

The following are functional and design specifications for the team to follow while creating the accessory. Some specifications govern the function of the accessory and how it integrates with the wheelchair on which it is installed, while others deal with the subsystems involved and safety.

4.1 Wheelchair-Accessory Assembly

1. The final design must require only one arm on one side of the body for steering, braking, and forward/backward propulsion.
    - This specification is the driving force for the design of this accessory. The intent of this project is to enable individuals with adequate use of only one hand/arm to fully control the wheelchair with just that arm.

2. All materials must be able to withstand everyday use for three to five years.
    - According to the article "Trends and Issues in Wheelchair Technologies" (Cooper, Cooper and Boninger, 2008), the average lifetime of a wheelchair is three to five years. The accessory must have a usable lifetime comparable to that of the wheelchair on which it is installed.

3. The overall wheelchair dimensions (minus accessory) shall not exceed 1300mm x 700mm x 1090mm (51" x 27.5" x 43"). [length x width x height]
    - These are the required measurements for a wheelchair in order to comply with ANSI/RESNA WC93-1991. Ideally, there will be minimal or no increase in the footprint of the chair (length and width), as greater increases require more time and practice for the user and attendant to acclimate to. The user and attendant must be aware at all times of the space the chair occupies and how it fits into the surrounding environment in order to minimize the risk of injury and damage to the surroundings and other individuals. Minimizing dimensional increases will make the accessory easier to use by requiring less time to become accustomed to it. This is not so much a specification as more of a constraint within which the

design must fit, but the team feels it is important to include as something to keep in mind while designing.

4. The accessory will not increase the weight of the chair by more than eight pounds.
    - According to the 2005-06 MQP, "...the average weight of a manual wheelchair is about 35 pounds" (Cassidy et al., 2006). Their prototype weighed 49 pounds, an increase of 14 pounds (40%) over the weight of the chair itself. Part of the goal of this project is to create a lighter accessory by using lighter materials, thus it was determined that an eight-pound (~20%) weight increase over the average of 35-40 pounds was both reasonable and acceptable.

5. The design must not impede the collapsibility of the wheelchair.
    - The goal of a wheelchair is to increase its user's mobility. For ease of travel and storage, many manual wheelchairs have been designed to be able to fold or collapse, and preservation of this feature is important in maintaining portability of the chair.

6. Accessory must be available for either side of the chair.
    - The accessory must be able to be installed on either the left or right side of the chair to appeal to as large a user population as possible. This may entail a design that works on either side of the chair, or a design specifically for each of the left and right sides.

7. Material and hardware costs associated with building the accessory cannot exceed $675.
    - The Mechanical Engineering Department at WPI typically allots $150 per student for MQPs. In addition, each student is expected to contribute at least $25 per term, and with three students and three terms the final figure comes out to be $675. This is only the figure for how much will be spent to *build* the accessory; the actual selling price of the accessory takes into consideration materials as well as labor and a markup to ensure the accessory is profitable. Determination of the selling price of the accessory can be found in Section 11.2.7.

8. Installation of the accessory will require only a Philips head screwdriver, flathead screwdriver, adjustable wrench, pliers, socket wrench, and hammer.
    - In order to make the accessory as user-friendly and easy-to-install as possible, it should only require basic tools that most individuals have in their home. These were determined to be the aforementioned tools.

9. The accessory will fit onto and work with the top 3 most common wheelchair models currently on the market. These models are: Sunrise Medical's Quickie 2, Drive Medical's Cruiser III, and Invacare's Tracer XS5.
    - To increase acceptance and usability of the design, it cannot be designed specifically to fit a single chair; rather, it must be adaptable to a variety of chairs.

4.2 Braking & Propulsion

1. The propulsion system must move the wheelchair and be steerable in both the forward and reverse directions.
    - This ensures that the basic functionality of the wheelchair is maintained. One of the biggest problems with many current one-arm propulsion systems is that they often do not allow the user to change between forward and backward propulsion and steer in both directions using the one-arm controls. Rather, the user must manually propel the chair backward by the pushrims or rely on an attendant.

2. Brakes must be able to slow the wheelchair in addition to bringing it to a complete stop.
    - The basic function of brakes is to slow or stop a moving object (i.e. wheels) to prevent loss of control of the object.

3. The brake lever cannot require more than 35 pounds of grip force to actuate.
    - Individuals with disabilities and the elderly both may have moderate to severely diminished physical strength capabilities compared to able-bodied adults. As such, the actuation force limit was based on grip strength data from elderly men and women. For elderly men, the first, fifth, and tenth percentile grip strength averages (of values from the right and left hands) are 33.2 pounds, 41.1 pounds, and 44.3 pounds, respectively (Panero, 1979). For elderly women, the grip strength range is 28.6-209 pounds. Thirty-five pounds was chosen because it is at the lower percentile range of these individuals, and will thus allow the majority of the target population to operate the brakes.

4. There will be a means of adjusting the mechanical advantage.
    - Adjustable mechanical advantage allows the user to change the force with which the wheels are propelled to best fit the environment/terrain they will be encountering. Many wheelchairs do not have this feature, thus including it will give the accessory a competitive advantage.

5. The actuating arm of the propulsion system must be able to be disengaged and lock into a secure stowed position while an attendant is pushing the chair.

- This is a major safety feature. The actuating arm must be able to move back and forth in order for the user to propel the chair. However, it is dangerous for the arm to be moving on its own while the chair is being pushed from behind by an attendant, and as such there must be some way to disengage it and stow it safely. This will prevent it from moving and flopping around loosely when not in use.

6. The actuating arm cannot require more than eighteen pounds of force for operation.
    - The maximum force an able-bodied adult is capable of applying to a lever using forward-aft motion while seated is 45 pounds (Woodson, 1981). Individuals using a self-propelled wheelchair, though they may have some strength impairment, must be capable of exerting some force if they are to propel themselves in the chair. It was determined that 40% of the maximum force, or eighteen pounds, was reasonable and acceptable.

7. The final assembly must have some means of locking the wheels to prevent rotation.
    - To prevent the chair from rolling away when the user requires it to be stable and non-moving (i.e. when using it for support while transferring into or out of the chair), there must be a means of locking the wheels so that they cannot rotate.

4.3 Steering

1. The user must be able to steer the chair at all times, unless an attendant is pushing the chair.
    - Maintaining control of the direction of the chair at all times is essential not only for user safety, but also to maximize the independence of the individual. When there is not an attendant pushing the chair, the user must have full control to be able to safely maneuver it.

2. The modification accessory cannot interfere with an attendant's ability to push/control the chair. This will be accomplished by providing a means of disengaging the steering to allow free motion of the casters.
    - Some current models of one-hand propelled manual wheelchairs have steering mechanisms which control the position of the front casters. This makes it very difficult or impossible for the chair to be steered by anyone other than the user, i.e. an attendant cannot have complete control of the chair. In order for the chair to be marketable to the largest possible population, this problem must be eliminated.

4.4 Safety

1. All mechanisms and wires must be encased or stored such that they do not interfere with use of the chair and its moving parts.

    - It is easy for foreign objects or other parts of the assembly to interfere with the moving parts of the wheelchair, damaging it and causing it to wear prematurely. To avoid this, moving parts should be encased as much as possible and wires bound together or stored away from moving parts.

2. Moving parts and pinch points must be located and/or guarded such that they pose minimal risk of injury to users, attendants, and others in the area during normal use of the chair.
    - The potential for injury due to inattentiveness to the mechanism's motion, especially in these areas, is quite large. As such, these features should be guarded or located on the chair such that it would be difficult and unlikely that an individual inadvertently injures him or herself while around the chair or using it.

5. Preliminary Design Concepts

The following chapter outlines the team's preliminary design concepts, from which the final design was chosen. The concepts are broken down into subcategories of braking, propulsion, and steering.

5.1 Braking Design Concepts

For safety reasons, it is essential for any wheelchair to have a means of braking to both slow the chair down and bring it to a complete stop. On a standard manual wheelchair, this is accomplished simply by varying the force with which the "brakes," typically the user's hands gripping the pushrims to prevent motion, are applied. To completely stop the chair, equal force must be applied to both wheels, otherwise the chair will turn. In a one-arm propelled wheelchair, braking of both wheels must be possible with the use of only one hand. The following sections describe possible methods of accomplishing this goal.

5.1.1 Cantilever Brakes

Cantilever brakes use levers and a cable to squeeze brake pads onto the rim of a wheel. One lever is mounted to the handlebar of the bike and has a cable running to two levers mounted on the wheel (Figure 23).

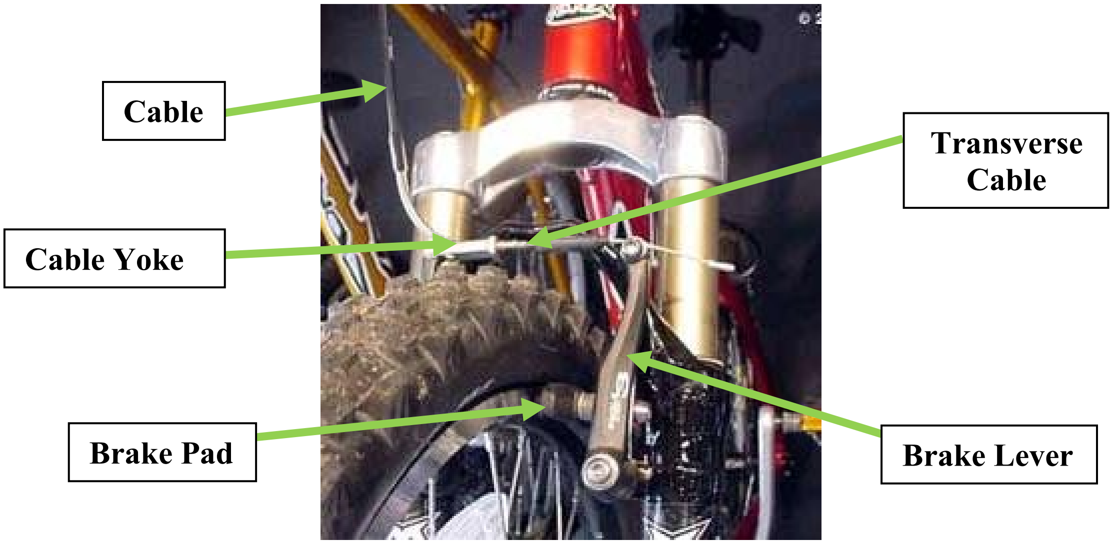


Figure 23: Cantilever Bicycle Brake (Nice, "How Mountain Bikes Work", 2008)

Squeezing the handlebar lever causes tension in the cable, which squeezes the levers on the other end of the cable together, pressing the brake pads against the wheel rim. The friction between the brake pads and the rim causes the wheel to slow down and eventually stop (Nice, "How Mountain Bikes Work"). These types of brakes are extremely vulnerable to poor ground conditions such as debris and mud that can damage the brake pad because the rim (i.e. surface which the brake grips to stop) comes so close to the ground (Sparks, "Stopping Power"). Mechanical advantage for this type of brake is defined as the ratio of the force of the brake pads on the wheel rim to the force required to squeeze the hand lever. In these brakes, mechanical advantage is usually pre-determined by the manufacturer, but if necessary it can be modified by adjusting the length of the transverse cable and/or the height of the cable yoke (Brown).

Using this style brake on a wheelchair would require some modification to the chair and brake system. The brakes need to be mounted such that the brake pads are in line with the surface of the wheel that they will be squeezing. This would likely require slight structural modification to the chair in the form of an added frame element. Each brake assembly has one hand lever, one cable, and a brake for only one wheel. To transmit the cable tension to two brakes using only one handle, the cable will have to be split/doubled using a cable doubler. The cable will stretch with use over time and must be checked regularly for proper tension. The hand lever will be integrated into the steering handle so that the user does not have to let go of the handle in order to apply the brake. This type of braking mechanism integrates very easily with lever-based propulsion designs because it can be mounted where the user grips the lever and the brake assembly mounts easily on a standard wheel. It would be difficult to use with a dual-pushrim style design because the hand rims greatly restrict access to the rim of the wheel, which is essential in this type of brake.

5.1.2 Disc Brakes

Disc brakes can be either hydraulic or cable-operated (mechanical), depending on their intended function. In both cases, the brake pads squeeze a thin metal disc that is mounted coaxial to the wheel (Sparks, "Disc Brake Basics"). Cable-operated disc brakes work the same way as cantilever brakes (described above), but instead of being mounted on the wheel, the brake assembly is mounted in line with the disc. Squeezing the hand lever causes tension in the cable, which (when transmitted to the brake assembly on the wheel) clamps the brake pads onto the metal disc. As with cantilever brakes, after an extended period of use, the cables tend to stretch and must be readjusted to maintain proper tension (Sparks, "Disc Brake Basics"). Hydraulic disc brakes, on the other hand, have a fluid-filled line running between the hand lever assembly and the brake assembly at the disc. When the hand lever is squeezed, a small piston in the handle pressurizes the fluid in the line. This pressure is transmitted through the fluid down to a larger piston in the brake assembly, which squeezes the brake pad onto the disc. Releasing the hand lever reduces the pressure in the line, and the brake pad releases the disc. As an added safety measure, the hand lever assembly contains a device that ensures there is always sufficient fluid in the reservoir for brake operation (Nice, "How Mountain Bikes Work"). Figure 24 shows an example of a disc brake.

Figure 24: Bicycle Disc Brake (Nice, "How Mountain Bikes Work", 2008)

Rotor size is chosen based on several factors, such as the torque required to stop the wheel, acceptable weight range, and the amount of cooling necessary for safe operation. For a given friction force F between the brake pad and rotor, the torque (moment) stopping the wheel is dependent on the radius of the disc, i.e. $\tau = F*r$. Figure 25 illustrates this (assume the "wheels" are turning clockwise).

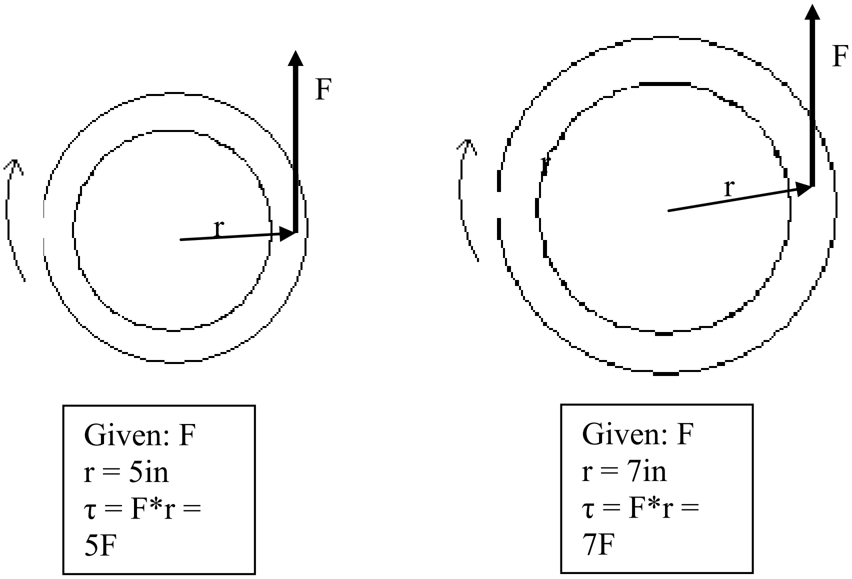


Figure 25: Disc Brake Torque

Although torque for cantilever brakes can be calculated similarly, disc brakes tend to have greater stopping power because the discs may offer a greater surface area of contact for the brake pad. The following equations explain this concept.

Frictional force is the product of the coefficient of friction, μ, and the normal force, N:

$$F_f = \mu * N$$

The normal force is typically represented by a resultant force applied at a single point. However, it is actually a force distributed over the contact area. In the case of disc brakes, increasing the contact area increases the resultant normal force, which then increases the frictional force acting to stop the rotor.

Disc brakes are also not as adversely affected by poor road and trail conditions as cantilever brakes (Sparks, "Stopping Power"). However, the friction between the brake pad and rotor causes the rotor to heat up (Nice, "How Disc Brakes Work"), which can potentially be dangerous and detrimental to the material properties of the rotor. Larger rotors have a greater surface area for heat dissipation, so they tend to stay cooler than smaller rotors would in a given situation. Despite the advantages, large rotors are also heavier, which may be undesirable. The decision must be made as to which of these properties take precedence in choosing a rotor size.

Similar to the cantilever brakes, the mechanical disc brake would work very well on a lever-propelled wheelchair. The disc/shoe assembly can be mounted directly to the axle of the chair, requiring little to no additional structural modifications. The hand lever could be mounted to the handle of the propulsion lever, meaning the user would not have to move their hand off the propulsion lever in order to brake. A cable doubler would be used to allow one hand lever to operate both brakes.

5.1.3 Drum Brakes

Drum brakes operate on the same principle as cantilever or disc brakes; that is, a wire is pulled which makes frictional pads (in this case, brake shoes) press against a rotating surface. As the name suggests, the brake shoes need to be enclosed in a drum in order to function. These brakes allow for both dynamic and static braking and are used in some single-arm propelled wheelchairs such as the Meyra chair. Drum brakes are more difficult to service than disc or cantilever brakes because they have more parts. Figure 26 depicts the inside parts of a drum brake. The drum is mounted on the axle of the vehicle. When the cable is pulled, two brake shoes are forced outward to make contact with the drum. The friction between the brake shoes and the drum slows the axle and consequently, the vehicle. When the cable is released, an arrangement of springs pulls the brake shoes back to the original position. The drum acts as an enclosure for the brake shoes and other components, and as a source of friction for braking.

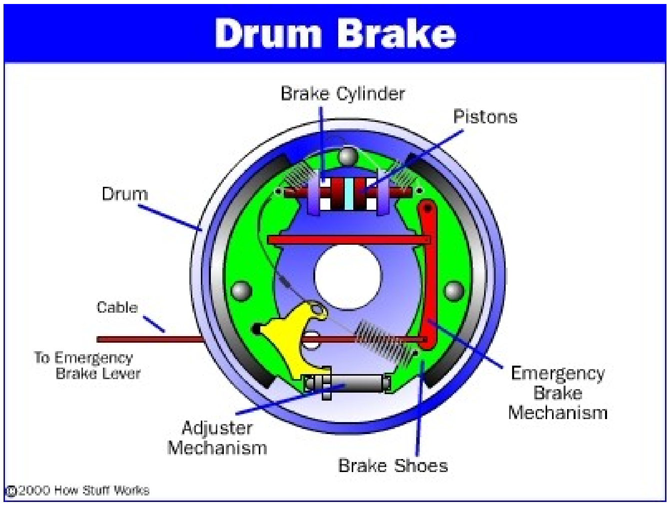


Figure 26: Drum Brake (Nice, “How Drum Brakes Work,” 2008)

The integration of drum brakes has been seen on other single-arm propelled wheelchairs such as the Meyra chair. It is therefore possible to adapt this type of brakes for the team's design. In comparing drum brakes to the other braking systems, it is necessary to analyze the forces required to actuate the pads. Figure 27 shows some of the forces and distances required for such calculations.

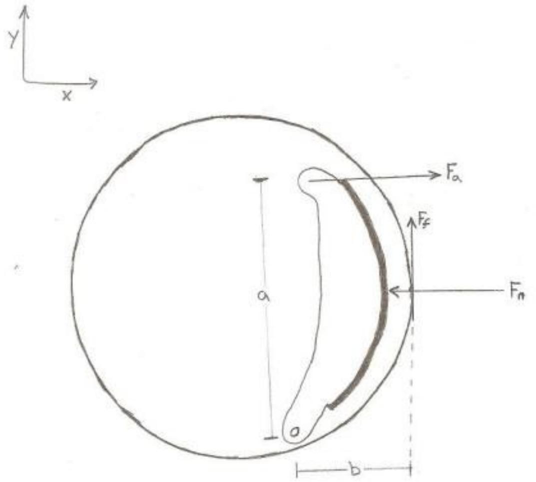


Figure 27: Drum Brake Forces Diagram

F_a: The force applied through the cable to push the brake pads against the drum.

F_n: The normal force of the drum against the brake pad.

F_f: The force of friction between the drum and the brake pad.

a: The vertical length of the brake pad.

b: The distance between the brake pad's pivot point and the drum

o: The pivot point of the brake pad.

Simplifying the calculations requires some assumptions. The normal force will be the resultant force of the pressure distributed over the brake pad's area by coming into contact with the drum. It is assumed that the resultant normal force acts halfway through the vertical length of the brake pad. In addition, it is assumed that the force of friction acts perpendicular to the normal force and at a distance b from the pivot point of the brake pad.

To find the actuating force F_a, one must take the sum of the moments about the brake pad's pivot point o. The resulting equation is below.

$$\sum M_o = -F_a * a + M_{F_f} + M_{F_n} = 0$$

$$M_{F_f} = b * F_f$$

$$M_{F_n} = \frac{1}{2} a * F_n$$

$$F_f = \mu * F_n$$

The actuating force is then:

$$F_a = \frac{(\mu * b + \frac{1}{2}a)}{a} F_n$$

If the drum has two brake pads inside, it must be considered that the actuating force must be doubled.

5.1.4 Hydraulic Brakes

Unlike the other types of brakes discussed in this section, hydraulic brakes are somewhat more complex. They require hydraulic brake fluid, a cylinder, and a piston in combination with either disc or drum brakes. Hydraulic brakes would require the least amount of force to actuate because the force applied at one point is multiplied and transmitted though the system by an incompressible fluid.

The system includes two cylinders with different cross-sectional areas connected by a hose. Each of the two cylinders would have a piston to actuate the brakes. The smaller-area cylinder would be installed on or near the user interface. The force applied at the user interface would be transmitted to a piston that would apply a pressure on the incompressible fluid in the smaller-area cylinder. This pressure would then be transmitted through the hydraulic lines to the larger-area cylinder and finally to the piston that would actuate the brakes.

The mechanical advantage of this braking system would depend on the ratio of the areas between the two cylinders. According to basic engineering principles, pressure is a relationship between force and area. Therefore, a force applied at the smaller area cylinder would be magnified in the cylinder with larger area.

The equations describing this principle are below.

$$\frac{F_1}{F_2} = \frac{A_1}{A_2}$$

F_1= Force applied on the smaller area cylinder

A_1= Area of the smaller cylinder

F_2= Force on the second cylinder

A_2= Area of the larger cylinder

Assume that the area of the larger cylinder is four times larger than that of the smaller cylinder.

$$4A_1 = A_2$$

This would imply that:

$$\frac{F_1}{F_2} = \frac{1}{4}$$

Therefore the force applied at the smaller cylinder would be 4 times greater at the larger cylinder.

$$F_2 = 4F_1$$

The magnified force comes at a cost. The distance that the piston in cylinder 1 must travel will be four times greater than the distance traveled by the second piston to actuate the brakes. Figure 28 depicts a simplified automobile hydraulic system.

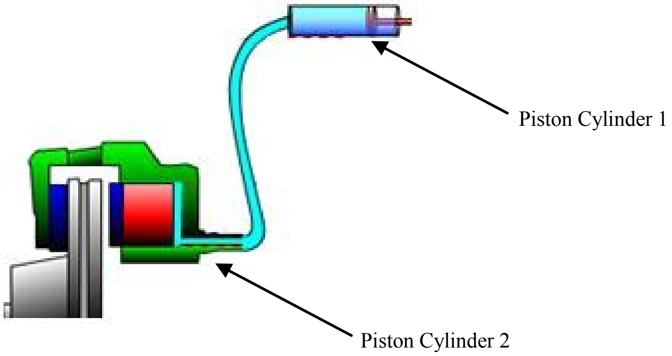


Figure 28: Hydraulic Brake (Nice, "How Brakes Work," 2008)

This type of system could be integrated into the team's design in combination with either disc or drum brakes to increase mechanical advantage. This type of system is seen on some bicycles, meaning that it is plausible for it to be integrated on a wheelchair because the scale is very similar.

5.2 Propulsion Design Concepts

One of the primary purposes of this project is to provide a means of propelling a wheelchair using only one hand. This mechanism must allow the chair to move both forward and backward, and as such have a means of switching between the two directions. In order to propel the chair in a straight line, it must also move both wheels simultaneously. The following descriptions outline several possible ways of accomplishing these goals.

5.2.1 Ratchet Propulsion

A ratchet mechanism could be a possible solution for single-arm propulsion. Ratchets typically consist of a toothed wheel and a pivoting arm called a pawl. The pawl engages the wheel's teeth to cause it to move. The teeth are slanted so that the pawl is only "engaged" during motion in one direction. When motion occurs in the "non-engaged" direction, the pawl is returned to its starting position to be ready for another power stroke. For this project's application a bi-directional or double ratchet would have to be used in order to be able to propel the wheelchair in both the forward and backward directions.

The ratchet mechanism can be mounted on the wheel/axle of the wheelchair and connected to a lever through a linkage system. The lever itself would also be attached to the wheelchair and would pivot about a point where it has a bearing. This mechanism fulfills the functional requirements previously set by allowing both forward and backward propulsion as well as a neutral position to enable a personal assistant to push the wheelchair. The simplicity of such a device would make it easy to implement and the associated cost would be low because it is commercially available and would not require special manufacturing. One of the main problems associated with implementing a ratchet for a propulsion mechanism is the noise it would generate.

5.2.2 Friction Propulsion

Friction propulsion is much like ratchet propulsion, where a finger or other limiting factor allows transfer of force in only one direction. The difference is that while a ratchet uses physical resistance in the form of teeth, these drive systems use static friction to transfer force.

One example is a freewheel (Figure 29). A freewheel is a device that keeps a drive shaft from interfering with the free spin of the rest of a drive system. The best example is on a bicycle. When a bicycle is going downhill quickly, regular pedaling cannot add force to the drive system. At the same time, coasting does not control the speed of the pedals; rather, this is accomplished with a ratcheting system. However, a better system appears on modern automatic clutch automobiles.

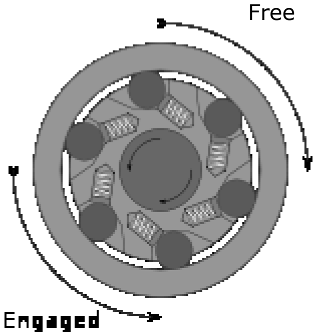


Figure 29: Freewheel Mechanism (Wikipedia: “Freewheel,” 2008)

A disc is housed inside a tube. The center of the disc can be considered the power input from a motor, while the tube can be considered the rest of a drive system. The disc is notched, with a shallow cut on one end, and a shaft with a compression spring inside on the other. The notches house ball bearings, which, when the disc spins faster, get locked between the shaft and the disc, providing power to the system. However, when the tube spins faster than the disc, the ball bearings are forced into the spring chamber, and can allow the tube to roll past.

The proposed design would use two freewheels oriented in opposite directions. A selector made of a translating pipe would allow only one to provide power at a time, thus allowing selection between forward and reverse propulsion. The lever setup that would be suggested for this propulsion device is a streamlined version of the four-bar linkage on the 2005-06 MQP wheelchair prototype. Figure 30 shows a simplified representation of this linkage.

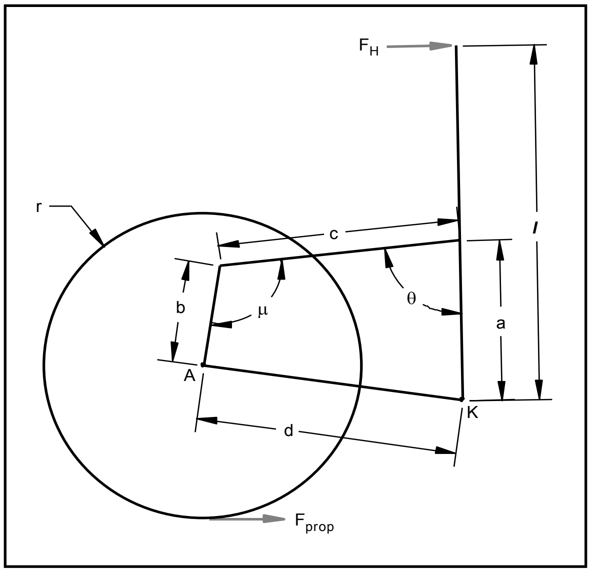


Figure 30: Four-bar Linkage on Wheelchair (Cassidy et. al. 2006)

The mechanical advantage provided by a design like this would be

$$\frac{l\cdot b\cdot \sin(\mu)}{a\cdot r\cdot \sin(\theta)}$$

where **l, b**, and **a** would all be set by the design team, taking into consideration the research done by the previous MQP team on the subject, and **r** is the radius of the wheel.

The noise created by a freewheel or other friction drive has the potential to be lower than a similar ratcheting drive. A bicycle freewheel uses a ratcheting mechanism, but one that is quieter than the 2005-06 MQP prototype chair because it is encased. In addition, it uses different numbers of teeth and strength of pawl springs. A friction freewheel like the one discussed above would theoretically be much quieter.

5.2.3 Dual Stroke Drive

In this design, a second, inverted linkage would be run from the input lever to a ratchet or friction drive, allowing propulsion to be delivered during the forward and backward stroke. Since both strokes are powered by a four-bar linkage, each stroke's mechanical advantage is given by the expression:

$$\frac{l\cdot b\cdot \sin(\mu)}{a\cdot r\cdot \sin(\theta)}$$

where **l**, and **r**, are shared, and **a, b**, **μ**, and **θ** are different for the two strokes. The primary advantage of a system like this is that the total force output of a full stroke is doubled over that of a similar single stroke four-bar linkage.

5.2.4 “Locomotive” Propulsion

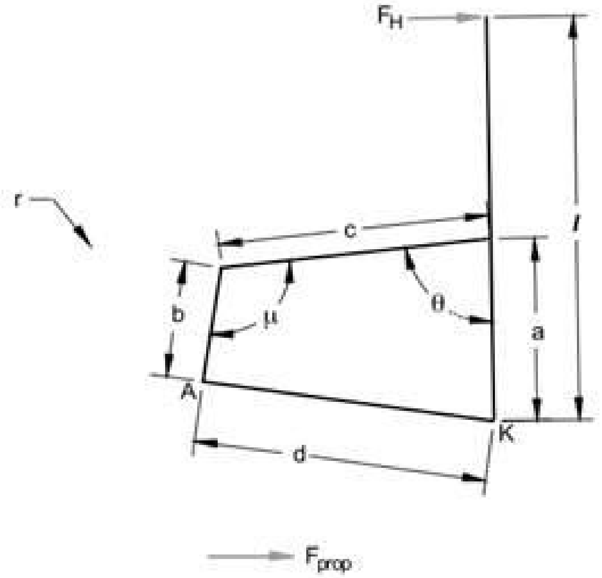


Figure 31: Four-bar Linkage with Full Rotation of Link b (Cassidy et. al. 2006)

In this design, a standard four-bar linkage (Figure 31) would be used. The unique element of this drive is that the linkage **b** is permanently attached to the drive wheel. In this model, **μ** can be equal to any value from 0° to 360°, allowing the linkage **b** to spin all the way around the axle in both directions (clockwise and counter-clockwise). This means that the drive can provide power on both its forward and backward strokes, and needs no special equipment to change from forward propulsion to backward propulsion. It should be noted that since the linkage has a full range of motion, two points on its rotation are "dead points" and the user can provide no force to the cycle. The momentum of the chair must carry them through. These spots are at the beginning and end of each stroke.

The mechanical advantage provided by this design is identical to that of the friction drive or other four-bar linkages:

$$\frac{l \cdot b \cdot \sin(\mu)}{a \cdot r \cdot \sin(\theta)}$$

The difference between this and other designs in terms of mechanical advantage is that **μ** can be equal to any value, so the range of advantages is much larger, even including zero at the previously mentioned "dead points". However, since the passenger can provide propulsive force during almost the entire stroke of the lever, the total force output would be twice that of a similar single-stroke design.

This design would add no noise-making parts to the chair, and any noise that would arise from this propulsion system due to play in the joints would be slight.

5.2.5 Two Lever Through-Axle Design

Much like the Quickie wheelchair, this propulsion subsystem (Figure 32) would use a through-axle to provide force to both wheels of the wheelchair. Two parallel plates would be mounted at the axle and act as levers. Each lever would provide drive to a different wheel and would have its own brake and drive systems (either friction or ratchet). The through-axle would be composed of a row of linked bars, much like a car's driveshaft, so that power could be transferred while the chair is still able to fold completely with little extra transitioning.

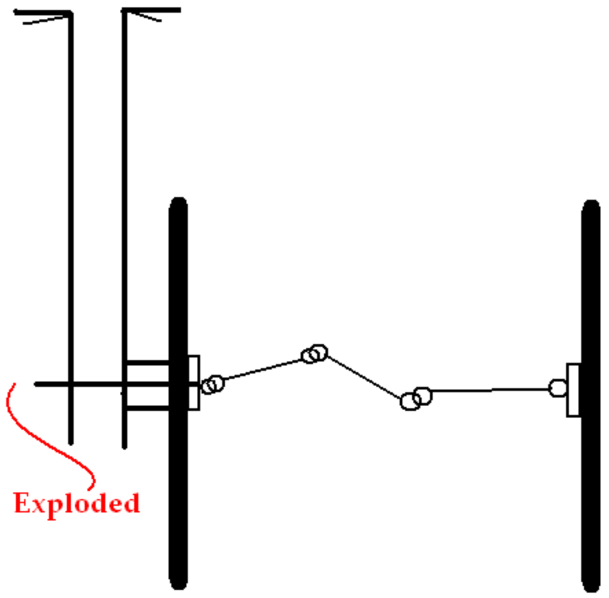


Figure 32: Proposed Through-Axle Design

The chair could be steered by providing force to only one lever at a time, or by braking on one wheel only. Because of the positioning of the levers in this design, the maximum mechanical advantage is

$$l/r$$

where l is the length of the lever from the handle to the axle and r is the radius of the wheel.

5.2.6 Erg Machine or "Seatbelt" Propulsion

In this design, propulsion is provided by pushing a lever away from the body. At the top of the lever is a three-position switch connected to two rigid links which run from the top of the lever down to the axle of the chair. The bottom of each link has a pawl which can be raised or lowered onto one of two gears, depending on the direction in which the switch is flipped. When the switch is in the middle neutral position, neither gear will be engaged and the axle can rotate freely without moving the lever, allowing an attendant to safely push the chair without moving the lever. On either side of the lever, coaxial to both the lever and the wheels of the chair, are ratchet gears oriented in opposite directions. By flipping the switch to one of the extreme positions (i.e. not the middle position), one of the ratchets will be engaged and allow motion only in either the forward or reverse direction (Figure 33). The ratcheting setup allows the lever to be returned to the neutral position for the next power stroke without driving the chair.

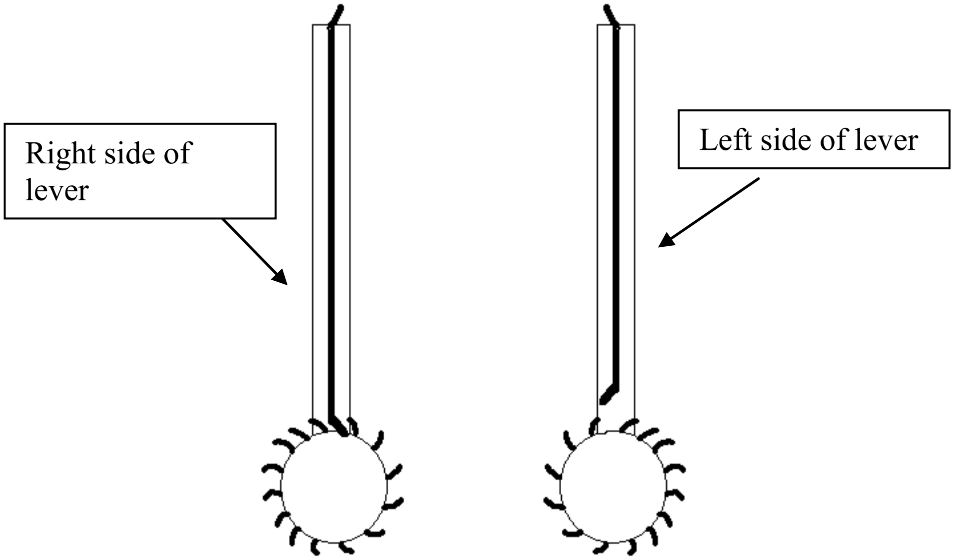


Figure 33: Seatbelt Propulsion Ratchets

In an earlier "seatbelt"-style design concept, each of the gears would have had a spring attached to its outer surface (i.e. not the lever side) and to the axle so that motion of the lever, and thus the axle, would unwind the spring (Figure 34).

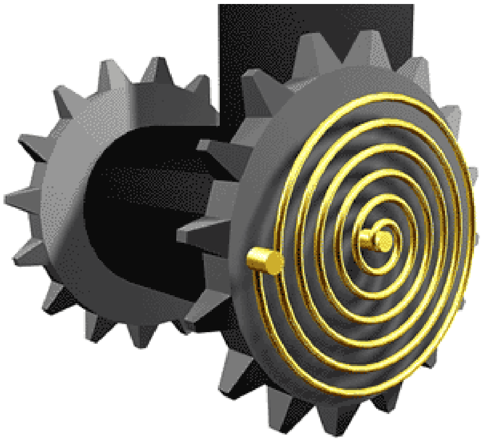


Figure 34: Seatbelt Gear Spring (Harris, 2008)

At the end of the power stroke, the spring would attempt to recover and coil back up, bringing the lever back to the starting position. The team realized, however, that this design would not allow for easy propulsion by an attendant because the springs would not be able to recoil under constant unidirectional motion, and thus it was decided that these springs would not work. Instead, a spring would be attached to the lever and a frame element of the chair so that the power stroke would stretch the spring, and recoil would help bring the lever back to the neutral position.

This concept can be used as a basis for another type of propulsion mechanism (Figure 35). The mechanism includes a cord holder which can slide up and down the lever to adjust mechanical advantage. The further the cord holder is placed down the lever from the point where the user applies a force for propulsion, the more mechanical advantage the user will have.

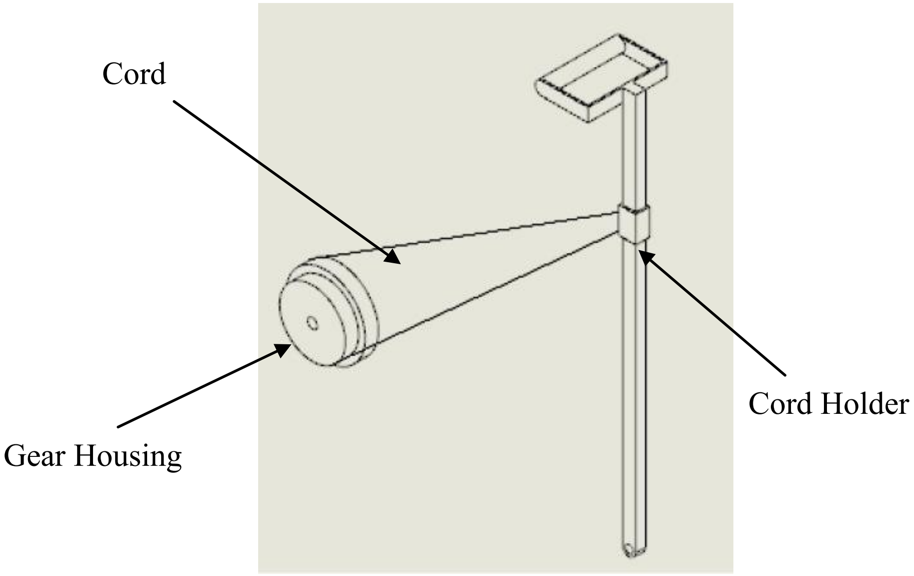


Figure 35: Erg Machine Drawing

Figure 36 shows one possible lever and cord arrangement in which $\mathbf{F}_c$ is the force on the cord required to propel the device, $\mathbf{F}_a$ is the force applied by the user at user interface, and **x** is an arbitrary length. From basic engineering principles it is known that moments are equal to a force times a distance and can be taken about any point. For this case, the moments will be taken about the pivot point of the lever. Consider the cases when the cord holder is placed at a distance **x** and at a distance **2x** from the pivot point, while the force applied at the user interface is always applied at a distance **3x** from the pivot point. To simplify the equations, it is assumed that the angle between the cord and the horizontal is always 0°. Both cases are taken into consideration and the equations solving for the force applied by the user are described below.

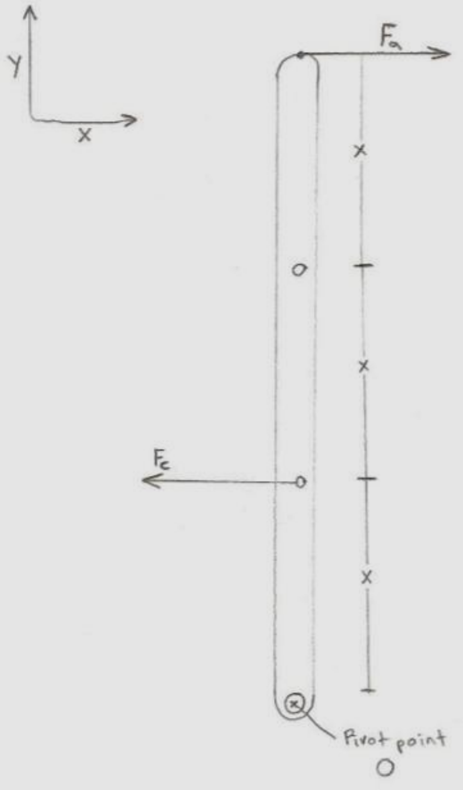


Figure 36: Lever Forces Diagram

Case $\mathbf{F_c}$ applied at distance **x** from pivot **o**.

$$M = F * x$$

$$\sum M_o = F_c * x - F_a * 3x = 0$$

$$F_a = \frac{1}{3} F_c$$

Case $\mathbf{F_c}$ applied at distance **2x** from pivot **o**.

$$\sum M_o = F_c * 2x - F_a * 3x = 0$$

$$F_a = \frac{2}{3} F_c$$

Notice how mechanical advantage can be increased the further away the force of the chord is located from the user interface. In these cases when the force of the cord was a distance of **x** from $\mathbf{F_a}$, it was equal to (2/3)*$\mathbf{F_c}$ .When $\mathbf{F_c}$ was a distance of **2x** from $\mathbf{F_a}$, the force was equal to (1/3)*$\mathbf{F_c}$. Using this principle, adjustable mechanical advantage can be implemented into this propulsion system.

Due to the fact that propulsion is only achieved in the forward stroke, the subject sitting in the wheelchair will never slide forward due to backstroke reaction forces of the lever. In other words, there is no danger of the user pulling him or herself out of the chair while trying to propel it. Some custom manufacturing may be necessary to make this device, but many of the parts can be taken from rowing machines. The housing of the cords and recoiling spring can be attached to the wheel and axle of the wheelchair to transmit the force to the wheel. The lever will also be attached to the frame of the wheelchair and will pivot about a lower point with a bearing.

5.3 Steering Design Concepts

For safety reasons, the steering mechanism of this design must allow the user to have full control of the chair when engaged. In addition, the user must be able to steer the chair both left and right while simultaneously propelling it forward or backward. Ideally, the mechanism's steering ratio would be close to 1:1 because this minimizes jerkiness from over-steer (a common complaint about the 2005-06 MQP prototype) and does not require excessive input for a small amount of turning. One of the most important design criteria for the steering mechanism was for it to be able to be disengaged. Many one-arm propelled chairs cannot be steered by an attendant because the steering mechanism controls caster motion; therefore, by allowing the steering to be disengaged, this accessory has an advantage over many of the commercially-available products. The descriptions that follow are possible methods of satisfying all of these criteria.

5.3.1 Electronic Steering

One of the possible solutions for single-arm steering of a wheelchair is electronic steering. Implementing this system would be possible by mounting a gear on one of the wheelchair's casters and having a small electric motor with a mating gear to rotate the caster (Figure 37). The user interface would be similar to the 2005-06 MQP's prototype with a rotating handle. A potentiometer or some sort of position transducer would be attached to the handle in order to translate the mechanical movement of the handle into an electrical signal that would run the motor and rotate the caster by the desired amount.

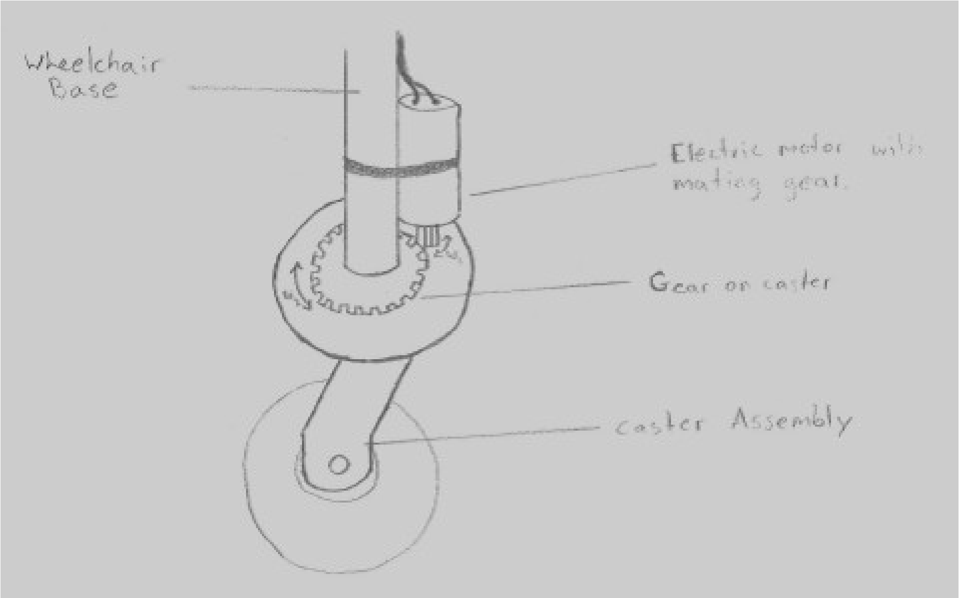


Figure 37: Electronic Steering Mechanism Diagram

This steering system would require the least amount of force to operate because a bearing could be mounted on the handle’s pivot point to reduce friction, and the user would not have to input the energy necessary to turn the caster because this work will be done by the motor. Integrating a motor to the steering system implies that a rechargeable battery will also be included to power the motor. This steering system can be disengaged by eliminating contact between the motor and gear.

5.3.2 Foot Steering

The foot steering concept requires use of one foot to steer the wheelchair. A larger footrest would be mounted in place of one of the standard fixed plates, with room for both feet to rest (Figure 38). The opposite footrest would be able to swivel by being attached directly to one of the wheel housings. To disengage steering, the user need only move their foot from the drive footrest to the larger one. The most recent developments with this design were made by a student team at Cambridge University, whose goal was to make a wheelchair for hemiplegics.

Figure 38: Foot Steering, Cambridge Design Chair (University of Cambridge, 2008)

Without many moving parts, the system is easily adaptable to allow pushing and steering by an attendant. Once the wheelchair user puts both feet on the larger non-steering footrest, the wheelchair can be pushed with no other modifications.

The mechanical advantage in a system like this is directly related to the length of the steering foot rest, and is given by

$$l/r$$

where l is the length of the footrest, and r is the distance of the trail of the front wheel. Additionally, since the muscles in the leg are larger than those in the arm, depending on the user's condition, the available input force could be much larger than that available for upper body steering.

5.3.3 Linkage Steering

In this design concept, a small bar will extend from a circular steering plate, similar to that found in the 2005-06 MQP's cable design. This design would require the propulsion lever to be mounted with the pivot near one of the front casters to allow the linkage steering to transfer motion easily from the propulsion lever to the caster. When the steering plate is rotated, the protruding arm would transfer displacement down a linkage run parallel to the propulsion lever, which would be attached to a linkage at the caster housing. Using a physical linkage would address complaints from the team's initial testing that some of the steering was "jerky" or "loose."

Additionally, the linkages can be designed such that they create a mechanical advantage for the user, much like in cable steering. The simplest adjustable mechanical advantage arrangement would be one in which the advantage comes from the ratio of moments at the handle and wheel, much like the cable steering arrangement. This would provide a mechanical advantage of

$$h/r$$

where **h** is the distance from the handle pivot to the wrist lever arm and **r** is the radius of the wheel disc.

5.3.4 Brake Power Steering

The brake power steering concept is taken from a standard manual wheelchair. When gliding, manual wheelchair users can apply pressure to one pushrim to slow its rotation, forcing one side of the wheelchair to travel faster than the other and making the chair turn. In the team's design, separate brakes would be installed for both wheels, with separately-actuated controls. A through-axle would be required in order to transfer power from one side to both wheels. When one brake is actuated independently, it will force the wheelchair to turn. When both are actuated, they will slow the wheelchair to a stop.

The force required to steer will be variable, requiring at most the maximum force for actuation of the chosen braking system (see braking concept section, above, for values). A point of interest for this particular design is that it requires a through-axle for power to be provided to each wheel while also still allowing them to spin independently. This means there will need to be two of whichever drive system is employed. The noise will be increased based upon the chosen drive mechanism, again since two will be required.

5.3.5 Cable Steering

The cable steering design is essentially the design used by Cassidy et al. in the 2005-06 MQP prototype. A handle-pulley assembly is mounted at the top of the propulsion lever, and can rotate through pronation and supination of the user's forearm. Bicycle cables are wrapped and secured around the disc, and run to a similar disc mounted at the top of one of the front casters, where they are also wrapped partway around the disc and secured. The caster disc is parallel to the floor/ground. When the handle is turned, tension on one of the cables causes the caster disc to rotate, turning the caster and thus steering the chair. According to Cassidy et al., the ratio of the disc radii determines the amount by which the front caster is rotated for a given rotation of the handle, and this ratio can be selected for optimum user comfort and turning radius. Figure 39 is the diagram of this design drawn by Cassidy et al. (2006).

Because much of the design work has been done for this steering mechanism, the team would focus on improving it based on the recommendations of the prior team. In particular, they recommended reducing the weight and size of the mechanism, decreasing the disc diameter while maintaining a "workable ratio of diameters" (Cassidy et al., 2006), and using a more ergonomic handle. By investigating various other materials commonly used in similar applications, and comparing their properties with aluminum, the team will determine whether it is feasible to use a different, possibly lighter material. The team will also investigate the effects of changing disc size and reducing the size of other elements.

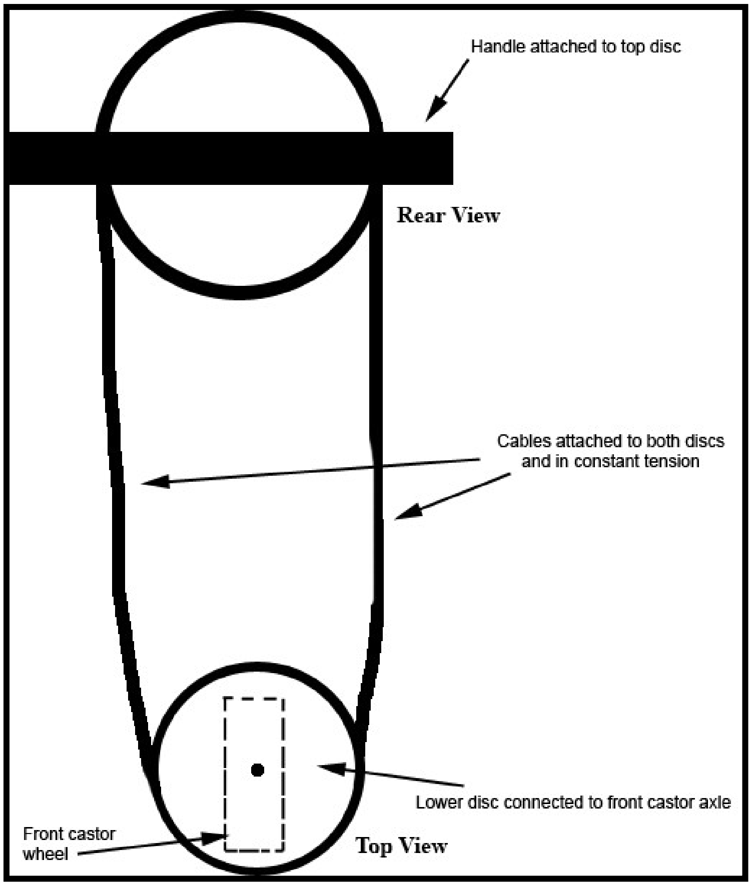


Figure 39: Cables in Tension (Cassidy et al., 2006)

6. Design Selection

The following section shows the process and criteria the team used to arrive at the final design. Each of the aforementioned design concepts were given a score one to five (five being "better" than one) by the team for several different criteria within the concepts' specific subsections. Each of the possible combinations of the top two designs in each category were then evaluated by the team using a final decision matrix and categories important in the final design, again giving each component a score of one to five. The highest-scoring combination was chosen as the final design. Each of the criteria was given a weight out of 100, and the scores were multiplied by this weight to get the final number of points. The points from all the criteria were tallied to get each concept's final score.

6.1 Preliminary Decision Matrices

The following matrices compare the different options for each subsystem against a set of criteria the team chose as the most important design considerations. Many of the criteria are shared across subsystems, though some are not. Each subsystem concept was given a score of one to five, with the different criteria being weighted according to importance. The total scores were evaluated with the assigned weights, and the highest-scoring system was considered the raw winner. Other considerations were made when deciding upon the final design, and in cases with very small differences in score, multiple subsystems from that category may be considered. Following the matrices is a brief description of the scoring rubric for each category. Table 2 shows the preliminary decision matrix used for the steering design concepts, Table 3 shows the preliminary decision matrix used for the propulsion design concepts, and Table 4 shows the preliminary decision matrix used for the braking design concepts.

6.1.1 Matrices

Steering

	Weight	Cables		Linkage		Brake Power		Foot		Electronic	
Ability to be Disengaged	N/A										
Provides left and right during propulsion	N/A					x					
Steering advantage	20	3	60	2	40			4	80	5	100
Ratio near 1:1	20	4	80	3	60			5	100	5	100
Estimated cost	5	4	20	3	15			5	25	1	5
Estimated weight	15	3	45	2	30			3	45	1	15
Smallest profile	10	3	30	2	20			5	50	5	50
Ease of manufacture	10	4	40	2	20			5	50	4	40
Ease of assembly	5	4	20	3	15			5	25	1	5
Ease of installation	15	4	60	1	15			5	75	2	30
total	100		355		215				450		345

Table 2: Steering Decision Matrix

Propulsion

	Weight	Ratchet		Friction Drive		Dual Motion		Through Axle		Erg Machine		Locomotive
Ability to be disengaged	N/A											x
Has variable mechanical advantage	N/A							x				
Can provide forward and reverse	N/A											
Potential advantage	25	3	75	3	75	5	125			2	50	
Smallest profile	15	2	30	3	45	2	30			0	0	
Estimated cost	10	5	50	3	30	4	40			2	20	
Estimated weight	10	3	30	3	30	2	20			4	40	
Ease of manufacture	10	4	40	4	40	3	30			2	20	
Ease of assembly	5	3	15	4	20	2	10			1	5	
Ease of installation	15	2	30	2	30	1	15			3	45	
Noise	10	2	20	4	40	1	10			3	30	
Total	100		290		310		280				210	

Table 3: Propulsion Decision Matrix

Brakes

	Weight	Disc		Drum		Cantilevered		Hydraulic	
Force required for actuation	30	4	120	3	90	2	60	5	150
Estimated cost	10	3	30	3	30	5	50	1	10
Estimated weight	5	3	15	1	5	4	20	1	5
Ease of manufacture	10	5	50	4	40	5	50	3	30
Ease of assembly	5	4	20	3	15	5	25	3	15
Ease of installation	15	4	60	2	30	3	45	2	30
Smallest profile	10	4	40	5	50	3	30	4	40
Maintenance	15	4	60	4	60	2	30	2	30
Total	100	395		320		310		310	

Table 4: Brake Decision Matrix

6.1.2 Criteria Descriptions & Rubric

Steering

Ability to be Disengaged: One of the most important design requirements for the steering subsystem is that it must allow the chair to be pushed by an attendant; i.e. it must have some means of being disengaged so that the attendant has full control. Any steering systems that did not fulfill this specification were not considered. This is a yes or no question, and thus not a ranked category.

Provides Left and Right Steering During Propulsion: Another basic design requirement is that the steering system provide left and right steering during propulsion and while stationary (to a degree). Since this is a basic functionality and safety issue, the group did not consider steering systems that could not perform this function.

Force for Operation: This is a measure of the calculated theoretical force required for use. All models were assumed for this category to be optimized near a 1:1 ratio of displacement of handle to steering. The force required was considered in terms of the mechanical advantage potential of the design, on a 1-5 scale. A 3 was no mechanical advantage, a 5 was a mechanical advantage of 2:1 or better, and a 1 was a substantial disadvantage (1:2 or worse). The other numbers were evenly graduated.

Ratio near 1:1: This criterion is drawn from suggestions of the 2005-06 MQP group

(Cassidy et al., 2006). They found that their steering ratio created a jerky ride, most likely caused by over-steer. The current team therefore aims to have the steering ratio fall as close to 1:1 as possible. Each steering design was rated as if it had been optimized for force of operation, on a scale of 1-5. A score of 5 is a ratio of exactly 1:1, with 1 being over 2:1 or 1:2. The remaining numbers are graduated accordingly.

Propulsion

Ability to be Disengaged: As with steering, one of the most important design requirements for the propulsion subsystem was that it allow the chair to be pushed by an attendant. If the propulsion is not disengaged while an attendant is pushing the chair, the lever arm could be moving back and forth, creating a significant safety hazard. Any propulsion systems that did not fulfill this specification were not considered. This is a yes or no question, and thus not a ranked category.

Has Variable Mechanical Advantage: One of the biggest successes of the 2005-06 MQP was that their chair provided a variable mechanical advantage for users. That team was explicit that this was their most important goal, and given this importance the current team felt designs should not be considered if they do not take this into account.

Provides Forward and Reverse Propulsion: Once again, a question of basic functionality. Without these features, designs will not be considered.

Force of Operation (Potential Advantage): Each of the subsystems requires force input from the user. Unlike with some static considerations, such as the weight of the system, small differences in required input force can greatly affect long-term comfort for the user. Consequently, the estimated force of operation must be considered for each subsystem. This means that the potential mechanical advantage is examined in different situations. Unlike with the other systems, here advantage is expected, thus the total force output in terms of input was considered over a full stroke (a forward and a return stroke) on a scale of 1-5. A score of 1 would be a force return of less than 1:1, 2 a direct translation (1:1), and 5 being a return of 3 or better, with the remaining numbers being evenly distributed.

Noise: One of the major complaints during initial testing was that the MQP chair was noisy. With that in mind, the team wanted to judge the concepts on what their potential comparative noise levels will be. They were graded on a scale of 1-5, 1 being a painful or unbearable amount of noise for the user and 5 being no noise at all, with a score of 3 as a middle ground of a low white noise. The other numbers were graduated accordingly.

Braking

Force for Actuation: With braking, as with the rest of the systems, it must be taken into account that the accessory is going to be primarily used by those with decreased strength (as compared to able-bodied individuals). With that in mind, a low required input force for application of an component like the brakes should be a primary design goal. For scoring in this category (on a scale of 1-5), potential advantage was once again considered, combined with the actual forces present in the braking systems. A score of 5 was a high advantage (better than 2:1) and an efficient transfer of force to the brakes, while 1 was a deficient advantage (less 1:1) requiring greater force than the lowest 10-15th percentile values found in anthropometric data, with 3 being no advantage (1:1) and the remaining numbers being graduated appropriately.

Maintenance: Because brakes are an absolutely essential safety feature, care must be taken to ensure that they are properly maintained in working order. As such, the group rated each braking concept on the frequency and difficulty of the maintenance it would require. A score of 1 indicates a system that would require very frequent maintenance and/or moderate to extensive disassembly of the system to perform the maintenance. A score of 5, on the other hand, is given to a design which is relatively maintenance free and/or requires very simple tools for what maintenance is required. Intermediate designs are scored appropriately.

Shared Criteria

Smallest Profile: Some parts will increase the profile of the chair by protruding beyond the chair's original width. Since there is already very little room to spare while maintaining RENSA/ANSI width standards, even small decreases in the profile of the accessory are beneficial. This category is ranked on probable location on the chair and estimated size of the system. The average chair width was considered to be 26.5 inches wide, with the narrowest doorway/entrance being 30 inches wide, allowing a 2.5 inch width increase for the device while maintaining an inch of clearance. Thus, on a scale of 1-5, a 1 would be given to a design adding over 2.5 inches, and a 5 to a design that adds no additional width, with the intermediate numbers being graduated evenly.

Estimated Cost: Since the final goal is a commercially-available kit, the cost of each system is of utmost importance. The cost was estimated based on the number and complexity of parts, potential materials selection, size of the final system, and some manufacturing and assembly considerations. The team projected that the propulsion system would be the most complicated and thus require approximately 50% of the total budget, with the remaining 50% split evenly between the other two systems. On a scale of 1-5, the group considered 1 to be a prohibitive cost, eliminating the feasibility of producing and/or using that system without a budget increase, and a 5 to be a considerably economical system (less than half of the budgeted percentage) with the intermediate numbers graduated appropriately.

Estimated Weight: Similar to cost in terms of importance, weight must be considered for handling, folding, pushing, and even steering of the final chair. Weights of the potential designs were either found or estimated based on materials, size of systems, and number of parts. The group decided that the target maximum weight increase would be 20% over the 35-40 pound weight of a standard chair, or approximately 6-8 pounds. A 1 indicates a design adding more than eight pounds, while a 5 indicates one adding approximately three pounds or less. Intermediate weights are scored accordingly.

Ease of Manufacture: This criterion is a measure of the acquisition or manufacture of parts. It is based on market research, and estimated complexity of individual components. The scale is measured in a holistic sense, considering the technical skill required to fabricate or otherwise create the parts, or in any other way acquire them. For purchased parts, the scarcity or specialty of the wholesaler was considered. On a scale of 1-5, a 1 was considered a prohibitive level of technical expertise necessary for manufacture or limited availability of parts, while a 5 was considered to be something well within the team's combined capabilities, with the intermediate numbers being graduated as evenly as possible.

Ease of Assembly: This is a measure of the pre-market construction of the accessory, or the creation of what the kit product would be. The ease of assembly of the manufactured or otherwise procured parts was measured by the estimated time to construct the system, its complexity, and the level of technical expertise required. On a scale of 1-5, a 1 was given to designs requiring technical knowledge outside the abilities of the team and the abilities of individuals at or near WPI whom the team could contact for assistance, and/or requiring an excessive amount of time (i.e. longer than 5 hours). A 5 was given to designs well within the group's combined abilities and available resources, with the intermediate numbers being graduated as evenly as possible.

Ease of Installation: This is a measure of the potential difficulty for the end user to install a system onto a standard wheelchair. Factors considered include the number and types of tools that a person would require, the amount of modification to the standard wheelchair, and the technical expertise required. This criterion was also approached from a more comprehensive viewpoint, thinking of the size and detail required for an instruction manual, and judged not only on the complexity of instructions, but also the number of steps required. On a scale of 1-5, a 1 was considered to require technical knowledge beyond that of the average person, complex and/or unusual tools, and an excessive amount of time (more than 2-3 hours) , while a 5 was considered very simple, almost single-step installation, with the intermediate scores distributed as evenly as possible.

6.2 Final Decision Matrix

From the evaluations conducted with the preliminary decision matrices, the group chose the two top-scoring designs in each category. These designs were combined and compared to one another in the final decision matrix (Table 5) with respect to a set of criteria the team chose as the most important final design considerations. The winning designs from each subsystem category were: friction and dual motion (propulsion), disc and drum brakes, and foot and electronic steering. The group felt that foot steering would eliminate some of the potential user population, however, and so cable steering (the next highest scoring concept) was used in the final matrix instead. Once again, each potential design was given a score of one to five for several criteria, with the different criteria being weighted according to importance. The total scores were evaluated with the assigned weights to determine the highest-scoring design. As shown in the matrix, a friction drive propulsion system with disc brakes and cable steering had the highest score, and as such will serve as the basis of the team's final design. A brief description of the decision rubric for each category follows the matrix.

6.2.1 Final Decision Matrix

	Weighting Factor	Friction Drive w/Disc, Electronic		Friction Drive w/Disc, Cable		Friction Drive w/Drum, Electronic		Friction Drive w/Drum, Cable		Dual Motion Drive w/Disc, Electronic		Dual Motion Drive w/Disc, Cable		Dual Motion Drive w/Drum, Electronic		Dual Motion Drive w/Drum, Cable	
		Score	Points	Score	Points	Score	Points	Score	Points	Score	Points	Score	Points	Score	Points	Score	Points
MANUFACTURABILITY																	
Number of Parts	**7**	3	21	4	28	2	14	3	21	2	14	2	14	1	7	2	14
Cost of Manufacturing	**9**	3	27	4	36	1	9	2	18	2	18	3	27	1	9	2	18
Technical Skill Required for Manufacturing	**8**	2	16	4	32	2	16	3	24	1	8	2	16	1	8	2	16
EASE OF INSTALLATION																	
Technical Skill Required for Installation	**12**	4	48	3	36	3	36	2	24	3	36	2	24	2	24	1	12
INTEGRATION & ERGONOMICS																	
Ease of Use of User Interface	**9**	4	36	3	27	4	36	3	27	3	27	2	18	3	27	2	18
Potential Market	**7**	5	35	4	28	5	35	4	28	3	21	2	14	3	21	2	14
Force for Operation	**10**	5	50	4	40	5	50	3	30	3	30	2	20	3	30	2	20
PHYSICAL SPECIFICATIONS																	
Added Weight to Chair	**9**	4	36	5	45	3	27	4	36	2	18	3	27	1	9	2	18
Maneuverability/Turning Radius	**7**	5	35	3	21	5	35	3	21	5	35	3	21	5	35	3	21
Added Width	**9**	4	36	3	27	5	45	4	36	3	27	1	9	4	36	3	27
Difficulty of disengaging propulsion and steering to allow attendant propulsion	**13**	3	39	5	65	3	39	5	65	2	26	4	52	2	26	4	52
TOTAL	**100**		379		385		342		330		260		242		232		230

Table 5: Final Decision Matrix

6.2.2 Explanation of Final Decision Matrix Criteria

Manufacturability

Number of Parts – More parts means longer manufacturing time, more labor-intensive manufacturing, and a higher risk of delays due to parts not meeting specifications, machinery breaking down, etc, all of which complicate and raise the cost of manufacturing. Therefore, having fewer parts minimizes these deleterious effects and such a system will score higher than one with more parts. In scoring the designs on this criterion, the team did not attempt to put an exact number of parts to each design (i.e. an exact number of bolts/screws, circuit board components in the case of electronic steering, etc); rather, the designs were considered on a broader scale in terms of the approximate number of major components. A score of 1 indicates a design with a high number of major components (~30 or more), while a 5 indicates a design with very few components (10 or less) and intermediate numbers indicate a number of parts within that range.

Cost of Manufacturing – Manufacturing costs must be recoverable in order for the production of the system to be sustainable, and as such are often reflected in the commercial price. In order for the system to be available and attractive to as many consumers as possible, the price needs to be relatively low, meaning manufacturing costs must be minimized. On a scale of 1-5, the group considered 1 to be a cost high enough that it eliminates the feasibility of manufacturing that system without a budget increase, and a 5 to be a considerably more economical system with manufacturing costs well within the budget. Intermediate numbers were graduated appropriately.

Technical Skill Required for Manufacturing – Skilled laborers and machinists have higher costs than unskilled laborers, and so a system that requires advanced manufacturing skill will cost more to produce. To maximize the marketability of the design, costs must be minimized; therefore, a system with less technical skill required for production will score higher. A score of 5 means the system can be made with primarily commercially available parts, and any specially-made parts can be made by someone with basic manufacturing skills such as knowing how to use a drill, hammer, and saw. A design which receives a score of 1 requires a large number of specialty parts which must be made by advanced, trained technicians, while a score of

3 requires only some complex manufacturing skill (i.e. within the capabilities of Washburn Shops).

Ease of Installation

Technical Skill Required – Once purchased, the accessory must be installed onto the wheelchair, which requires the use of tools. Most individuals have access to at least a very basic toolkit (consisting of a hammer, flat-head and Phillips screwdrivers, and an adjustable wrench) and the knowledge or access to knowledge of how to use it, therefore accessories which only require these tools would receive a score of 5. More advanced tools might be more difficult or even impossible to obtain, thus the accessory should require only very basic tools for installation. A score of 1 would be given to designs requiring highly specific or hard-to-obtain tools for which one must be extensively trained to use. For convenience, the system should be as simple and quick to install as possible.

Integration/Ergonomics

Ease of Use of User Interface – The accessory should be as easy and intuitive to use as possible, and also be designed such that even individuals with severe physical and cognitive impairments could use it with minimal instruction. A higher-scoring design (scoring a 4 or 5) would require very little initial instruction to learn to use, and little to no further instructions or reminders. Designs requiring extensive training and constant reminders will be given a score of 1.

Potential Market – A certain portion of the potential target population may be excluded by a given design because they are physically unable to provide the required input. For example, foot steering eliminates the population that has no control/use of their lower extremities. To ensure that the accessory remains attractive and usable by as many individuals as possible, these exclusions should be avoided. A 5 would be given to designs that excludes less than ~5% of the target market, while a design given a 1 excludes 50% or more. Intermediate exclusion percentages are distributed evenly among the remaining scores.

Force for Operation – This accessory is designed for use by individuals with impaired physical abilities, and as such should not require extensive physical exertion. Designs which require less force input on the user’s behalf for normal operation will score higher than those demanding greater physical exertion. As with the force categories in the preliminary matrices, potential advantage was considered along with the actual forces present in subsystems. A score of 5 was a high advantage and efficient transfer of force to the brakes, while 1 was a poor advantage and force translation, with 3 being no advantage and the remaining numbers being graduated appropriately.

Physical Specifications

Added Weight to Chair – Based on market research, a typical chair weighs about 35-40 pounds. The team deemed a 20% weight increase an appropriate limit, which is approximately eight pounds. Adding more weight beyond the eight pounds would make the chair noticeably heavier and more difficult to maneuver, whereas lower weights would have less noticeable effects. A 1 indicates a design adding more than eight pounds, while a 5 indicates one adding approximately three pounds or less. Intermediate weights are scored accordingly.

Maneuverability/Turning Radius – The steering mechanism should allow the chair to be easily maneuvered through the user's environment; for example, it should not require excessive space in order to turn around. ANSI/RESNA standards specify that a wheelchair must be able to completely reverse direction within a 5-foot (60-inch) circle. Ideally, the input-to-output (turning) ratio should be 1:1 for maximum ease and intuitiveness of use. A high-scoring (i.e. score of 5) design is one that exceeds this regulation (can turn around in less than a 5-foot circle) and has an input/output ratio of close to 1:1. A score of 1 means the design prevents the chair from meeting the ANSI/RESNA standard and has an input/output ratio drastically different from 1:1 (i.e. 1:2, 2:1, etc.).

Added Width – Increasing the chair's width requires more time and practice to become accustomed to the maneuverability of the chair. It also requires extra effort on the user/attendant's behalf to gain and maintain awareness of where the chair is, i.e. what space it is taking up and how it fits into the surrounding environment. A wider chair is more difficult to become accustomed to, and so a design with minimal added width will be easier on the user/attendant and receive a higher score. As in the preliminary matrices, a 1 would be given to a design adding over 2.5 inches to the width of the chair, and a 5 to one adding no additional width at all, with the intermediate numbers being graduated evenly.

Difficulty of Disengaging Propulsion and Steering to Allow Attendant Propulsion – The design must allow for propulsion/steering of the wheelchair both by the individual using it and an attendant. For an attendant to push and steer the chair, the propulsion and steering mechanisms must be disengaged so that the attendant has full control. A design that allows easy disengagement with minimal time and tools required will be more attractive to the consumer and thus score higher. A score of 1 means the systems cannot be disengaged, while a 3 indicates a system that takes moderate time (over five minutes) and/or semi-sophisticated tools which some people may not have access to (vices, ratchet wrenches, etc). Designs scoring a 5 require less than five minutes to disengage and only simple tools such as a screwdriver.

7. Final Design: Preliminary Analysis

In order to further determine component specifications for the three major subsystems of the single-arm propelled accessory, it is necessary to look at commercially available products and evaluate them according to the wheelchair's operating conditions. Once the specifications have been determined, one can identify which specific product or components to purchase in order to satisfy the requirements of that subsystem.

7.1 Disc Brakes

After evaluating a number of braking systems in the decision matrices, it was decided that disc brakes would be used. Disc brakes are a commercially available product and are seen in various applications, including cars and bicycles. The wheels of bicycles and wheelchairs are similar; therefore, the team's intention is to adapt bicycle disc brakes for each of the wheelchair's two main wheels. An analysis is needed to determine whether bicycle disc brakes will be effective for wheelchair applications, and can be found in Section 9.3.

The main variable in selecting disc brakes is the rotor size. Usually bicycle disc brake rotors come in diameters of 160mm, 180mm, and 203mm. Discs with larger diameter can provide more braking power than the smaller diameter discs because there is a larger contact area between the rotor and the brake pad. Such discs are optimal for braking on downhill slopes. The larger discs also run at a cooler temperature because there is a larger area for heat dissipation. Disadvantages of having larger discs include added weight, more difficulty keeping them from bending/bowing, and they are not as smooth when braking hard. Given that wheelchair use is primarily restricted to level ground and low speeds, in order to reduce the weight of the braking system and reduce cost, the optimal brake rotor size for this particular project would be the smallest available (i.e. the 160mm rotors). These same rotors have also been seen on other wheelchair disc brake applications such as the ADI wheelchair disc brakes by Invacare.

7.2 Steering System

The steering user interface of the 2005-06 wheelchair MQP was a good, ergonomic design that was well-received when presented at a RESNA conference in mid-2008. For the most part, the team plans to keep the same design with some minor changes in dimensions and streamlining it for a more appealing look.

The major problem of the 2005-06 MQP steering system was over-steering because the turning radius of the handle did not match the turning radius of the caster. This meant steering was not as simple and intuitive for users as it could be. The plan for the current project is to make the rotation of the steering handle a 1:1 ratio with the rotation of the caster by having equal-radius cable pulleys on the steering handle and mounted on the caster. The radius of the pulleys should not be so small as to decrease the mechanical advantage of the steering system, but not so large that they will take up a significant amount of space.

The 2004-05 wheelchair MQP group took some measurements on the force required to turn a caster and the weight distribution on each of the wheels of the chair. The maximum force input required to turn a caster with a mobile user in the wheelchair was recorded as 15lbs (Cofske et al., 2005). According to basic engineering principles of moments, by increasing the radius of the steering system pulley mounted on the caster, one can decrease the amount of force necessary to turn the caster.

If the original radius of the point at which the 15lb force was applied was 1" and a pulley of diameter 4" was added onto the caster for steering, the resultant force required to turn the pulley would only be 3.75lbs, as shown in the equations below. In this way, pulley radius can be used for mechanical advantage of the steering system.

$$M = r * F$$

$$\sum M_o = r_1 * F_1 - r_2 * F_2 = 0$$

$$\sum M_o = (1in.) * (15lbs) - (4in.) * F_2 = 0$$

$$F_2 = 3.75lbs.$$

Another part of the steering system is the cables in tension that will be wrapped around the pulleys. These cables should be able to withstand the amount of force described in the calculations above, which will translate into tension. The cables should also be able to withstand environmental conditions such as rain and dust without rusting, and should not be too thick to ensure that they are easy to handle and install. The past MQP teams have used bicycle cable. Bicycle cable is low-cost and commercially available, as well as easy to manage and install. It is designed to withstand the elements, and will also be able to withstand the load for this application.

7.3 Propulsion: Analysis of the 2005-06 MQP Wheelchair Four-Bar Linkage

7.3.1 Dependence

To create a fully functional mathematical model of the four-bar linkage used in the drive system of the 2005-06 MQP, variables must first be defined. Figure 40 shows the four-bar linkage and the corresponding variables.

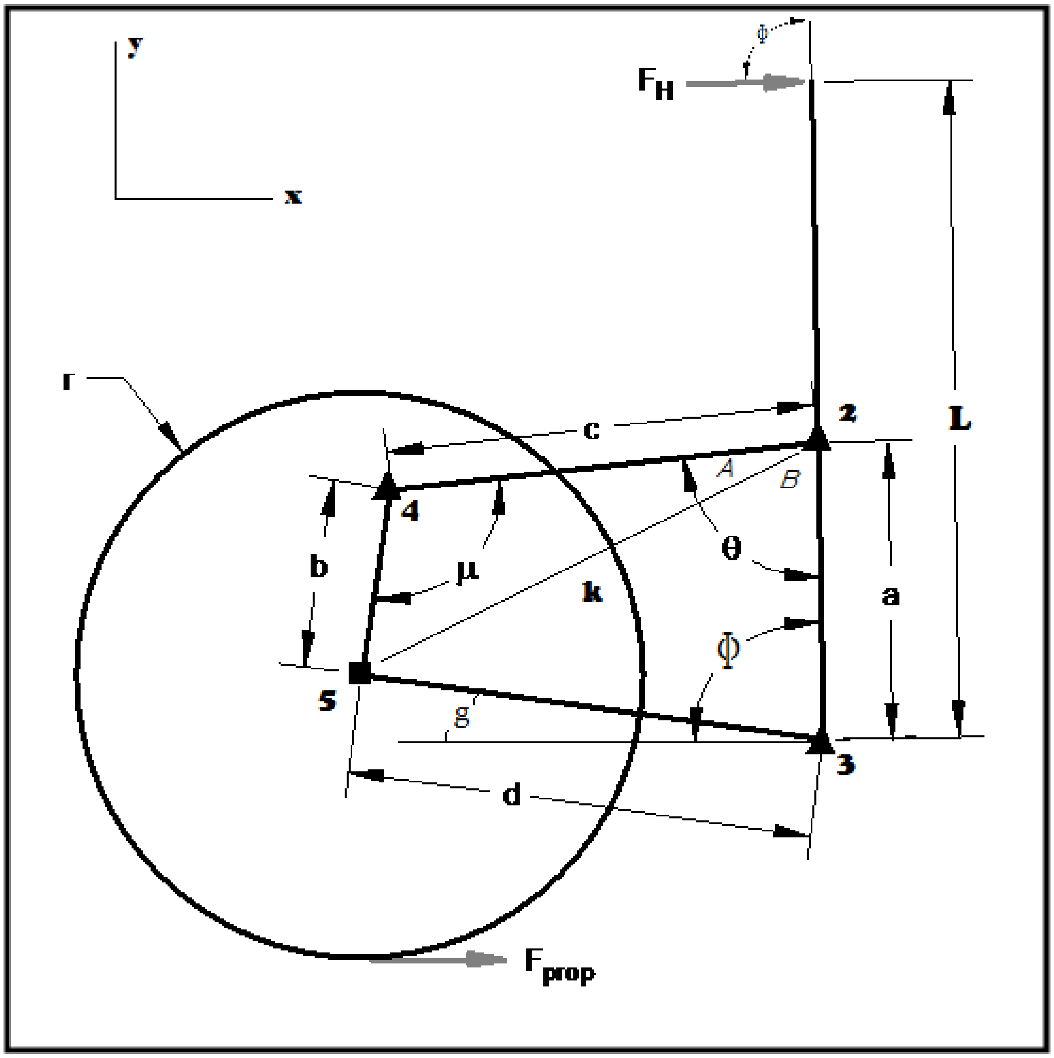


Figure 40: Four-Bar Linkage Diagram (Cassidy et al., 2006)

The independent variables can be defined by the user's control interface. The user has control over how hard they push, the position of their arm, and the variable member **a**, which is used to change mechanical advantage. Since the team wants to evaluate for maximum force, *F* will be considered constant. This means that the independent variables are **a** and the angle of the lever relative to the x axis, ϕ.

First is μ, which can be related to ϕ using the law of cosines. If the quadrilateral is split into two triangles, bisecting the angle θ, they both share a side, which will be called k.

The relation of μ to k is given by

$$\cos(\mu) = \frac{b^2 + c^2 - k^2}{2bc}$$

Similarly, the relation of ϕ to k is

$$\cos(\varphi - g) = \frac{a^2 + d^2 - k^2}{2ad}$$

which by solving for cos(μ) gives

$$\cos(\mu) = \frac{b^2 + c^2 - a^2 - d^2 + 2adcos(\varphi + g)}{2ac}$$

where *g* is the angle created by ground link d and the height difference between the wheel axle and joint 3. Both **d** and the height difference, *cos(g)* are measured as positive.

The other angle of importance to these calculations is θ, which can be related to μ and ϕ by the law of sines, using the same triangles as before.

The law of sines states that for any triangle with sides a, b, and c, and opposite angles A, B, and C, that

$$\frac{\sin(A)}{a} = \frac{\sin(B)}{b} = \frac{\sin(c)}{c}$$

So, with the internal triangles

$$\sin(A) = \frac{bsin(\mu)}{k} \qquad \text{and} \qquad \sin(B) = \frac{dsin(\varphi + g)}{k}$$

To find the internal angle θ, the law of the addition of angles can be used, such that

$$\sin(\theta) = \sin(A)\cos(B) + \cos(A)\sin(B)$$

And remembering that

$$\sin^2(x) = 1 - \cos^2(x)$$

All of the relations are now in place to optimize the problem and calculate maximum forces.

7.3.2 Forces on Joints and Members

In this section, maximum possible forces will be calculated given a worst case scenario. In this scenario, the chair drive mechanism locks, creating a statics problem (Figure 41). The joints act as pins, with the exception of joint 5 which is fused. Forces will be calculated symbolically first, and dimensional information from the 2005-06 MQP will be used to solve for approximate forces in the system.

The 2005-06 MQP assumed that the force applied at the handle would always be acting perpendicular to the lever arm L. While this assumption may be near true for small changes in ϕ from its neutral state of 90°, it would be more accurate to model the force applied, F, as always acting along the x axis (i.e. away from the user's chest). This means that the direction of force F is dependant on ϕ, and the modeling will be completed with this assumption.

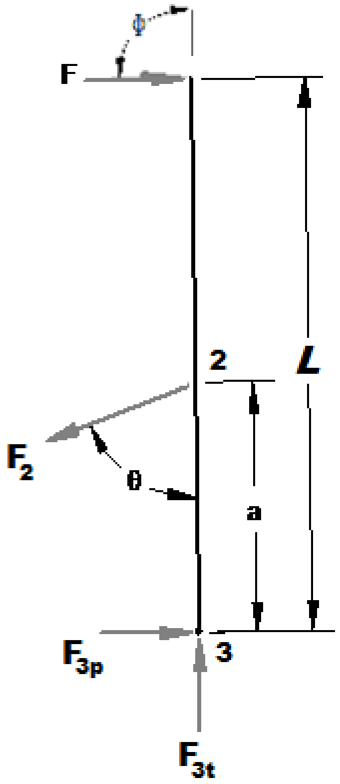


Figure 41: Forces on Member L (Cassidy et al., 2006)

The forces at joint *2* can be calculated using a moment equation balance around joint *3*

$$\sum M_3 = LFsin(\varphi) - aF_2 \sin(\theta) = 0$$

And by solving for *F₂*

$$F_2 = \frac{LFsin(\varphi)}{\text{asin}(\theta)}$$

F₃ is composed of its tangental and perpendicular components, such that

$$F_3 = \sqrt{F_{3p}^2 + F^2{}_{3t}}$$

F_{3p} can be found using the sum of the moments around joint 2

$$\sum M_2 = Fsin(\varphi)(L-a) - aF_{3p} = 0 \qquad \textbf{so} \qquad F_{3p} = Fsin(\theta)(\tfrac{L}{a} - 1)$$

F_{3t} can be found using the sum of the tangential forces

$$\sum F_t = Fcos(\varphi) + F_2 cos(\theta) - F_{3t} = 0 \qquad \textbf{so} \qquad F_{3t} = Fcos(\varphi) + F_2 \cos\,(\theta)$$

Becoming in total

$$F_3 = \sqrt{\left(Fsin(\theta)\left(\frac{L}{a} - 1\right)\right)^2 + \left(Fcos(\varphi) + \frac{LFsin(\varphi)}{\text{asin}(\theta)}\cos(\theta)\right)^2}$$

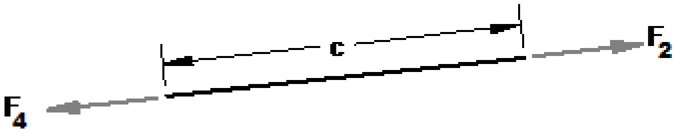


Figure 42: Forces Acting on Member c (Cassidy et al., 2006)

Since member **c** (Figure 42) is a two pin member, it cannot support a moment, which means that it can support no perpendicular force component. Because of this, the only equation available is

$$\sum F_t = F_2 - F_4 \qquad \text{so} \qquad F_2 = F_4$$

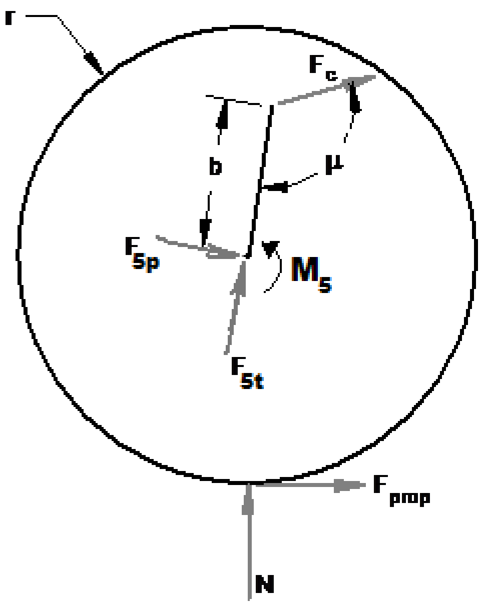


Figure 43: Forces Acting on Member b (Cassidy et al., 2006)

Since joint 5 is fused, it can support a moment (Figure 43), given by

$$M_5 = bF_2\sin(\mu) \quad \text{or} \quad M_5 = \frac{FLbsin(\varphi)\sin(\mu)}{\text{asin}(\theta)}$$

Also, the sums of the forces must be zero, so

$$F_5 = F_4 = F_2$$

Finally, the radius of the wheel, r, can be used to calculate mechanical advantage

$$MA = \frac{Lbsin(\mu)sin\varphi)}{arsin(\theta)}$$

7.3.3 Numerical Analysis

The system can be modeled now that dependence of the internal angles has been analyzed and mathematical equations for the forces have been found. The software program Maple 12 was used for the following mathematical models. First, the variables must be defined. Values from the 2005-06 MQP prototype were used:

L = .68m

a = .1m-.555m

b = .26m

c = .525m

d = .53m

To give an idea of user control, mechanical advantage was graphed against both the angle of the lever ϕ, and also the variable linkage, **a** (Figures 44-46).

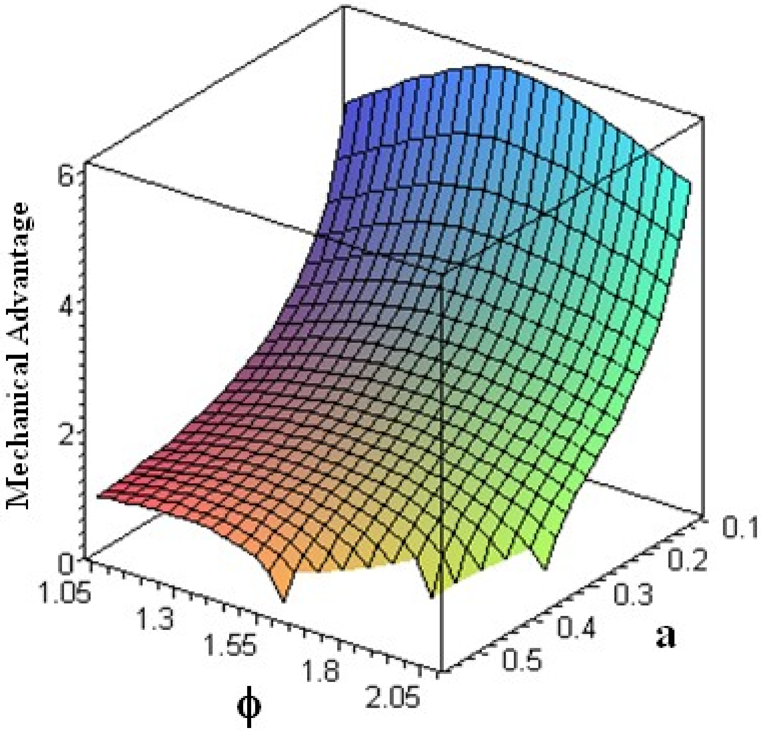


Figure 44:3D Graph of Mechanical Advantage vs. a, ϕ

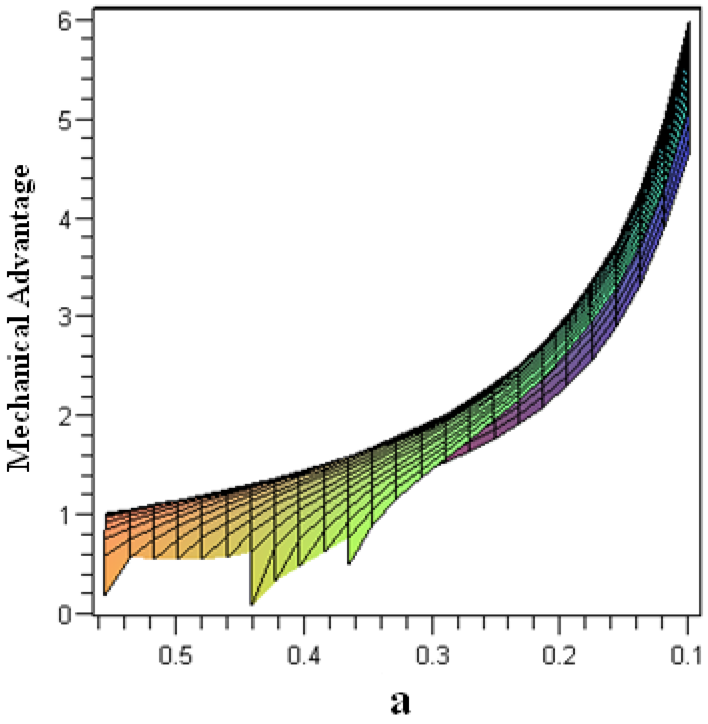


Figure 45: Mechanical Advantage vs. a

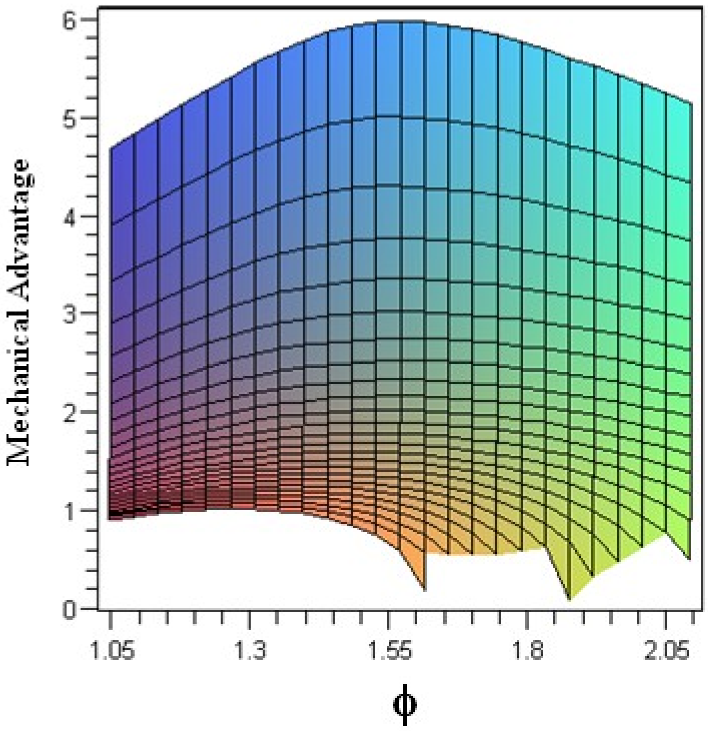


Figure 46: Mechanical Advantage vs. ϕ

8. Final Design Description

The following sections contain descriptions of the components which comprise the final accessory design (Figure 47):

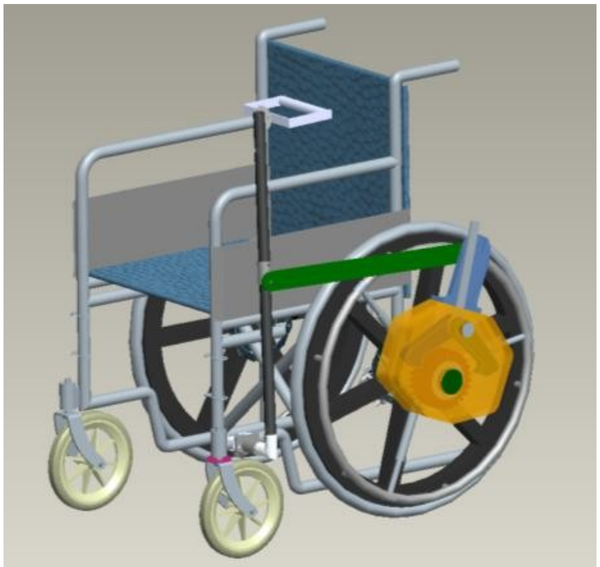


Figure 47: Final Design

8.1 Steering & Lever Design

The handle of this device (Figure 48) will be manufactured by screwing a piece of circular cross-section aluminum tube on both ends to a bent rectangular piece of aluminum bar. Three holes will be drilled on the back plate to fasten a pulley and a screw to attach the handle-pulley assembly to the lever.

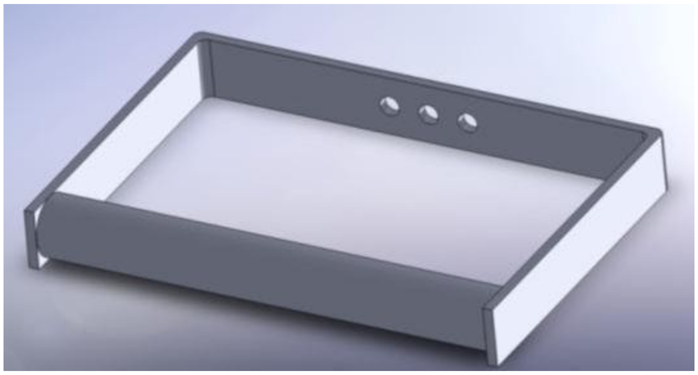


Figure 48: Handle

The steering handle pulley (Figure 49) will have three holes through it. The two outer holes will be to fasten the pulley to the back of the handle, and the center hole will be used to insert the bolt that will hold the handle-pulley assembly. It will have two socket head cap screws to fasten the steering cable and to tighten it. The pulley will only have one groove, as opposed to the two grooves seen on the 2005-06 MQP, to facilitate cable tensioning at only the handle pulley and not the steering caster pulley.

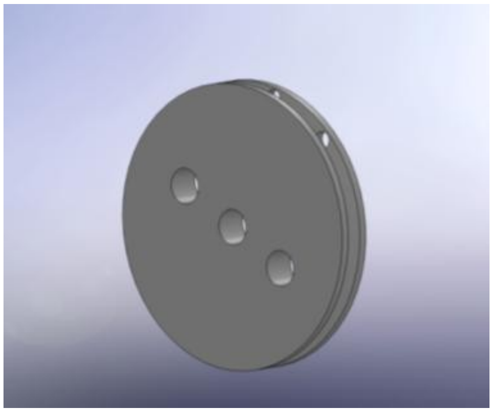


Figure 49: Steering Pulley (Attached to Handle)

The handle and pulley will be fastened to the lever with a bolt which will rotate in a ¼" inner diameter bushing. Three holes will be drilled into the lever; one to accommodate the handle and pulley, and the others to insert the steering cable inside the lever. The lever itself (Figure 50) is made of ¾" aluminum tubing, which is commercially available at a local hardware store.

Figure 50: Lever

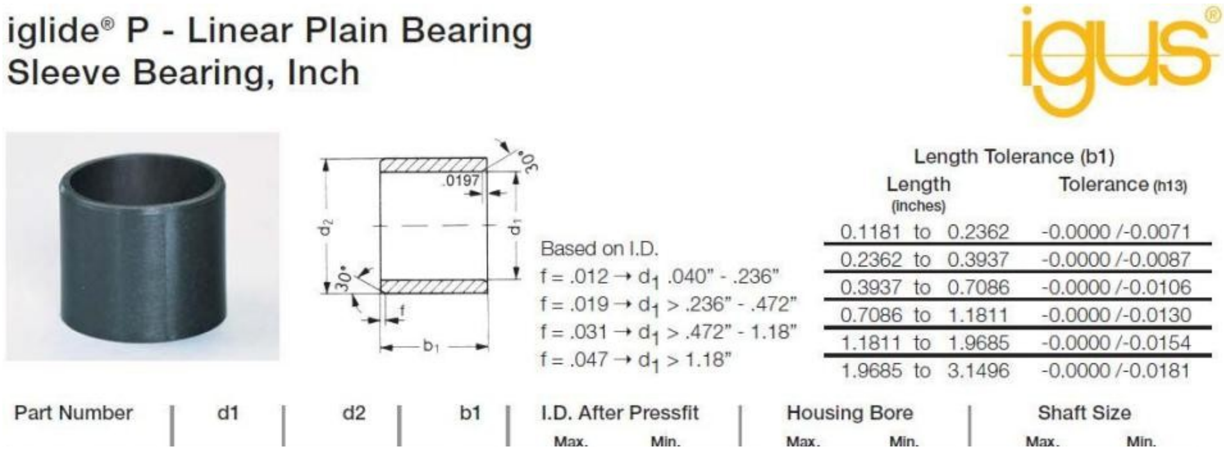
The propulsion member holder/slider (Figure 51) will be inserted on the outside of the lever tube. A small piece of aluminum will be screwed to this piece using the two screws shown. The aluminum piece will have a hole in the center for another screw, which attaches the coupler link to the slider. This piece has the capability of sliding up and down the tube to adjust mechanical advantage. It is commercially available, including set screws to tighten to the lever tube and coupler, and it need not be manufactured except for the small aluminum piece, which only requires three drilled holes.

Figure 51: Propulsion Member Holder/Slider

The elbow (Figure 52) will attach to the bottom of the lever tube. This elbow is commercially available and comes with pre-drilled holes and set screws to tighten to the lever tube and to the rotating shaft. If need be, holes can be drilled into the lever tube so that the screws can go through the pipe to better secure it.

Figure 52: Commercially-Available Elbow

An aluminum tube shaft will be inserted and tightened on one end to the elbow, and the opposite end will be inserted with a clearance fit into the attach plate shaft, which houses a bushing. The shaft of the attachment plate (0.8741”, 0.8729”) is toleranced to have a running fit into the sleeve, and the housing (1.0050”, 0.9997”) is toleranced for the plastic sleeve to be press fit into it. Figure 53 shows the sleeve dimension information.



iglide® P - Linear Plain Bearing
Sleeve Bearing, Inch

Based on I.D.
$f = .012 \rightarrow d_1$ .040" - .236"
$f = .019 \rightarrow d_1 >$ .236" - .472"
$f = .031 \rightarrow d_1 >$ .472" - 1.18"
$f = .047 \rightarrow d_1 >$ 1.18"

Length Tolerance (b1)

Length (inches)	Tolerance (h13)
0.1181 to 0.2362	-0.0000 /-0.0071
0.2362 to 0.3937	-0.0000 /-0.0087
0.3937 to 0.7086	-0.0000 /-0.0106
0.7086 to 1.1811	-0.0000 /-0.0130
1.1811 to 1.9685	-0.0000 /-0.0154
1.9685 to 3.1496	-0.0000 /-0.0181

Part Number	d1	d2	b1	I.D. After Pressfit		Housing Bore		Shaft Size	
				Max.	Min.	Max.	Min.	Max.	Min.

Figure 53: Plastic Sleeve Dimensions

Two holes will be drilled to accommodate frame attachment pieces. A side plate will be screwed onto the attachment plate with two holes to hold the steering cables. Figure 54 shows the final attach plate.

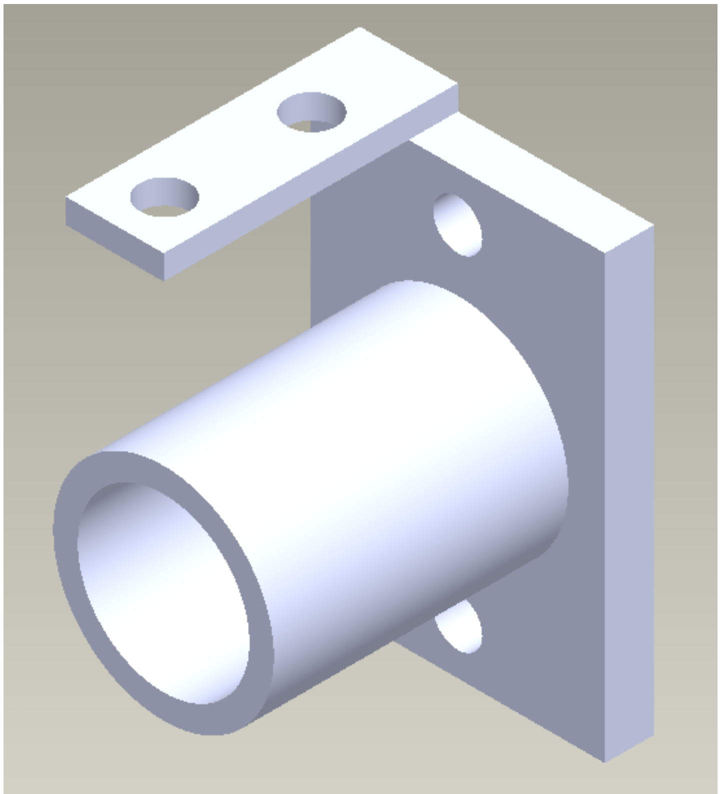


Figure 54: Frame Attachment Plate

The wheelchair frame attachment pieces (Figure 55), of which there will be two, will be screwed to the back of the frame attachment plate. These pieces will clamp onto the wheelchair frame and be tightened with screws. This piece is commercially available and need not be manufactured.

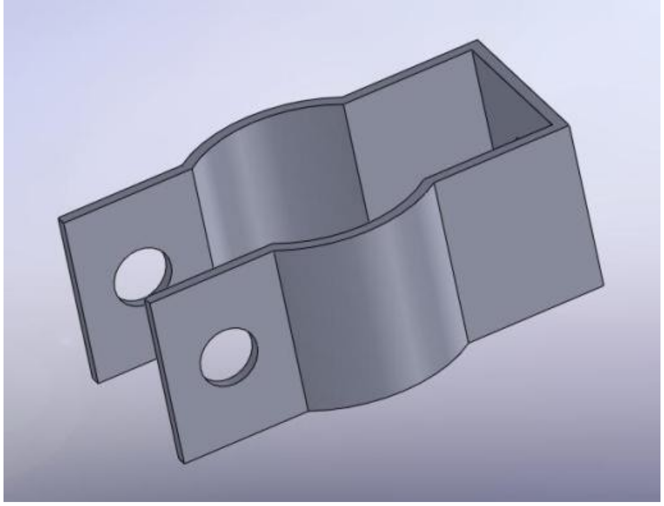


Figure 55: Frame Attachment Piece

The caster steering pulley (Figure 56) will be mounted by unscrewing the caster from the wheelchair frame, dropping the pulley through the caster screw, and fixing it onto the caster frame with two tabs that are on the bottom of the pulley before screwing the caster back onto the wheelchair frame. This piece will be manufactured. The pulley has a groove to accommodate the steering cables, which are controlled at the handle. Tension on the cables will cause the pulley to rotate, forcing the caster to rotate. The steering cable will be wrapped around the caster steering pulley. This pulley only has one groove because the extra length available on the screw which mounts the caster to the wheelchair frame is very limited and can only accommodate a single-groove pulley. A pulley with two grooves would be too thick and require a specially-manufactured bracket for the caster. The caster pulley will be manufactured and will have the same diameter as the pulley on the handle in order to keep a 1:1 steering ratio.

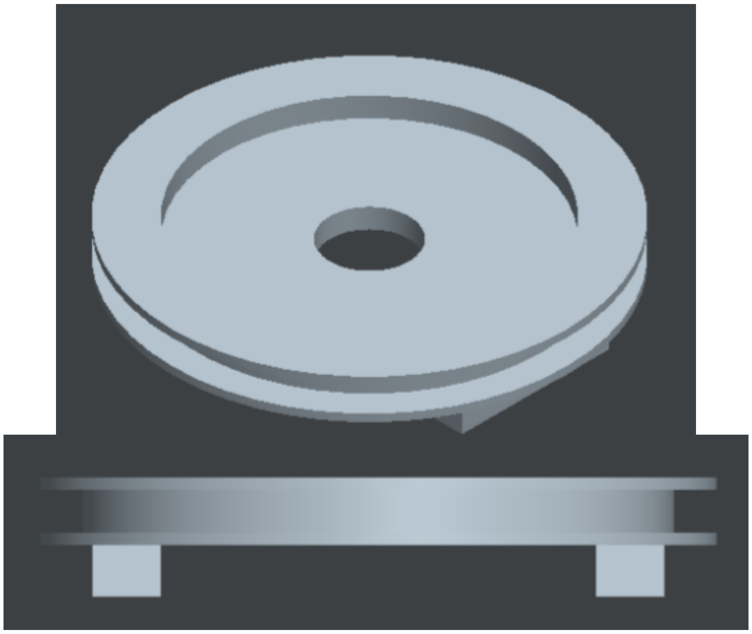


Figure 56: Caster Steering Pulley

Figure 57 shows the setup of the steering system. The two ends of a single cable will be fastened with two socket head cap screws to the pulley on the handle, which will provide a means of maintaining tension. To ensure that the cable is wrapped at least 180° around the pulley for proper functionality, the cable ends will cross one another and be secured by the screw on the opposite side from the side of the pulley which they wrap around. The same cable will also be wrapped around a similar screw on the caster steering pulley to prevent the cable from slipping. This set-up allows for easy tightening of the cable at the handle if it begins to slacken. There will be a cable holder placed immediately below the handle pulley to hold the cable sheath (which will be pulled through holes in the holder and secured with crimped end caps). Another cable holder, which is part of the attachment plate, will have the same functionality. The slack cable between both cable holders will be routed through the hollow interior of the lever.

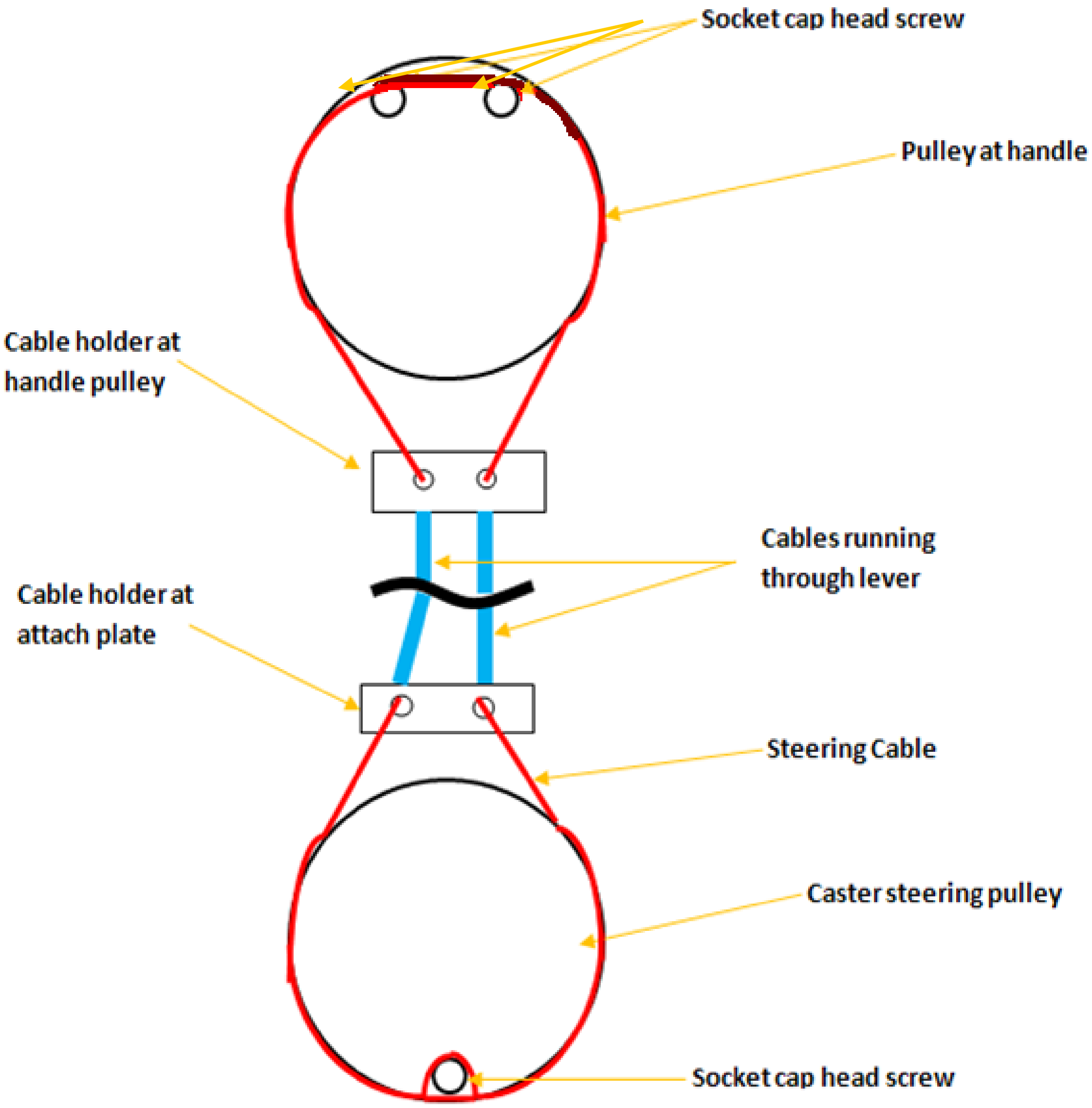


Figure 57: Steering Diagram

8.2 Propulsion Subassembly

The main axle of the propulsion assembly is an aluminum bar with a diameter of 1.5748 inches (40mm), which will be pressed into a 1.5748-inch (40mm; inner diameter) plastic bushing. The bushing manufacturer gives a tolerance of +0.005906"/0.001969" (+0.15mm/+0.05mm) for the inner diameter of the bushing after it has been press-fit into its housing, for a range of 1.5768"-1.5807" (40.05mm - 40.15mm). For a proper fit, the shaft which will be inserted into the bushing (in this case, the propulsion assembly axle) must be toleranced at +0.002441"/+0" (+0.062mm/+0mm) for a diameter range of 1.5724" - 1.5748". A ¼" (6mm) wide keyway is milled 1/8" deep into the surface of the axle, centered along an axis of symmetry. The axle bar is 4.173" (106 mm) long. Centered ½ inch from one end of the bar are three threaded ½" diameter, ½" deep holes, arrayed 120° apart. Into the holes are screwed ½" diameter pieces of aluminum pipe, with one threaded end and an inner diameter of 0.37" (Figure 58).

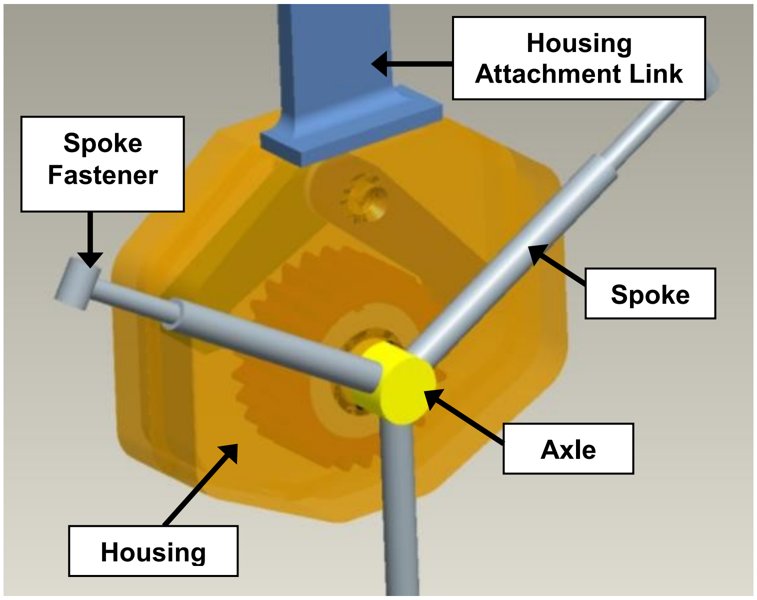


Figure 58: Propulsion-Pushrim Spoke Attachment

Each pipe is 7.874" (20cm) long. A 1" long compression spring with an outer diameter of 0.343" and a spring constant of 18.43 lb/in is pressed down the tube towards the axle. These springs are available for order from W.B Jones Spring Co. Nested into the ½" diameter pipe is a 3/8" diameter pipe, also aluminum, with a length of 11.024" (28cm). Current pushrim models have an average radius of 11.811" (30cm), meaning that each spoke would need 12lbs of force to be compressed so that it will fit inside of the pushrim. This includes the load required to begin deflection of the spring. This pipe is topped with a conduit fastener and cut such that the fasteners can hug the inside of a standard pushrim. These pieces are pressed out towards the pushrim by the spring in order to keep the propulsion assembly centered. The telescoping arms can be locked in place with set screws, but will not be permanently housed inside one another so that they can be taken apart for packaging.

The following parts are fitted onto the axle, starting at the back plate: a flanged igus iGlide plastic bushing 0.354" (9mm) long, with an inner diameter toleranced for a shaft h9 clearance fit, and an outer diameter toleranced for press fit into H7 housings. Because the axle is designed for a press fit, these bushings require their inside diameters to be lathed down by approximately 0.008". The backplate of the drive case has a 1.732" (44mm) diameter hole toleranced for an interference fit at H7, giving an acceptable range of 1.732" to 1.733". This is the hole into which the flanged bushing is press fit. Then, a 0.866" (22mm)-wide CDK40 roller clutch is press fit directly onto the axle. This part is factory toleranced, but requires a housing with an inner diameter of 3.15" (80mm) toleranced at ISO interference fit N6 (*note: this is the only ISO tolerance used in the manufacturing of this accessory, as the clutch was toleranced by the manufacturer using ISO tolerances), giving an acceptable inner diameter range of 3.148" to 3.149". This housing is a purchased gear which has to be modified after acquisition to have the required inner diameter. A ¼" wide, 1/8" deep keyway must be cut into both the surface of the housing's inner diameter and the clutch's outer diameter (Figure 59) so that the keyways may be aligned to accept ¼" key stock. This will ensure that the two parts do not slip relative to one another. These parts and are designed to be machined and assembled on campus.

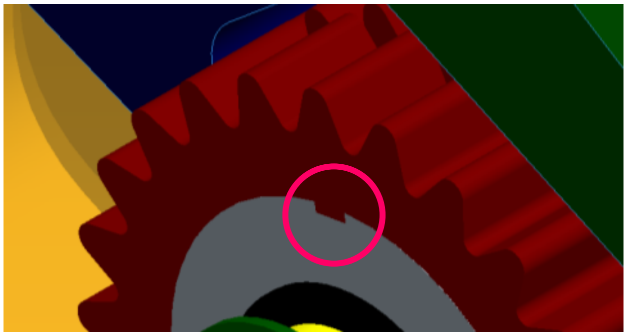


Figure 59: Gear/Clutch Keyways

Next is a manufactured plastic bushing 0.197" (5mm) wide, followed by a second CDK 40 with its housing, and finally, a second flanged manufactured plastic bushing 0.354" (9mm) long, ending in a 0.079” (2mm) thick flange. The front half of the drive case will be press fit onto this second flanged bushing, mirroring the back plate of the housing. Figure 60 shows a section view of the parts assembled onto the axle, as well as some parts whose descriptions follow.

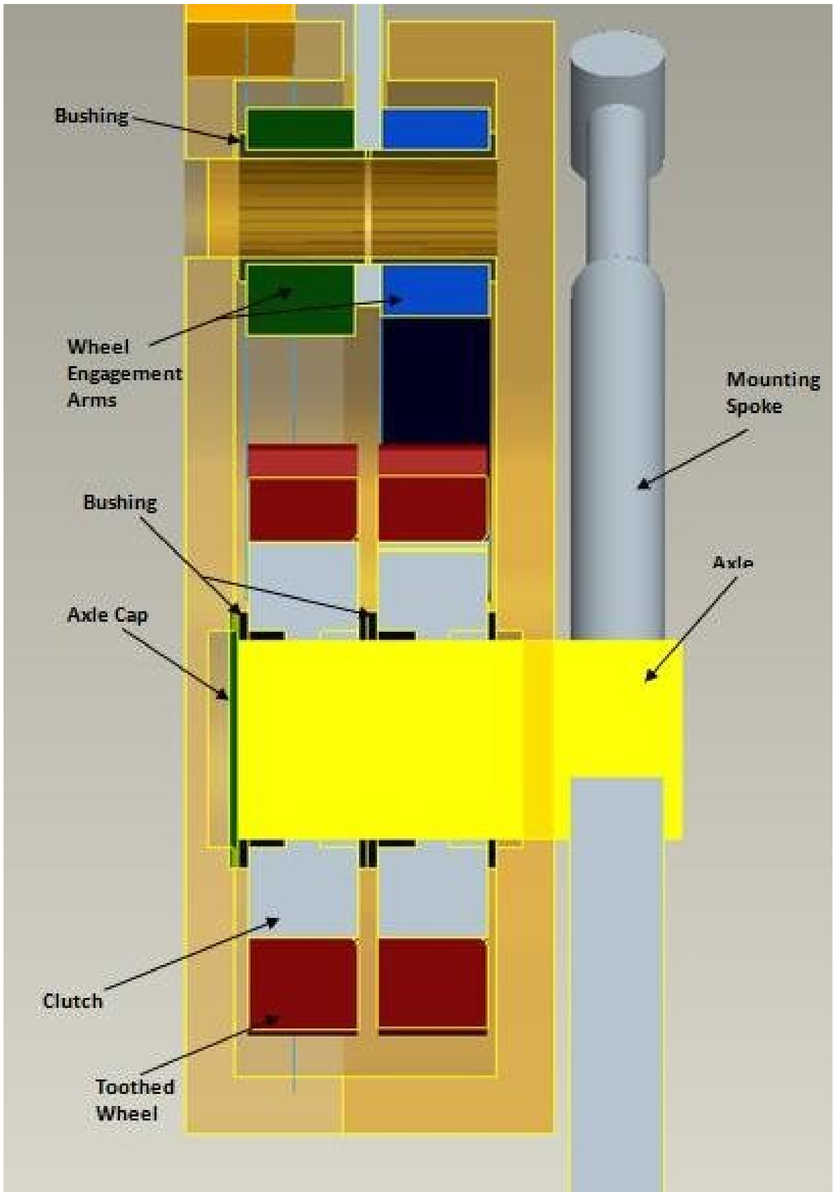


Figure 60: Propulsion Assembly Section View

The shifting mechanism sits 4.238” above the axle along the plane of symmetry. Both halves of the housing have 0.905” (23mm) diameter holes, toleranced at FN1 (H6 hole) so that identical-diameter flanged plastic bushings may be press-fit inside of them. Inside of these bushings is a 0.787” (20mm) diameter aluminum rod (toleranced for an h9 clearance fit so that it can rotate freely). This rod will be mounted to the backplate by a bolt inserted through holes in both the backplate and the rod. This assembly acts as the shifting mechanism's axle. The rod supports the two pawls and the shifting lever, all of which are held in alignment with dowel pins and welded together to move as one unit. The shifting lever is used to toggle between reverse, neutral, and forward arrangements of the drive system and is held in a given position by grooves on the back of the housing attachment link (Figure 61), which is attached with machine screws to the top of the housing. The user's input force on the lever causes the coupler to pull or push on the housing attachment link. The shifter is essentially locked to the housing attachment link and will thus move with it. If the propulsion mechanism is in either the forward or reverse configuration, the motion of the shifter will cause one of the pawls to transfer this force to one of the gear and clutch assemblies, which rotate the axle (and thus the wheel).

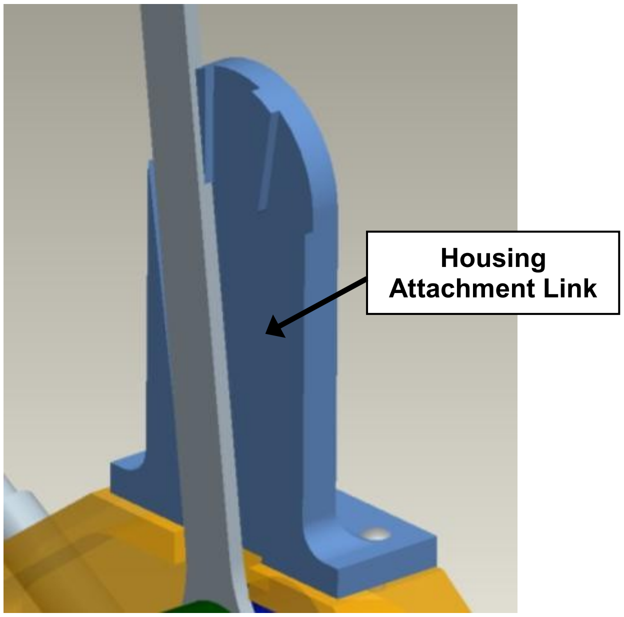


Figure 61: Shifter Locking

The housing attachment link is machined from aluminum, and connects to the coupler link by way of a shaft with a diameter of 0.787" (20mm) toleranced for a LC4 clearance fit (h9 shaft). The shaft is fitted with a purchased plastic flange bearing (outer diameter of 0.905" or 23mm), to be press-fit into a similar hole on the coupler link. The joint is held together by a 0.905" diameter, 0.079" thick aluminum plate that is machine-screwed to the column on the housing attachment link. The coupler is 1.575" wide and transfers force from the lever mechanism to the drive housing. It is also manufactured from aluminum. Figure 62 shows the arrangement of these parts.

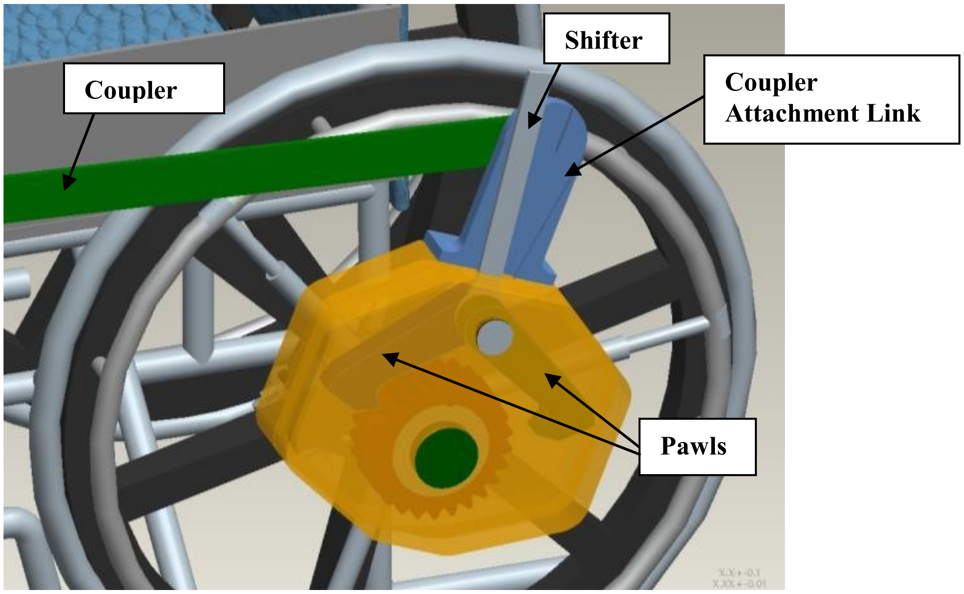


Figure 62: Shifting Mechanism & Coupler

8.3 Brake Assembly

The brake assemblies for each wheel are mounted on the inner side of the chair frame. This helps minimize the overall addition to the chair's width, which is a major design criterion.

The brake rotors are screwed to a wooden disc, which has a center hole to allow it to fit onto the wheel axle. There are also three holes spaced 120° apart, which allow hex head bolts to be inserted on the opposite side of the wooden disc from the brake rotor (Figure 63).

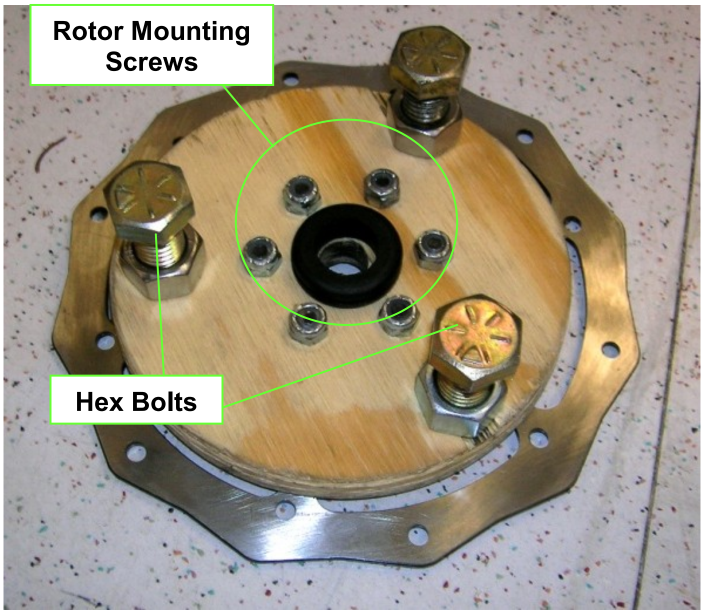


Figure 63: Brake Rotor Wooden Disc & Bolts

The rotor is mounted on the axle such that the rotor faces the wheelchair frame. The bolt heads are then pressed into the spokes on the wheelchair wheel. This provides the interference necessary to allow the rotor to rotate with the wheel, without modifying the wheelchair itself.

The calipers are attached to the wheelchair frame using sheet-metal brackets (Figure 64). The brackets have screw holes which hold the mounted caliper in the appropriate orientation on the wheelchair frame near the axle (Figure 65). Each one is made out of two mirror-image pieces of sheet metal and bent around the diameter of the wheelchair frame.

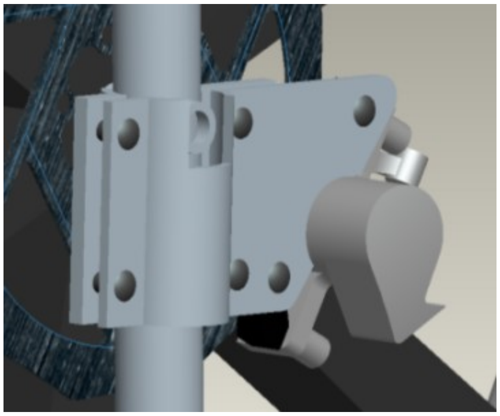


Figure 64: Initial Caliper Bracket Design on Wheelchair

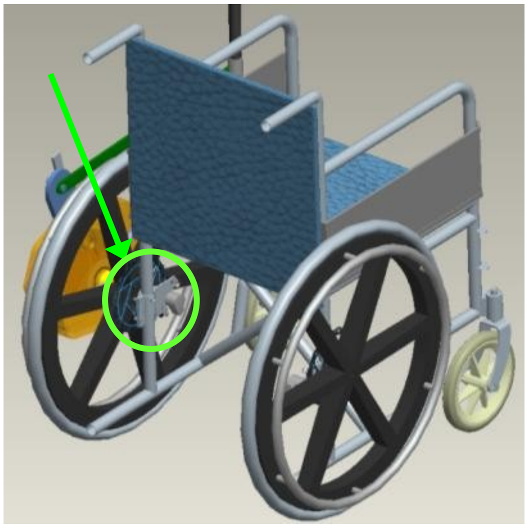


Figure 65: Caliper Bracket Location

These brackets allow relatively easy assembly of the brakes onto the chair without structural modification of the wheelchair itself, which could void the chair's warranty. The brackets also have mounting holes for the two-post calipers. The hand lever for brake actuation is mounted to the steering handle (Figure 66) in order to uphold the "all controls in one place" design specification.

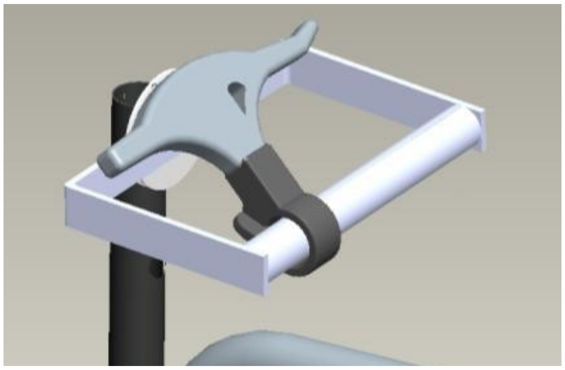


Figure 66: Brake Lever Mounting

A single cable will be run down from the handle and loosely secured to the lever, such that the cable can slide during lever motion. This single cable will run to a cable doubler, which essentially “splits” the cable into two cables, one for each brake assembly. This allows the force input (squeezing the brake lever) from one lever to be transmitted to two brakes. Because the cables very often get in the way and can be a hazard, they will be secured at various points to the wheelchair frame, again loosely enough to allow them to slide when necessary.

8.4 Entire System Assembly

All of these subsystems must integrate smoothly in order for the entire system to work properly. The propulsion subassembly mounts onto the hand rim of the wheelchair using three self-centering spring-loaded spokes. The outermost housing of this assembly and the housing attachment link act as one rigid link and will always move together. When the user pushes or pulls the handle on the lever, this motion is transmitted to a coupler link attached to both the lever and the aforementioned rigid link of the propulsion assembly (Figure 67).

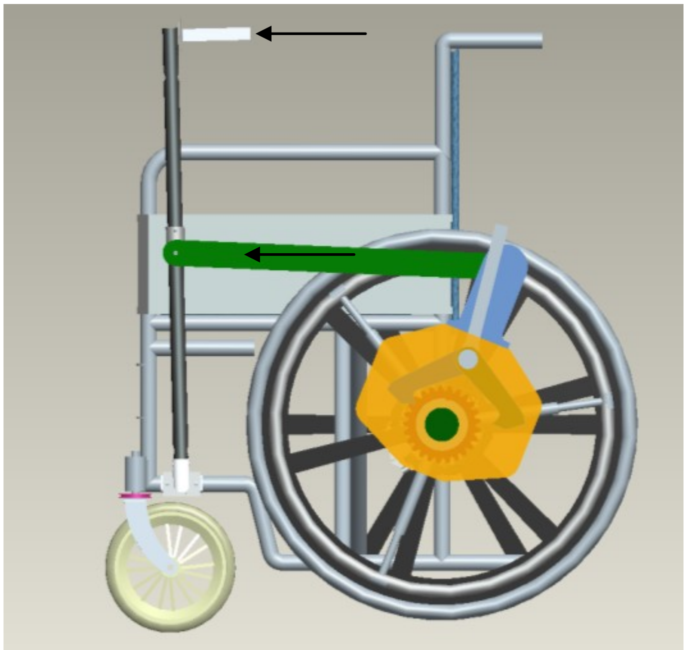


Figure 67: Handle-Coupler Motion

The pawls then engage one of the two toothed wheels, which are attached to the axle via a unidirectional clutch. By engaging the teeth of the wheel, the pawl converts the user's input force (pushing or pulling the lever via the handle) into torque at the axle in order to turn the wheelchair's wheel. This requires flexion-extension motion of the user's arm. Diagrams of the force transmission are shown in the next section.

In order to steer the wheelchair, the user must use a pronation-supination motion to turn the handle mounted at the top of the main propulsion lever. The handle is attached to a pulley which has a cable secured around its circumference. This cable is wrapped around another pulley mounted to the caster, and then goes back up to the handle pulley, forming a loop. The pronation-supination motion causes tension in one side of the cable loop, which is transmitted to the caster pulley and causes it (and thus the caster) to turn in a certain direction, thereby steering the wheelchair. In order to brake, the user must simply squeeze the brake lever mounted to the handle. A cable runs from the handle to a cable doubler, which “splits” the cable into two cables, one of which runs to the disc brake caliper on either wheel. Squeezing the hand lever causes tension in the cable, which is transmitted down to the caliper, causing it to squeeze the rotor and stop rotation of the wheels.

9. Detailed Analysis of Final Design

The following sections contain analyses and figures important in understanding the operation of the wheelchair accessory. A partial stress analysis can be found in Appendix G

9.1 Extreme Positions of the Assembly

Figures 68-72 show the assembly at its extreme forward and backward lever positions (i.e. at maximum protraction and retraction of the arm, respectively). Based on anthropometric/ergonomic data, the maximum protraction and retraction were designed to be lever angles of approximately ±30° from vertical (60° to 120° on the Cartesian coordinate system). For each extreme position, the mechanism is shown engaged for forward and reverse motion, with arrows corresponding to resultant propulsive forces (note: they are not shown if the position is the return stroke for that particular direction). The neutral position is also shown. To limit the stroke to within these extreme positions, the attach plate shaft has a slot to accommodate a screw that has been screwed into the pipe fitted inside the shaft. The pipe rotates with lever motion, but the shaft does not.

9.1.1 Neutral Engagement

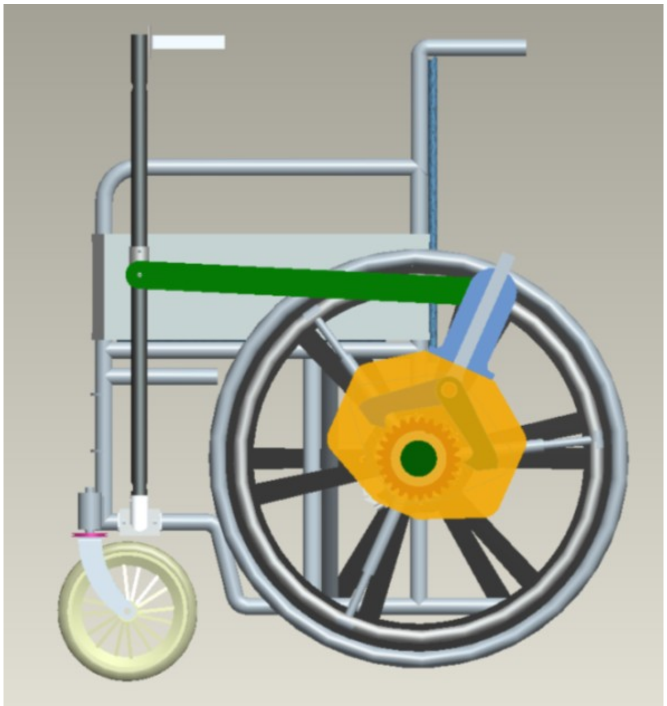


Figure 68: Neutral Position of Mechanism (Lever Angle = 0°)

9.1.2 Maximum Protraction

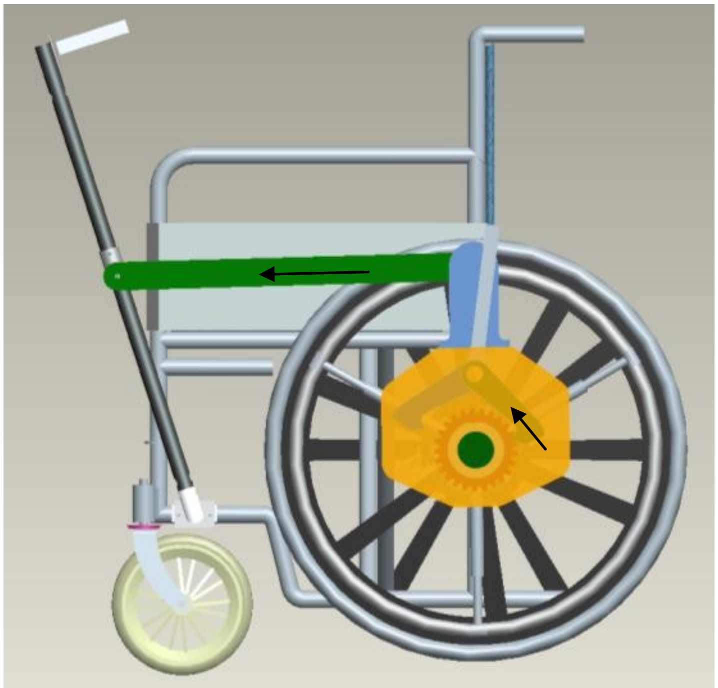


Figure 69: Maximum Protraction, Forward Motion (Lever Angle = +30°)

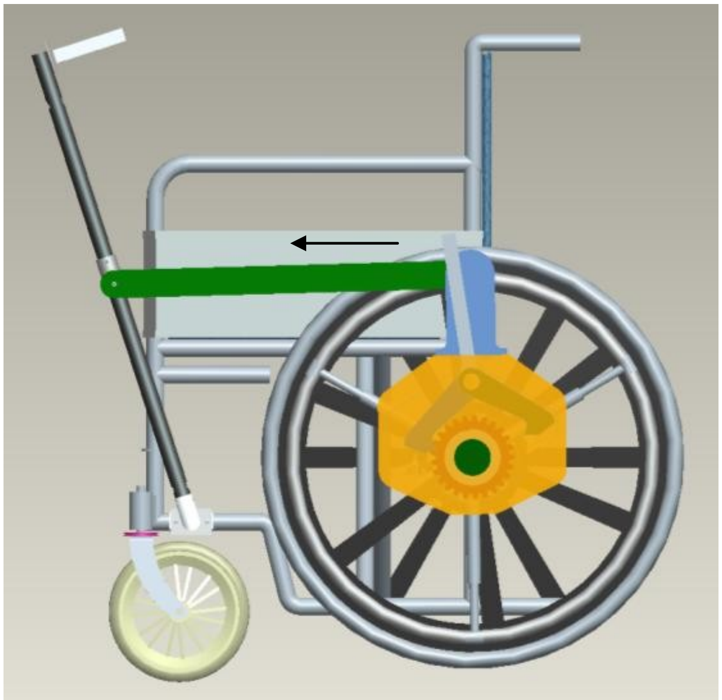


Figure 70: Maximum Protraction, Reverse Motion (Lever Angle = +30°)

9.1.3 Maximum Retraction

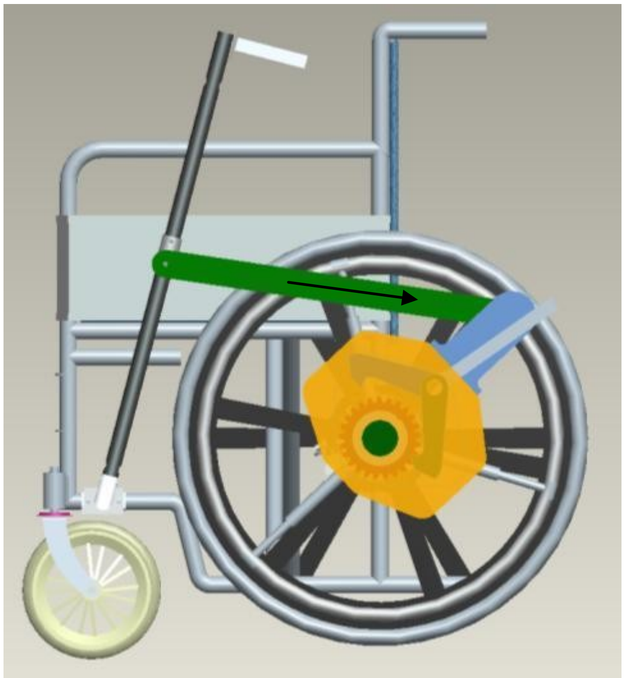


Figure 71: Maximum Retraction, Forward Motion (Lever Angle = -30°)

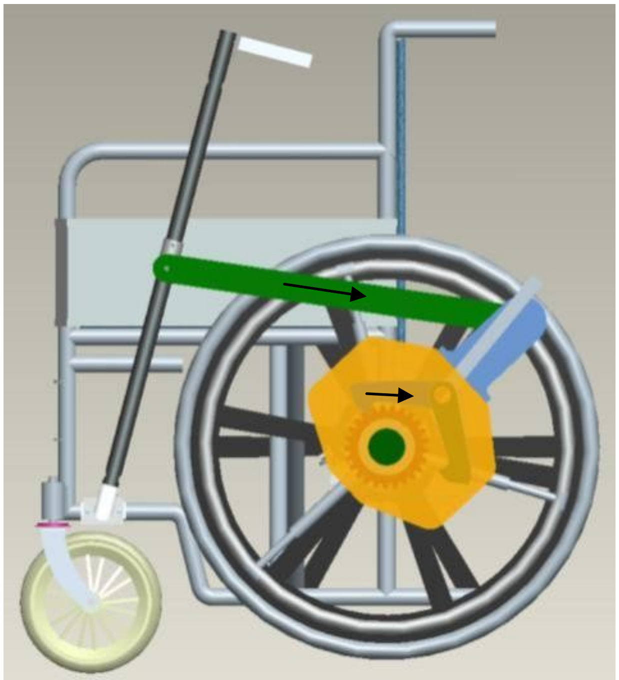


Figure 72: Maximum Retraction, Reverse Motion (Lever Angle = -30°)

9.2 Kinematic Analysis of Propulsion Linkage

In order to ensure that the entire wheelchair-accessory assembly will move as intended, it is necessary to perform a kinematic analysis to determine the assembly's degrees of freedom (DOF). This analysis will examine the forward propulsion motion of the wheelchair (i.e. drive and return strokes), which occurs in the YZ plane (Figure 73). As such, a two-dimensional analysis is applicable. Any free object in two dimensions has three degrees of freedom – horizontal and vertical translation, and rotation in the plane created by the horizontal and vertical axes. Where used, the term "half joint" indicates joints which remove one DOF, and "full joint" indicates joints which remove two DOF.

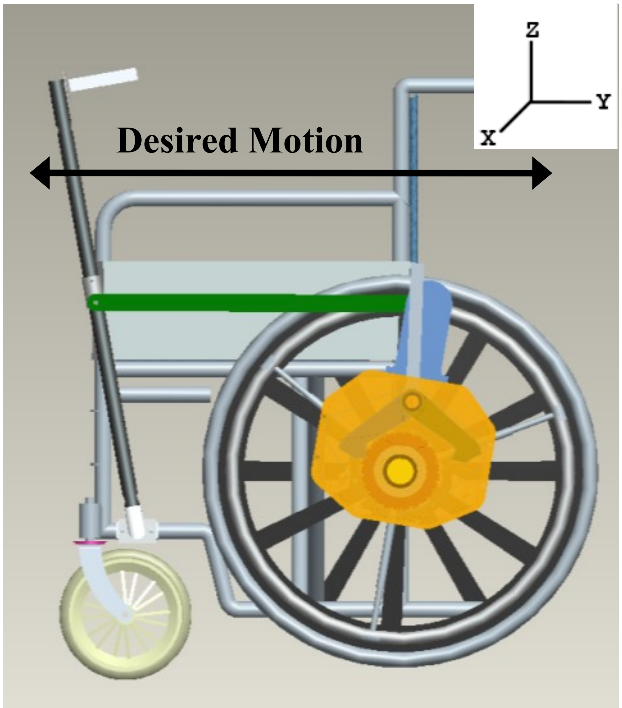


Figure 73: Desired Wheelchair Motion

Figure 74 shows a simplified representation of the wheelchair to aid in visualizing the links for analysis.

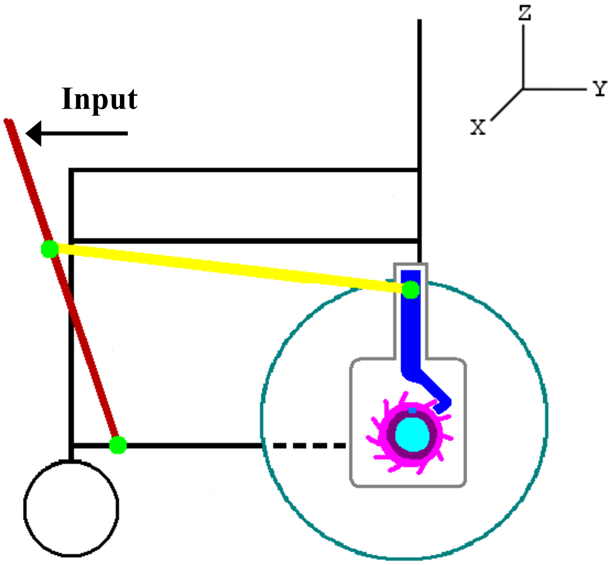


Figure 74: Propulsion Kinematic Diagram

There are eight links which comprise the propulsion mechanism and which will be used in further analysis to determine the overall degrees of freedom of the mechanism. They are as follows:

- Link 1, the ground, is the wheelchair frame
- Link 2: lever (dark red)
- Link3: coupler (yellow)
- Link 4: housing attachment (grey)
- Link 5: shifter/pawl (blue)
- Link 6: gear/external clutch ring (gear is pink, entire clutch is purple)
- Link 7: bearings inside clutch
- Link 8: internal clutch ring (entire clutch is purple); is also rigidly attached to the accessory axle (cyan), accessory axle spokes, and wheelchair wheel (teal)

The clutch is press-fit inside the gear, and as such the gear and external ring of the clutch act as one rigid joint. Similarly, the internal ring of the clutch is rigidly attached to the axle, thus it is also rigidly attached to the accessory spokes and wheelchair wheel, meaning these components all move as one rigid link. The clutches are overrunning clutches. Figure 75 shows a simplified version of an overrunning clutch. (Note: the clutch actually contains a cam "attached" to its internal-diameter ring, but here this piece will be referred to as the internal clutch ring.)

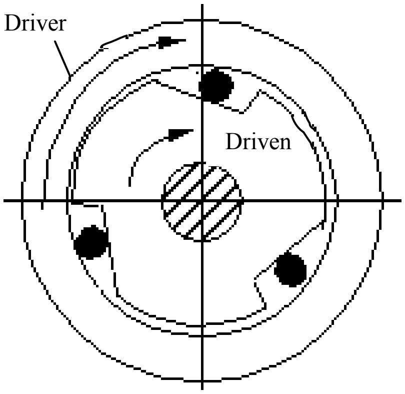


Figure 75: Overrunning Clutch (Zhang, Finger, and Behrens, 2009)

When a propulsive driving stroke is applied to the lever, the force is transmitted through the propulsion system and is applied as torque to the gear (and thus the driver component of the clutch) causing the bearings inside the clutch to become wedged between the driver and driven components. This forces the driven component to rotate, turning the axle and wheel of the wheelchair.

In this case, the gear/external clutch ring, bearings, and internal clutch ring /axle/wheel (i.e. links 6, 7, and 8) act as one rigid body because there is no relative motion between them. The ground-lever, lever-coupler, coupler-housing, housing-shifter/pawl, and internal clutch ring-ground connections are all pin (full) joints. There is also a pin joint between the housing and ground, because the housing pivots about the axle. In addition, in order to shift between forward, reverse, and neutral, the shifter portion of the shifter/pawl fits into one of three slots on the housing link, creating a “detent”-type half joint. Finally, the engagement interface between the shifter/pawl and gear can be described as a roll-slide half joint. This yields a mechanism with six links, six full joints, and two half joints. The Gruebler equation is used to determine DOF in two-dimensional planar systems and is written as follows:

$$DOF = 3(L-1) - 2J_1 - J_2$$

In this equation, L = # of links, J_1 = # of full joints, and J_2 = # of half joints. Substituting the appropriate values as described above gives:

$$DOF = 3(6-1) - 2(6) - 2 = 15 - 14 = 1$$

As expected, the mechanism has one degree of freedom during a propulsive stroke in which the clutch is “engaged.” This means that the input stroke will cause motion in the other parts of the propulsion assembly. Next, the condition in which the clutch is freewheeling, i.e. the return stroke, will be examined.

During the return stroke of propulsion motion, many of the aforementioned links and connections do not change. There are still pin joints at the following locations:

- Ground to lever
- Lever to coupler
- Coupler to housing
- Housing to shifter/pawl
- Housing to ground
- Internal clutch ring to ground

The detent half joint between the shifter and housing link also remains, as does the roll-slide half joint between the gear and pawl.

Unlike in the previous case, where the drive stroke forced the three components to act as one rigid body, the return stroke allows the clutch to freewheel, meaning its three components can move relative to one another. The gear/clutch external ring is joined to the bearings by a roll-slide half joint. Likewise, the bearings and internal clutch cam/ring are joined by a roll-slide half joint. Due to the dissociation of the components, there is also an additional pin joint between the gear and ground. There are now eight links, with seven full joints and four half joints. The Gruebler equation for this condition can be written as:

$$DOF = 3(8-1) - 2(7) - 4 = 21 - 14 - 4 = 3$$

Contrary to what might be expected based on the previous case, there are actually three degrees of freedom in the freewheeling condition. The lever is able to move about its pin joint with the ground without causing the wheelchair wheel to move, providing one DOF. The bearings inside the clutch are also free to rotate and slide without causing motion in the whole mechanism, providing the second DOF. The third and final DOF is the motion of the wheelchair wheel, which can occur without causing the lever to move.

These analyses show that the wheelchair and propulsion mechanism will indeed move as intended. The drive and return strokes in the reverse direction occur in the same plane as forward propulsion, with the same kinematic conditions, thus the results would be the same if an identical analysis was performed on backward propulsion motion.

9.3 Disc Brake Analysis

After evaluating a number of braking systems in the design selection matrix it was decided that disc brakes would be used in the accessory. Disc brakes are a commercially-available product and are seen in many different applications, such as cars and bicycles. The wheels of bicycles and wheelchairs are similar in size, shape, etc; therefore, the team's intention is to adapt bicycle disc brakes on each of the wheelchair's main wheels. It must first be investigated, however, whether bicycle disc brakes will be effective for wheelchair applications?

The following analysis describes the momentum and kinetic energy of a wheelchair as well as the work done by the friction between the wheelchair wheels and the ground in order to stop the wheelchair's movement. The analysis is done in metric units using values of typical wheelchair weight, a 91-kg individual, and typical wheelchair propulsion speed and stopping distance as measured using the Meyra chair on the carpet surface on the second floor of Higgins Labs at WPI. Parameters are defined in the table below.

Parameters	
$\mathbf{m_p}$	mass of person (91kg)
$\mathbf{m_w}$	mass of wheelchair (18kg)
$\mathbf{v_w}$	velocity of wheelchair (1m/s)
$\mathbf{F_w}$	Friction force between wheelchair and ground
d	stopping distance
$\mathbf{P_w}$	momentum of wheelchair
KE	kinetic energy
W	work

Table 6: Braking Analysis Parameters

From basic engineering principles, the momentum of the wheelchair-user system is calculated by multiplying the mass by the velocity.

$$P_w = m_w * v_w \qquad (1)$$

$$P_w = (18kg + 91kg) * \left(\frac{1m}{s}\right)$$

$$P_w = 109\frac{kg \cdot m}{s}$$

The kinetic energy of the wheelchair-user system can also be calculated by multiplying one-half the mass times the square of the velocity. One can also calculate the work done by friction to stop the wheelchair's movement by multiplying the frictional force between the wheelchair and the ground by the stopping distance. According to conservation of energy principles, the work done by friction in order to stop the wheelchair's movement is equal to the change in kinetic energy of the wheelchair. Knowing the mass of the system, the initial and final (zero) velocity and the stopping distance, one can solve for the average frictional force between the wheelchair wheels and the ground.

$$\Delta KE - W = 0 \qquad (2)$$

$$KE = \frac{1}{2}mv^2$$

$$W = F * d$$

$$\left(\frac{1}{2}mv^2 - 0\right) - F * d = 0$$

$$\frac{1}{2}(109kg)\left(\frac{1m}{s}\right)^2 - F_w * (2m) = 0$$

$$F_w = 27N$$

Knowing the frictional force between the wheelchair wheels and the ground, the radius of the wheel, and the rotor radius, one can solve for the frictional force between the rotor and the pad and subsequently the brake actuation force. The wheel-ground friction force is 27N as calculated previously, the radius of a typical wheelchair wheel is approximately 0.3m, and the radius of the rotor is one half of 160mm (0.16m), or 0.08m. Using these values and moment equilibrium, one can solve for the rotor-pad frictional force and the actuation force. Table 7 defines these parameters while Figure 76 shows them graphically.

Parameter		Value
F_f	Rotor-pad frictional force	?
R_r	Rotor radius	0.08m
F_w	Wheel-ground frictional force	27N
R_w	Wheel radius	0.3m

Table 7: Brake Friction/Actuation Force Parameters

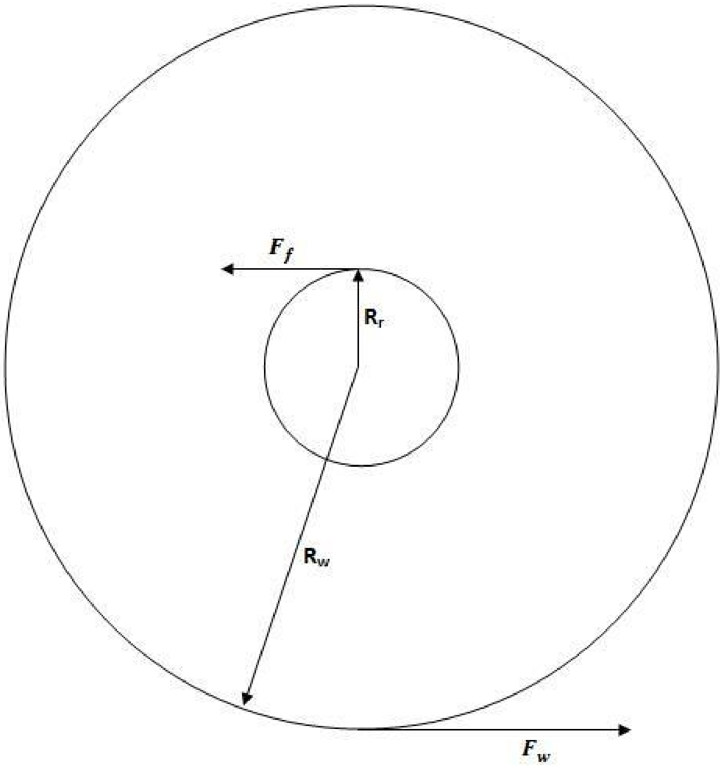


Figure 76: Brake Friction/Actuation Free Body Diagram

$$\sum M = 0 \qquad (3)$$

$$F_f R_r + F_w R_w = 0$$

$$F_f = \frac{-F_w R_w}{R_r} \qquad (4)$$

$$F_f = \frac{-(27N)(0.3m)}{0.08m}$$

$$F_f = 101N$$

One can now calculate the required brake actuation force or axial force by dividing the frictional force by the coefficient of friction between the rotor and the brake pad. Depending on the material of the rotor and the brake pad, the range of the coefficient of friction can vary between 0.4 and 0.8.

$$F = \frac{F_f}{\mu} \qquad (5)$$

$$F = \frac{101}{0.8} = 126N$$

$$F = \frac{101}{0.4} = 253N$$

After substituting the frictional force and both limits of the coefficient of friction between the rotor and brake into the equation, one ends up with a range of values for the required axial force on the brake pad.

$$F = [126N, 253N]$$

However, the axial force is not exactly the input force by the user to the brake handle because the brake handle has some mechanical advantage for the user. The maximum mechanical advantage and the resulting force applied by the user on the brake handle can be calculated using moment equilibrium (Figure 77). The dimensions shown in Table 8 are those from the brake handle used on the 2005-06 wheelchair MQP by Cassidy, et al. (2006).

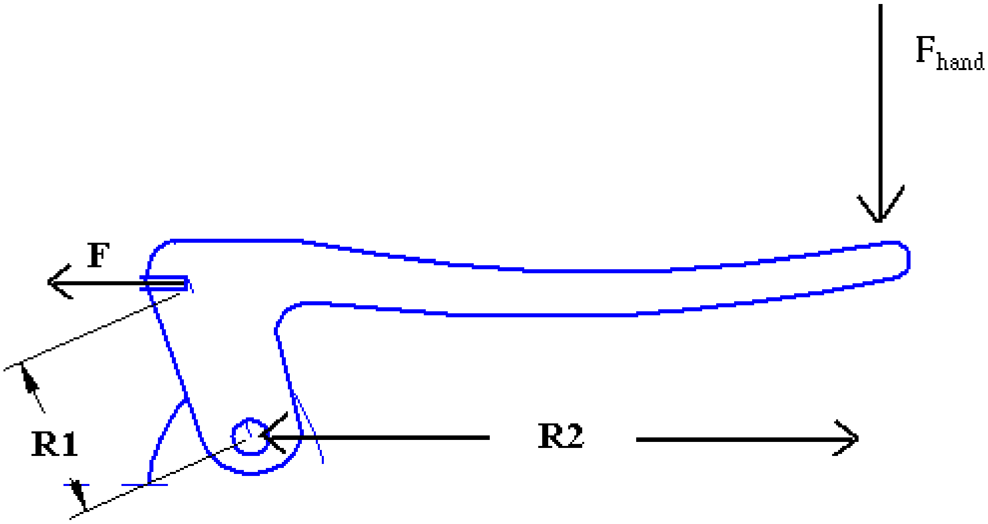


Figure 77: Brake Handle Parameters

Brake handle parameters	
F	[126N, 253N]
R1	0.03m
F_{hand}	?
R2	.08m

Table 8: Brake Handle Parameters

$$\sum M_0 = 0$$

$$FR_1 - F_{hand}R_2 = 0$$

$$\boldsymbol{F_{hand} = \frac{FR_1}{R_2}} \quad \textbf{(6)}$$

By substituting the range of values of the required brake pad axial force and the brake handle geometry into the equation above (14), one can solve for a range of values of the required hand force applied by the user.

$$\boldsymbol{F_{hand} = \frac{(126N)(0.03m)}{(0.08m)}}$$

$$\boldsymbol{F_{hand} = \frac{(253N)(0.03m)}{(0.08m)}}$$

$$\boldsymbol{F_{hand} = [47N, 95N]\ or\ [11lbf, 21lbf]}$$

This is the resulting force applied by the user given the conditions that a 91kg person is riding an 18kg wheelchair at a speed of 1m/s and brakes with a stopping distance of 2m. Top speed and stopping distances were similar for pavement and concrete floor surfaces and the resulting forces applied at the brake handle for these surfaces only varies within a few pounds from carpet. Many disc brake systems have additional mechanical advantage at the caliper therefore the actual required force applied by the user may be less than these calculated values. According to the research done on individuals with disabilities and the design specifications the brake lever should not require more than 35 pounds of grip force to actuate. The calculated values are within the desired specifications.

10. Manufacturing

10.1 Commercially Available Parts

Lever Tube

The lever tube is made of 9/10" electrical wiring tube, cut with a saw to the proper length of 27” to act as a lever for the single arm propulsion accessory. A 1/2” hole was drilled on one end of the tube to accommodate a bushing which holds a 1/4” fastener on which the handle and pulley rotate. Two 1/2” holes were also drilled on the pipe; one right under the 1/2” bushing-fastener hole and one on the other end of the pipe, right before the elbow through which the steering and braking cables will be run.

Lever Elbow

The elbow (Figure 78) which connects the lever tube to the connecting pipe was commercially available and is used to house 9/10” electrical wiring tube. The end of the connecting pipe which is housed by the elbow was turned down to a diameter of 9/10” using the lathe.

Figure 78: Lever Elbow

Frame Attachment Pieces

The frame attachment pieces (Figure 79) were commercially available and are fastened to the attachment plate using 1/4-20 UNC Allen-head fasteners. These pieces attach to the wheelchair frame and have tightening screws to secure the piece to the frame.

Figure 79: Frame Attach Piece

Propulsion Member Holder/ Mechanical Advantage Slider

The slider piece (Figure 80) was commercially available. However, a secondary operation had to be carried out in order for it to serve the desired purposes, as this piece is originally a coupler for 9/10" electrical wiring tubes. There was a groove on the inside of the part which had to be worn down using a file before it would slide up and down the lever pipe. A small aluminum plate is screwed to the two screws on the slider, and has a hole in the center for a third screw. This third screw attaches the coupler to the slider.

Figure 80: Mechanical Advantage Slider

10.2 Manufactured Parts

The following section describes the fabrication process for parts that had to be specially manufactured. Drawing numbers are included where appropriate, and refer to the drawings found in Appendix D.

Handle

The handle of the propulsion device was manufactured at Washburn Shops. A 1.75” by 14” by 1/10” piece of aluminum was bent into a square U shape. A 8/10” diameter solid aluminum rod was then cut to a length of 5 3/4", tapped on both sides, and fastened into the open end of the rectangular U-shaped aluminum piece (Figure 81).

Figure 81: Handle

Caster Steering Pulley

The caster steering pulley (Appendix D, Drawing 6) was manufactured at Washburn Shops from a solid 2” diameter aluminum stock cylinder. To manufacture this part, two different procedures had to be carried out; a turning procedure done with an SL10 lathe and a milling procedure done with a Haas Mini Mill. These procedures are described below.

Turning Procedure

In the turning process, the stock material turns and the tool makes small linear movements to cut off material and create a profile from the stock. Before this procedure was carried out using the lathe, the paths which the tools had to make in reference to the stock piece to create the different profiles were generated using ESPRIT software and then translated into NC code, the language of the CNC machines.

The solid model of the caster steering pulley was generated in SolidWorks and imported into the ESPRIT software, then merged with a template containing the tools available on the lathes in Washburn Shops. Once the solid model was loaded, chains of tool paths were created and tools were selected that would create the desired groove and cutoff profiles. The stock piece was also defined and the turning procedure was simulated multiple times to ensure its validity and accuracy. The tool paths produced in the ESPRIT software were then translated into NC code and the code was transferred to the lathe's operating control. Once the code was loaded onto the lathe, a preliminary graphical simulation (Figure 82) was run on the lathe display screen in order to ensure once more that the code worked properly.

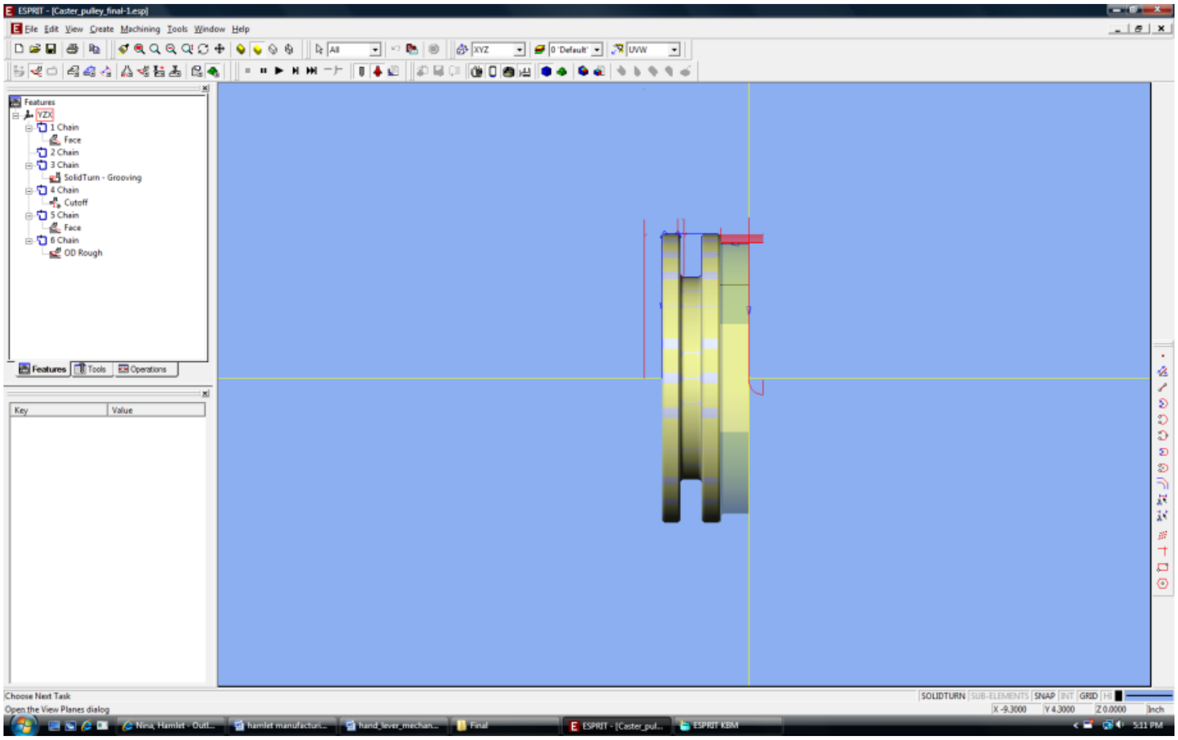


Figure 82: Pulley Turning Tool Paths on ESPRIT

Before beginning the turning cycle, the lathe tools that needed to be used were probed and the 2" stock cylinder was tightened onto the chuck and probed as well. This process tells the machine exactly how large everything is, and where in space the stock is located.

In the turning procedure, a diamond tool faced off some material from the stock surface to smooth it out and then a 3/10" pulley groove was produced on the stock using a cutoff tool.

The pulley was then separated from the rest of the stock material using the same tool, making sure that there was enough material left on one side of the pulley to create the tabs and center hole features on the Mini Mill.

Milling Procedure

In the milling process, the tool rotates in place while the stock, secured to a table inside the milling machine, moves linearly into and across the tool. The milling procedure removed any excess stock on the pulley and milled out material to create the tabs on the bottom side of the pulley. Before this procedure was carried out, the toolpaths were again generated in ESPRIT software and then translated into NC code.

The solid model of the caster steering pulley generated in SolidWorks was imported into the ESPRIT software and merged with a template containing the tools available on the Haas Mini Mills in Washburn Shops. Once the solid model was loaded, tool paths were created and tools were selected that would create the desired features. Again, the manufacturing procedure was simulated multiple times (Figure 83). The tool paths produced in the ESPRIT software were then translated into NC code and the code was transferred to the mill's operating control. Once the code was loaded, a preliminary graphical simulation was done on the mini mill display screen in order to ensure that the code worked properly.

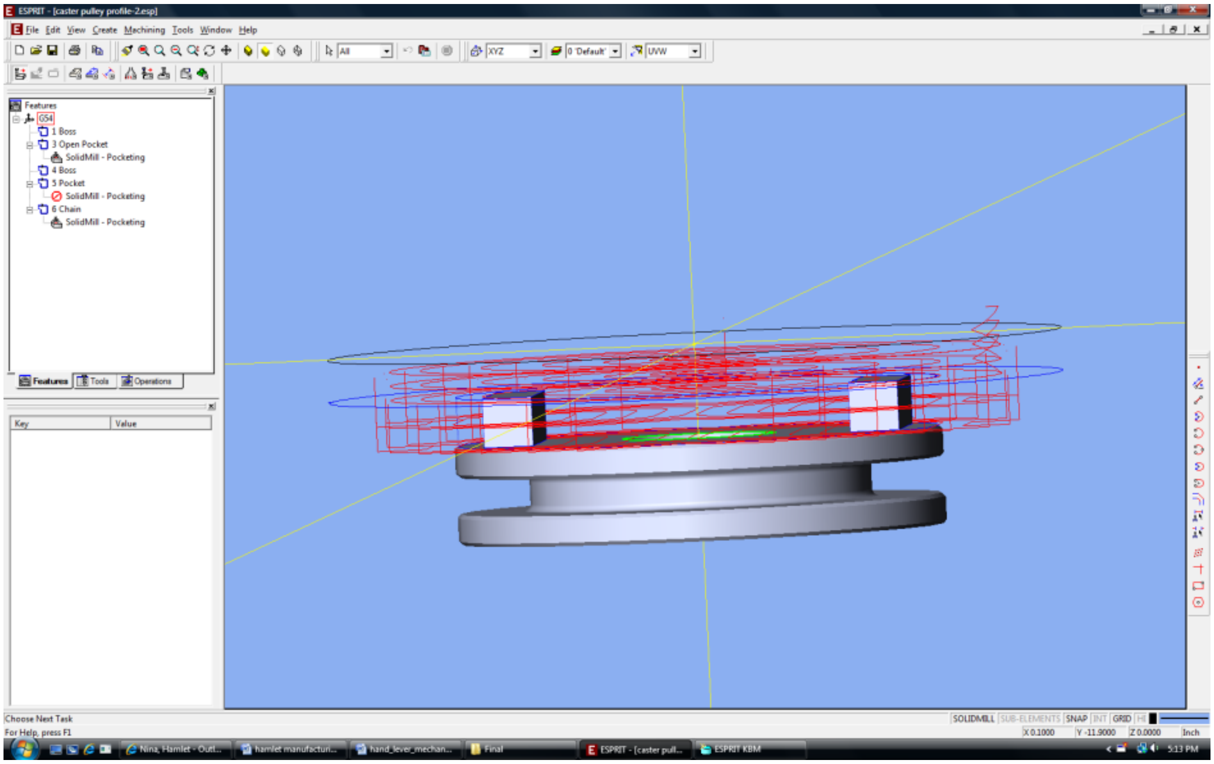


Figure 83: Facing and Tab Tool Paths for the Mini Mill on ESPRIT

Before beginning the milling cycle, the pulley was loaded onto a chuck with the excess material facing up, and then clamped onto the mini mill work surface. The part and the tools were then probed. In the first milling operation a 1/2" end mill was used to face off some of the excess material on the pulley, then a 1/4" mill was used to create the profile of the tabs on the pulley, and finally a 3/8" drill was used to create the 5/8" center hole on the pulley.

Once the part was completed, a size 10-24 hole was drilled and tapped through the top flange to accommodate the fastener around which the steering cable will be wrapped to prevent slippage. Finally, the pulley (Figure 84) was mounted onto the caster to make sure it was a good fit.

Figure 84: Bottom of Caster Steering Pulley

Handle Pulley

The handle pulley (Figure 85; Appendix D, Drawing 13) was made out of the same stock material as the caster steering pulley using the same turning operations, except that all excess material was removed because this pulley did not need tabs. Three holes were then drilled into this pulley using a 1/4” drill on a drill press so that it could be attached to the handle and the screw about which it would rotate. Additionally, two holes were tapped through the top flange of the pulley to accommodate two size 8-32 fasteners that will be used to hold and tension the steering cable.

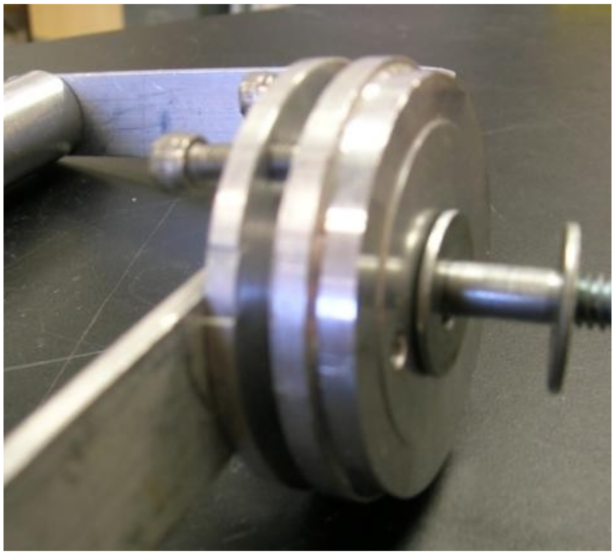


Figure 85: Handle Pulley

Connecting Pipe

The connecting pipe was made out of a 1” diameter solid aluminum stock piece. It was turned down on one end to 0.93” diameter to fit into the lever elbow, and turned down to 0.874” diameter on the other side so that it could properly fit into the bushing inside the pipe of the attach plate. This operation was done using a lathe in Higgins Labs.

Coupler Link

The coupler link (Figure 86; Appendix D, Drawing 8) was milled in Higgins Labs from a 21” x 1.05” x 0.25” piece of aluminum. The piece was milled in a Do-All manual mill. The center of the piece was found using the digital positioning read out of the machine and a spring offset tool. After the center had been identified, one edge was identified with the same tool, and the relationships given on the drawings of the part were used to drill the holes. Chamfers were cut on the outside corners of the part with a band saw, and smoothed down with a file and polished. Finally, a plastic bushing was pressed into the smaller of the two holes on the part. Figure 86 shows the coupler, attached to the housing attachment piece.

Figure 86: Coupler Link

Drive Axle

The drive axle (Appendix D, Drawing 4) is composed of three parts: the purchased Formsprag CDK-40 one way clutches, their toothed housings, and the axle itself. The intent was to mount a keyway on the inside race of the clutches to assist in force transmission. The shop did not have a properly sized broach or cutter for the inside race of the part. Additionally, the races of the clutch are hardened steel, and as a result, Neil Whitehouse, manager of the Higgins Labs shop, noted that attempting secondary operations on the hardened steel could damage or deform the clutches. It was decided after a few initial attempts at cutting a keyway in the inner race of the clutch, with Neil present, that they would best be left unmodified.

The toothed housings for the clutches were cut from a U.S. Tsubaki DS50A22 double chain sprocket. First, the hole in the center of the sprocket was expanded to 80mm in diameter to match the outer diameter of the clutch, with tolerances in mind for press-fitting later. After the hole was milled all the way through the part, it was cut into two equal sections of approximately 20mm width. Both halves each had one set of sprocket teeth. After the internal diameter was expanded slightly with sanding and polishing, the clutches were press fit into the housings.

The axle was turned down from a 6” long, 2” diameter piece of aluminum stock to an outer diameter of 1.5756” (40 mm) using a CNC lathe in the Washburn shops. This machine also cut it to its final length of 3.9232”. The part was then taken to Higgins shops where an indexing radial vice was used to drill 1/2” diameter holes, 1/2” deep. The holes were equally spaced around the center axis of the part 120 degrees from one another. These holes were then tapped using a 1/2-13 pitch hand tap. A round keyway was milled down the length of the axle, before the futility of attempting to cut into the clutches was discovered. The diameter of the axle was brought down again using a hand lathe after the discovery that aluminum is soft enough to shear when being press fit into a steel housing. After bringing the diameter down, the parts press fit nicely, and the keyway was reserved for epoxy, should any slipping occur due to the decrease in diameter. The final process was to drill a centered 1” diameter hole 1/4” deep into the spoke side face of the axle, to prevent the axle from hitting the quick release button for the pin holding the wheelchair wheel to the frame.

Axle Spokes

The spokes for the axle were manufactured from three pieces of 1/2” outer diameter, 0.384” inner diameter aluminum tube. This was designed to telescope with three pieces of 0.375” outer diameter, 0.245” inner diameter aluminum tube. All of the pieces arrived in random lengths between 10” and 12”. The outer tubes were cut to a length of 7.75” and had 0.75” of one end threaded to a 1/2-13 pitch. These pieces were then screwed into the holes on the axle (Figure 87).

Figure 87: Axle-Spoke Attachment

Into these tubes were fed 1.5" long compression springs, with an outer diameter of 0.343". They provide 22.54 pounds of force for every inch they are compressed. These are used to hold the drive system centered. The inner tubes were cut to 7", and the inside of one side of each was threaded with a ¼- 20 pitch tap. The tapped ends then had a #0 conduit fastener attached to the end, the insides of which had gripping foam pads mounted with adhesive. The fastener/tube assembly is then slipped into the larger tubes, on top of the springs, the result composing the method to attach the drive to the push rim of the wheelchair. Figure 88 shows the attachment of the spokes to the handrim.

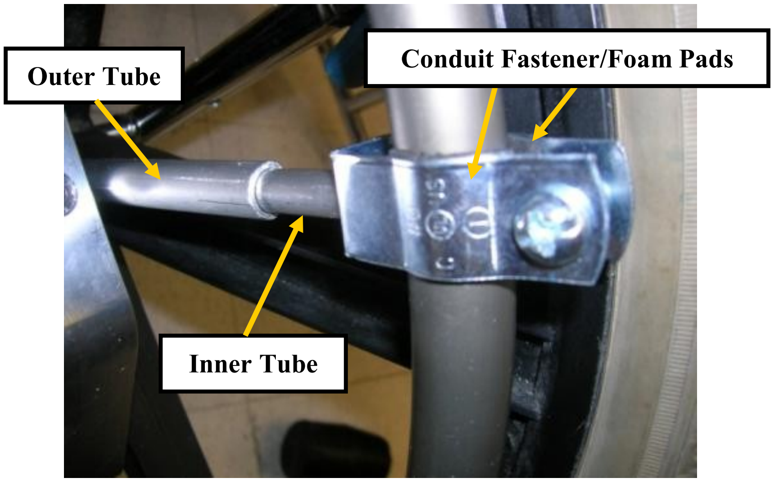


Figure 88: Spoke-Handrim Attachment

Backplate Shaft

The backplate shaft (Appendix D, Drawing 5) acts as the axle for the shifter mechanism. It was turned down from a piece of 1" aluminum bar stock using a CNC lathe in Washburn shops. Its final diameter was 0.7864”, with a final length of 2.47”. A 0.368” diameter hole, centered on one face, was drilled with the lathe. This hole was then tapped using a 7/16-14 pitch tap.

Shifter Assembly

The shifter assembly (Figure 89; Appendix D, Drawings 11 & 12) is made from three parts: two shifting arms and one shifting lever. All three parts were milled from aluminum in the Haas VF-4 CNC milling machine in Washburn Shops. They share the same axle (backplate shaft) and all have identical 0.9055” holes which line up to accept the shaft. Small holes for 1/8” dowel pins were drilled in opposite faces of the shifting arms and through the shifting lever. The pins were pressed into the holes to hold all three parts together in the proper angular alignment. The assembled parts were then welded together for added strength, and plastic bushings were pressed inside their axle holes.

Figure 89: Shifting Mechanism

Coverplate & Backplate

The housing for the propulsion system is comprised of the coverplate (Figure 90; Appendix D, Drawing 10) and backplate (Figure 91; Appendix D, Drawing 9), both of which were milled out of aluminum using the Haas VF-4 CNC milling machine in Washburn Shops. The NC codes for these parts were generated using the SurfCAM software package. Both parts have a web-like pattern on their largest interior faces. This was done to minimize the amount of material in the part (and thus its weight) while not compromising structural integrity. In addition, both plates have four holes on their outer edges which, when the plates are assembled, will line up to accept the 1/4-20 socket head cap screws that hold the plates together. The four backplate holes have a 1/4-20 tapped thread, while the counter-bored coverplate holes are slightly larger and not threaded to allow a close but free fit with the screws. The backplate has a hole drilled on its back face to accept a 7/16-14 countersunk screw, which threads into the threaded axial hole on the backplate shaft. This screw holds the shaft onto the backplate. Three 7/16-14 holes were drilled and tapped into the top face of the backplate to accept threaded inserts. The inserts have a 7/16-14 external thread and a 5/16-18 internal thread, and accept three 5/16-18 socket-head cap screws which hold the housing attachment piece onto the backplate. During operation of the propulsion mechanism, there is a considerable amount of force pulling these three screws out of the holes, thus threaded inserts were used to help keep the screws from stripping out of the backplate. Both the coverplate and backplate have a 1.7323” diameter hole horizontally centered on their large face which accepts the propulsion axle. On the backplate, the hole goes through all of the material. On the coverplate, the hole is actually a pocket so that the axle is held in place.

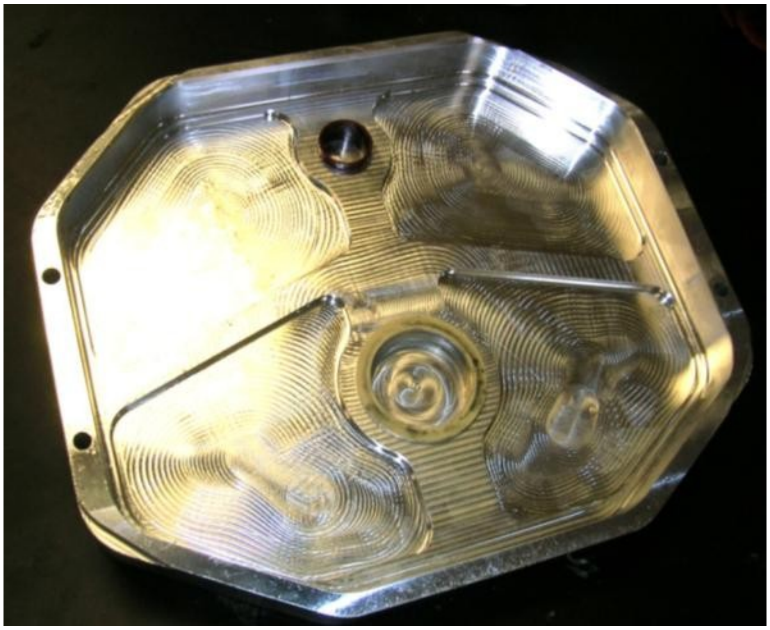


Figure 90: Coverplate

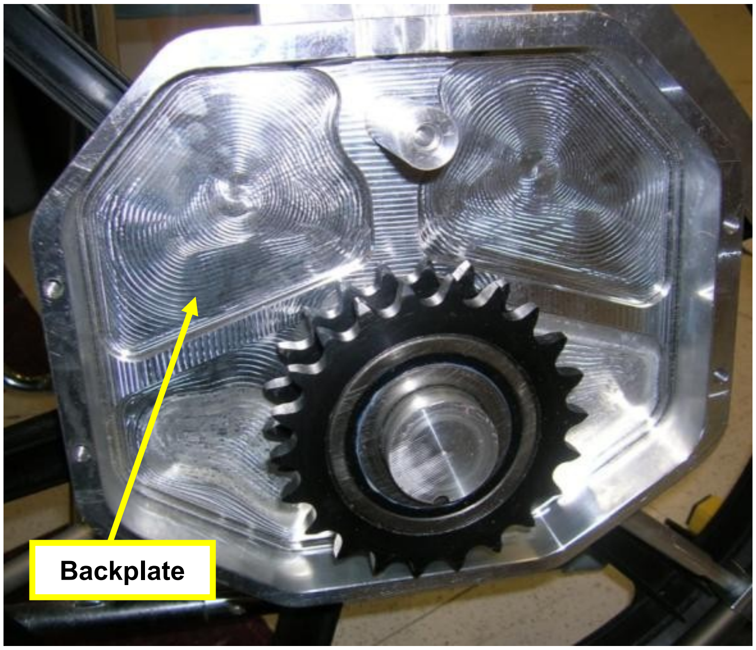


Figure 91: Backplate

Housing Attachment Piece

The housing attachment piece (Figure 92; Appendix D, Drawing 7) is attached to the top of the backplate with three 5/16-18 socket-head cap screws.

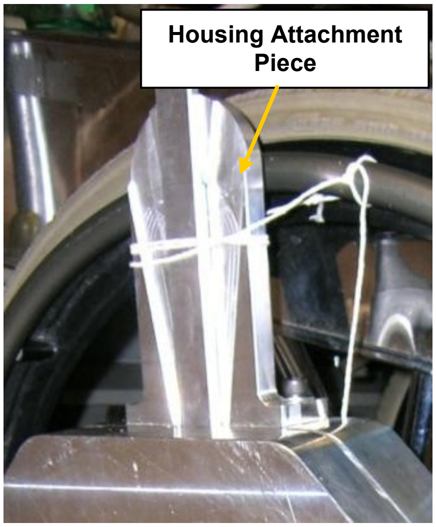


Figure 92: Housing Attachment Piece, Groove Side

Figure 93: Housing Attachment Piece, Shaft Side

As with the cover- and backplates, the housing attachment piece was machined out of aluminum on the Haas VF-4 CNC milling machine in Washburn Shops, using NC code generated with the SurfCAM software package. There are three grooves on one face of the piece (Figure 92), which hold the shifter in place when the user selects between forward, reverse, and neutral. On the opposite face (Figure 93) is a small protruding 9/16" diameter shaft which acts as a pin for the coupler link, allowing the coupler to pivot while attached to the housing attachment piece.

Attach Plate

The attach plate (Figure 94; Appendix D, Drawing 3), which holds the tube into which the lever arm is inserted, attaches to the wheelchair frame with two conduit fasteners. The plate itself was machined out of aluminum on the Haas VF-4 CNC milling machine in Washburn Shops, using a SurfCAM-generated CAM program. The plate has two size 3-48 holes drilled and tapped into one of its sides to accept two screws which hold the cable plate. Centered on the top face of the attach plate, a 9/16-18 hole was drilled and tapped with a 1.125-inch-diameter counterbore. This hole and counterbore accept the attach plate shaft, which holds the lever arm. In addition, there is a 1/4-20 tapped hole on either side of the center hole, into which the screws holding the conduit fasteners are inserted.

Attach Plate Shaft (Drawing 2)

The attach plate shaft (Figure 94) was manufactured using the manual lathe in Higgins shops. A 1.25" diameter by 2" length brass stock piece was turned down and threaded to a 9/16-

18 thread on one side so that it could screw into the attach plate. The inside of the stock piece was hollowed out using a 1” drill in order to accommodate the bushings and connecting pipe that it would house. Originally this piece was supposed to be made out of aluminum; however, the manufacturing time was cut down by finding a brass stock piece which already had the desired outside diameter.

Attach Plate Cable Plate

The cable plate (Figure 94; Appendix D, Drawing 1) has two holes to guide the steering cables from the caster pulley up into the hollow lever. A piece of 0.10”-thick aluminum of approximately the desired size was found and used instead of machining a piece of exactly the right size. Two ¼” holes were drilled to accommodate the cables and cable sheathes from the steering pulley, and two more 0.104” diameter holes were drilled to accommodate size 3-48 screws to attach the cable plate to the attach plate.

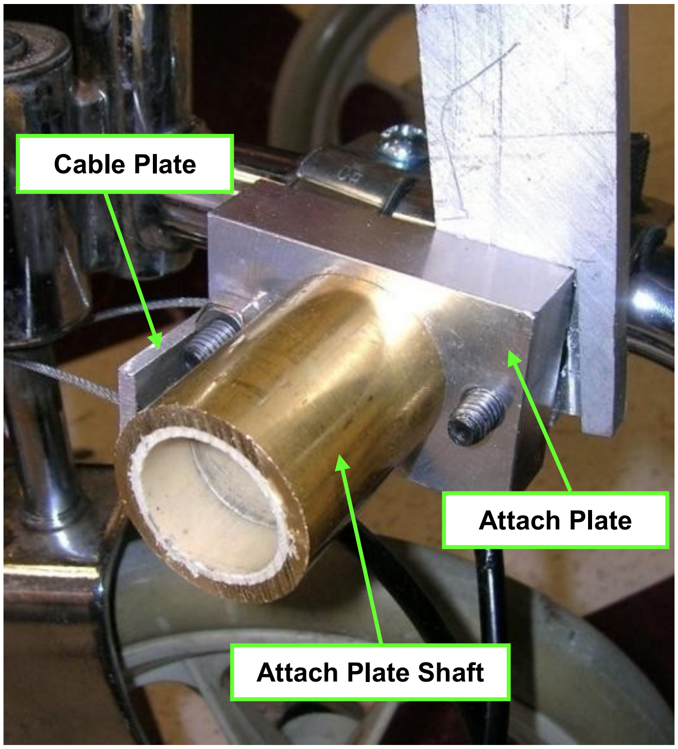


Figure 94: Attach Plate Assembly

All three of these attach plate assembly components were originally intended to be manufactured as one piece; however, due to machining constraints they had to be redesigned as three separate pieces.

Caliper Bracket

Each caliper bracket consisted of two mirror-image pieces of sheet metal bent into a semi-circle around the diameter of the wheelchair frame. Flat tabs were left on either side of the bend, into which holes were punched for both the caliper's mounting screws and screws used to tighten the two pieces together. Figure 95 shows the final bracket.

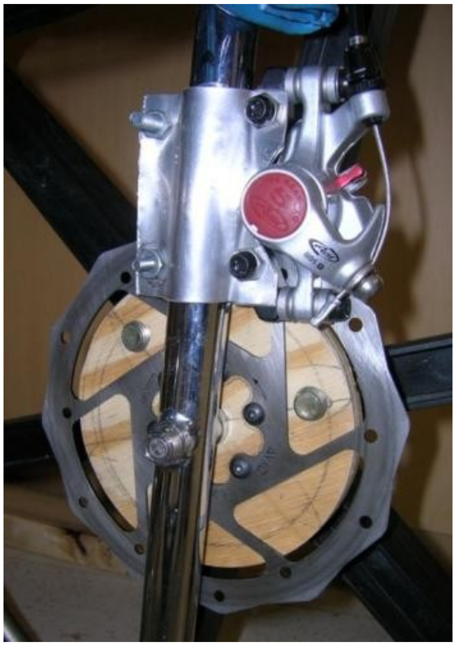


Figure 95: Caliper Bracket

An important part of the manufacturing and installation process was the routing of the brake cables. The steering cables were run from the caster up through the lever to the handle, and as such the routing was very simple. The brake cable required more careful routing so that the transmission of tension would not be interrupted, the chair could still fold, and the cable was carefully stowed out of the way to minimize the possibility of tangles and snags. The calipers were mounted such that the cable ran out the top of the caliper, toward the wheelchair seat. The cable from the left caliper was brought over to the frame on the right side of the wheelchair, where it and the right caliper's cable were loosely fastened to the wheelchair frame with a zip tie. The two cables were then run down the forward-most cross piece underneath the wheelchair and fastened to it with a zip tie. About halfway down the cross piece, the two cables run into the cable doubler, which has only a single cable protruding from the other end. This single cable was run down the rest of the cross piece and along the wheelchair frame toward the lever attachment point, secured in several places to the frame by zip ties. The cable was run up the hollow lever and attached to the brake lever at the handle. Figure 96 shows the cable routing, with yellow arrows indicating the path of the left caliper's cable, the red arrows indicating the right caliper cable's path, and orange arrows indicating the single cable.

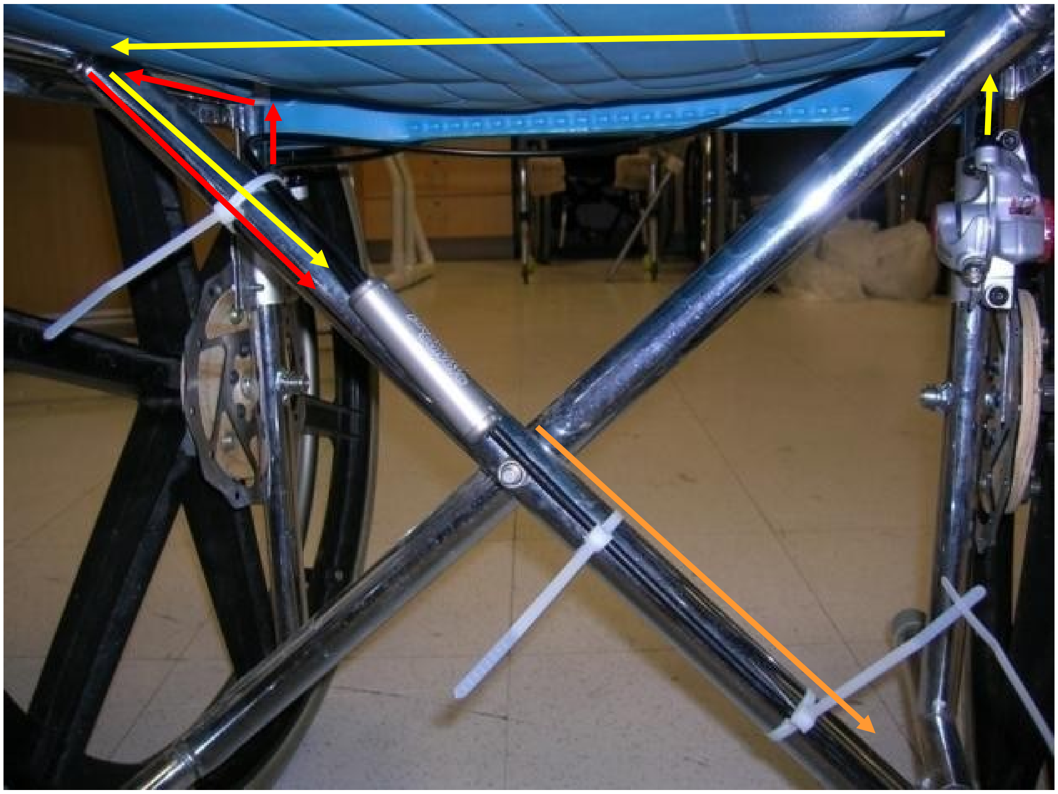


Figure 96: Cable Routing (Front View of Chair)

10.3 Assembly Process/Procedures

10.3.1 Pre-Assembled Components

The propulsion assembly will come as one large piece, with the clutches, shifter, coupler, etc. already in place (Figure 97). The spokes will be attached to the accessory axle and will only require that the user press the conduit fasteners into place around the pushrim and tighten the screws to hold them in place.

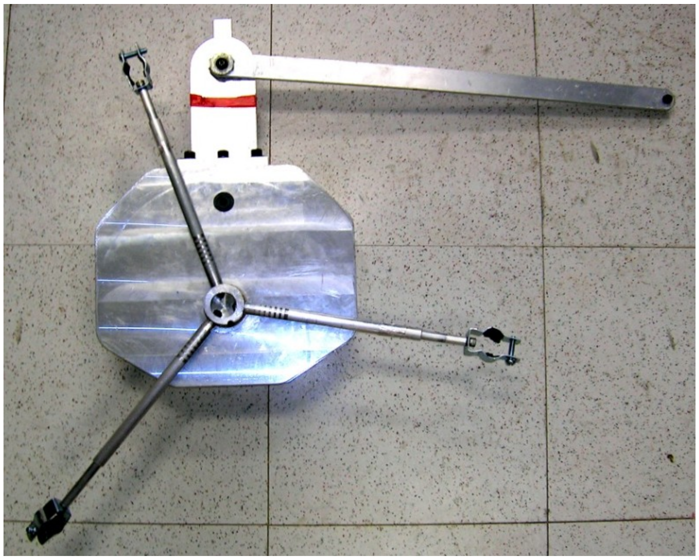


Figure 97: Propulsion Pre-Assembled Components

The handle, pulleys, lever, cable sheathes, and attach plate will also be pre-assembled. The brake cables, calipers, and cable doubler will also be attached to this assembly.

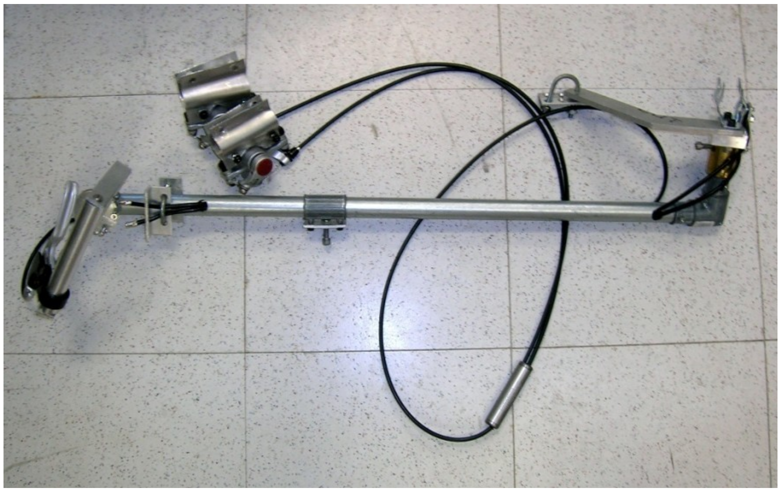


Figure 98: Lever & Brake Pre-Assembled Components

Both frame attachment pieces will already be fastened and tightened onto the attach plate. The attach plate pipe will be screwed onto the attach plate and the bushings inserted. The lever elbow will be pre-attached to the connecting shaft, which will come inserted in the attach pipe with the stop screw in place. The lever will be pre-inserted into the elbow with the handle steering assembly already in place. The brake lever will also be secured in place at the steering handle. Finally, the brake cables will be pre-attached to the handle, doubler, and calipers, such that they need only to be tightened and cut to length after the calipers are installed on the wheelchair frame.

This pre-assembly will allow easy installation for the consumer, requiring only that they attach the propulsion assembly to the wheel and the lever assembly onto the wheelchair frame, and then tighten the conduit fasteners using a screwdriver. The rotors must also be mounted onto the axles, which requires removing the wheels, and the calipers must be attached to the wheelchair frame. The full assembly/installation procedure is described below.

10.3.2 Assembly/Installation Instructions

1. Install brakes:
    a. Remove both main wheels of the wheelchair. Press rotor assembly onto axle on interior side of the wheel. Press hex-head bolts into slots on wheel.
    b. Replace wheels on chair.
    c. Slide caliper attachment pieces over wheelchair frame (vertical piece where wheels/axles attach), ensuring that caliper is oriented such that it is actuated by upward force from the cable.
    d. Slide caliper into place such that rotor spins freely between the brake pads.
    e. Tighten bolts on caliper attachment piece.
2. Attach propulsion housing.
    a. Tighten first conduit fastener onto pushrim.
    b. Compress spokes so that the remaining two conduit fasteners can be clipped onto pushrim.
    c. Tighten conduit fastener screws.
3. Attach caster steering pulley
    a. Remove drive-side caster.

   b. Slide caster steering pulley down threaded caster axle, ensuring that screw hole is positioned toward the back of the wheelchair.
   c. Press caster pulley down so that tabs on bottom surface hug caster yoke.
   d. Replace caster.
4. Install lever arm
   a. Attach lever assembly to wheelchair frame, just behind drive-side caster.
   b. Connect coupler link from housing to sliding attachment on lever.
5. Cables
   a. Wrap cable around caster steering pulley such that the two free ends can be run through the cable plate at the base of the lever and up through the lever arm. Secure with set screw. (Figure 57 shows steering cable diagram.)
   b. Put housing on both free ends of cable. Run cable up through lever arm to steering pulley at handle.
   c. Secure housing at lever-frame attachment plate and just below handle.
   d. Straighten caster and handle. Tension the cables and secure in place with screws on steering pulley.
   e. Cut excess cable.
   f. Tension the brake cables. Tighten cable clamps on calipers, cut cables to length, and press crimps onto free ends to prevent the cable from slipping out of place.

10.4 Ease of Installation

Overall, the initial assembly and installation processes went smoothly. The team conducted a time trial for installing the entire accessory in which two of the team members installed the accessory, as it would be provided to the consumer, onto the wheelchair a second time. This entire timed installation process took 51 minutes, including time to address issues with frayed cables. The team members installing the accessory were very familiar with the system, so installation by individuals who were not familiar with it would likely take longer. All of the parts will be provided, however, so the increase is not likely to be extensive. Based on the team's experiences, it was determined that two able-bodied individuals would be needed to install the accessory, mainly due to the cable tensioning that must be done. Though the initial installation of the accessory went relatively smoothly, some issues did arise.

First and foremost, many of the fasteners used on the subsystems were in hard-to-reach places once the subsystems were mounted on the chair. Some of this positioning is unavoidable, but where possible, greater attention could be paid to how the entire assembly fits together and fasteners could be moved to more accessible locations. A wide variety of fastener types and sizes were used across the accessory, requiring a variety of tools. Standardization of fasteners would greatly reduce the number and types of tools required for installation. These tools could then potentially be included with the accessory to maximize convenience. There were also many metal-on-metal fixturing interfaces that experienced undesired slipping during installation. The most significant amount of slipping was found at the frame attach pieces and wheelchair frame interface. The frame attach pieces hugged the wheelchair frame and were supposed to hold the attach plate and lever in place. However, the weight of the hand-lever mechanism was too great for the friction between the frame attach pieces and the wheelchair frame. Therefore, the frame attach pieces began to slip and the whole hand-lever mechanism began to rotate about the attach point. This problem was solved by using an additional bracket. The team also used pieces of rubber to increase friction and grip at the interfaces. In the future, the rubber could be included as a permanent design feature on the fixturing hardware. Finally, a large portion of the installation period was spent trying to achieve and then maintain proper tension in the cables used in the steering and brake systems.

There were several other difficulties encountered during installation such as installation of the brake rotors and calipers. The attachment for both of these parts was not extensively thought out and designed therefore the placement of both parts was not ideal. It became extremely difficult to properly align the rotors and the calipers and therefore undesired friction occurred even when the brakes were not actuated.

11. Testing of Final Design

11.1 Testing Procedures

The following section outlines the various types and procedures for the testing of the final prototype. Procedures have been directly quoted from the ANSI/RESNA Wheelchair Standards where appropriate, with modifications noted.

11.1.1 Stability Testing

Static Stability with Unlocked Brakes in the Aft Direction (ANSI/RESNA WC/01 1990)

"Position the wheelchair on a test plane and increase the slope gradually and at a uniform rate until the uphill wheels just lift away from the test plane. Determine and record the slope (within ±1 degree) by gently pulling a piece of paper at right angles from under the uphill wheels. During the test, prevent the wheelchair from rolling by placing a 100mm +/- 3mm high rectangular bar against the downhill wheels."

This test was carried out using the 08-09 MQP chair, the 05-06 MQP chair, and the Meyra Chair in order to determine if the design of the 08-09 chair had improved with respect to the 05-06 MQP and to see how it compared to a commercially-available product. When possible, the hand lever was secured in the neutral position or in the orientation which prevents the chair from rolling backward. Figure 99 shows the testing setup.

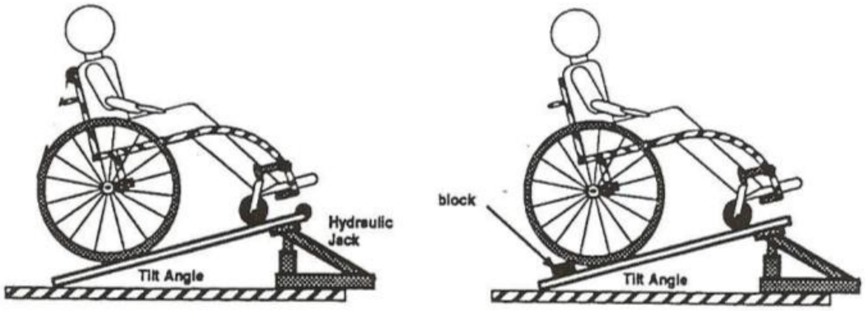


Figure 99: Static Stability, Unlocked Brakes (Cooper, Stewart, and VanSickle)

Static Stability with Locked Brakes in the Transverse Direction (ANSI/RESNA WC/01 1990)

"Position the wheelchair on a test plane and increase the slope gradually and at uniform rate until the uphill wheels just lift away from the test plane. Determine and record the slope (within ±1 degree) by gently pulling a piece of paper at right angles from under the uphill wheels. Perform the test with the wheelchair perpendicular to the slope. Ensure that the caster wheels are free to swivel. If the wheelchair slides (in any way) before the uphill wheels lift away, note the slope within 1 degree at which this occurs...Repeat the procedure...with a 40mm +/- 3mm high rectangular bar against the downhill wheels in order to prevent sliding."

Since the single-arm propulsion accessory is mounted on one side of the wheelchair, making that side heavier than the other, this test was repeated twice, once with each of the two sides going uphill. This test was carried out using the 08-09 MQP chair, the 05-06 MQP chair, and the Meyra Chair in order to determine if the design of the 08-09 chair had improved with respect to the 05-06 MQP and to see how it compared to a commercially available product.

Parking Brake Test (ANSI/RESNA WC/03 1990)

"With [the] brakes adjusted and applied fully, the wheelchair shall be positioned on the test plane such that, when the test plane is inclined, the wheelchair is facing down the plane with its casters in the trailing position. Increase the angle of the plane until one of the following occurs:

a) The wheelchair begins to roll down the plane (brakes failing to restrain the wheelchair);
b) The wheelchair begins to slide down the plane (insufficient friction between the wheelchair tires and the test plane);
c) The wheelchair becomes unstable (one or more of its wheels lift off the plane).

In each of these tests note...the maximum slope, within 1 degree, achieved with the test plane and record all observations." The test will be repeated with the wheelchair facing up the plane.

This test was carried out using the 08-09 MQP chair, the 05-06 MQP chair, and the Meyra Chair in order to determine if the design of the 08-09 chair has improved with respect to the 05-06 MQP and to see how it compares to a commercially-available product.

11.1.2 Dimensional Testing

Maximum Overall Dimensions (ANSI/RESNA WC/93 1991)

The overall length, width, and height of the wheelchair were measured in this procedure. The overall length (l) is defined as" the horizontal distance between the forward-most and rear-most part of the wheelchair" with the footrests in the "down" (i.e. ready to be used) position. The overall width (b) is defined as "the horizontal distance between the outermost side parts of the wheelchair when the chair is fully unfolded and the seat fully stretched out." The overall height

(h) is defined as “the vertical distance from the floor to the uppermost point on the wheelchair.” Figure 100 shows these dimensions graphically.

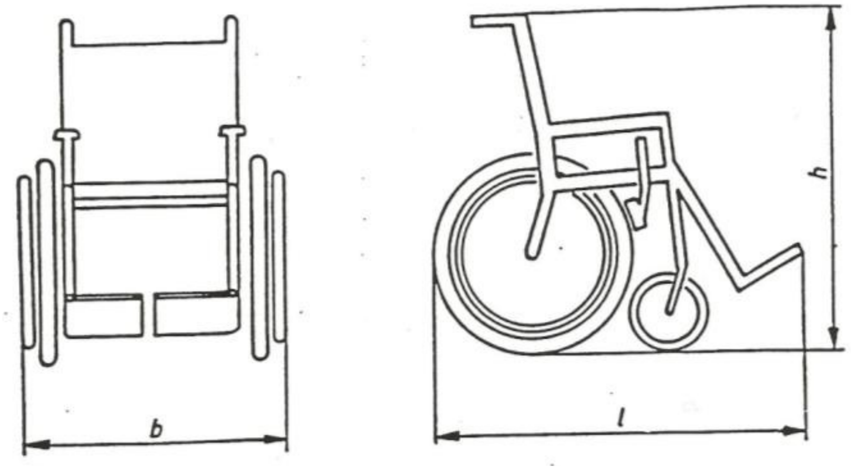


Figure 100: Wheelchair Dimensions (ANSI/RESNA WC/93 1991)

The wheelchair conforms to the RESNA WC/05 national standards if it does not exceed the following maximum values:

Overall length, l: 51” (1300mm)
Overall width, b: 27.5” (700mm)
Overall height, h: 43” (1090mm)

Folded Wheelchair Width (ANSI/RESNA WC/05 1990)

The minimum folded width (W) of the wheelchair was measured. The minimum folded width is defined as the overall width of the wheelchair between its outermost parts when it is fully folded. According to the design specifications the design must not impede the collapsibility of the wheelchair because the preservation of this feature is important in maintaining portability of the chair. The addition of the single arm-drive accessory and disc brakes will increase the width of the folded chair.

Mass of Wheelchair (ANSI/RESNA WC/05 1990)

The total mass (m) of the wheelchair and its accessories were determined to the nearest kilogram. The mass of the wheelchair without the additional single-arm drive accessory was also determined. The two masses were compared and the mass of the single-arm drive accessory was also determined. These values were then converted to English units (pounds) for the sake of unit continuity. According to the design specifications the accessory cannot increase the weight of the chair by more than eight pounds or approximately 20% the weight of the chair.

Minimum Turning Radius (ANSI/RESNA WC/05 1990)

The minimum turning radius was determined by measuring the radius of the smallest cylinder inside which the wheelchair can be turned 360 degrees (Figure 101).

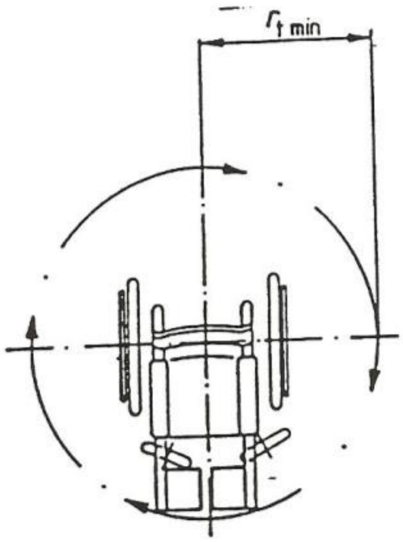


Figure 101: Minimum Turning Radius (ANSI/RESNA WC/05 1990)

Turnaround Width Between Limiting Walls, B (ANSI/RESNA WC/05 1990)

“Measure the minimum width of a “corridor” in which the wheelchair can be turned through 180 degrees by using only one backing operation (Figure 102). Construct the corridor so that its width is variable and determine the minimum turnaround width.”

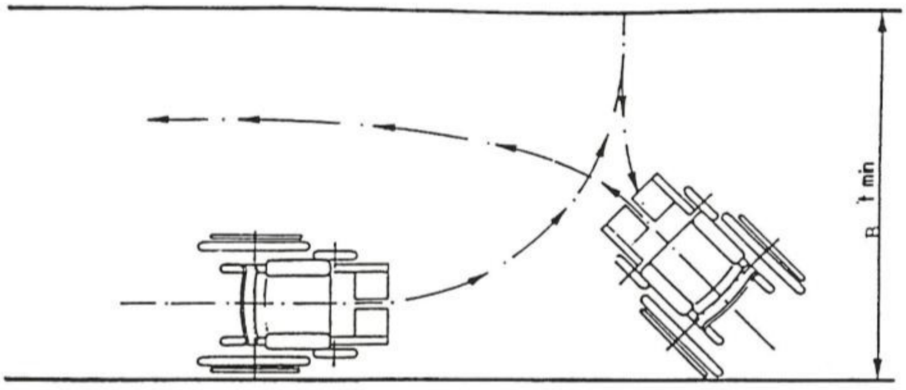


Figure 102: Turnaround Width Between Limiting Walls (ANSI/RESNA WC/05 1990)

According to specifications, the wheelchair should be able to do a turnaround with one backing operation in a corridor which is no more than 5ft wide. Compliance with this specification was tested. The 08-09 Wheelchair MQP chair was also compared in this test to the Meyra and to the 05-06 Wheelchair MQP to see if there was a significant improvement in turning. The smallest corridor width in which this operation can be done was measured for all three designs.

11.1.3 Operating Force Requirements

Measuring the Braking Operative Force (ANSI/RESNA WC/03 1990)

With the wheelchair on a flat surface, the force required to actuate and maintain the braking effect was measured by attaching a force gauge at the center of the operating handle, normal to the lever, and pulling until the brakes were fully engaged (i.e. the wheels stopped turning). According to the research done on individuals with disabilities and the design specifications the brake lever should not require more than 35 pounds of grip force to actuate. This value was determined by approximating the maximum grip force of the 5th percentile of elderly women (Panero, 1979; see Appendix B), who are generally not as strong as elderly men. Elderly people are typically not as strong as younger individuals, and so this limit would accommodate most adult groups.

Measuring the Propulsion Operative Force

With the wheelchair on a flat surface, the user input force at the handle required to propel the wheelchair for one stroke was measured by attaching a force gage to the center of the handle and pulling it until the wheelchair began to move. This test was repeated for forward propulsion (forward stroke) and backward propulsion (backward stroke) as well as for turning right and left. The test was conducted with users who ranged in weight from 150-200 pounds.

According to the team's research, the maximum force an able-bodied adult is capable of applying to a lever using forward-aft motion while seated is 45 pounds (Woodson , 1981). Individuals using a self-propelled wheelchair, though they may have some strength limitations, must be capable of exerting some force if they are to propel themselves in the chair. It was determined that 40% of the maximum force, or 18lbs, was reasonable and acceptable.

11.1.4 Subject Testing

Able-Bodied Student Testing and Rating

In order to determine the effectiveness of the single-arm propulsion accessory's user interface and compare it to other commercially available single-arm propulsion accessories, the team had eight able-bodied individuals test and rate each design. Each individual tested and rated the Meyra, Quickie, 05-06 Wheelchair MQP, and 08-09 wheelchair MQP design on a scale from 1 to 5 over 14 different categories; 1 being poor and 5 being excellent. The fourteen categories covered forward/backward propulsion, turning, braking, force required, and device usage comfort. The subjects used for this testing were different from the subjects who tested the chairs in the previous preliminary testing, so that they were completely unbiased. Additionally, the subjects tested the chairs in random order. This test was used to determine how the 08-09 MQP chair ranked against the Meyra chair and 05-06 MQP chair, and to see if there has actually been some improvement from the 05-06 MQP.

Each subject was asked to operate each of the three wheelchairs over a determined path. The users started in the Rehab Lab in Higgins Labs 129 and turned left once they exited through the lab door. They then turned right by the bathrooms and immediately left onto the main hall. At the end of the hall they performed a three-point turn and then drove down the hall in the other direction. They continued down the hall and brought the wheelchair to full speed, applied the brakes to stop the wheelchair completely, and then took a right turn toward the ME office and the elevator, and then another right turn to end back at the Rehab Lab.

The test subjects were also asked to provide additional comments on the experience and filled out the form in Table 9:

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	**Quickie (dual pushrim)**	**08-09 Wheelchair MQP**
Forward Propulsion			
Backward Propulsion			
Turning Right			
Turning Left			
Forward to Backward Shifting			
3-point Turning			
Braking			
Parking Brake			
Force Required for Operation			
Device Usage Comfort			
Intuitiveness of Use			
Overall Propulsion Mechanism			
Overall Turning Mechanism			
Overall Braking Mechanism			
Totals:			
Additional Comments:			

Table 9: Test Subject Rating Form

11.1.5 Performance Test Course

This section describes the test course which was intended as a more in-depth evaluation of the chair to be carried out after initial testing in Higgins Labs. By the time that testing had been completed, however, the chair was showing signs of structural weakness from extensive use. As a result, the team decided to carry out the test, but with team members rather than outside test subjects so as to minimize the risk to others.

The more extensive performance course includes different floor surfaces, slopes, elevators, and more crowded spaces than the first round of tests. It ends with the subject folding the wheelchair and trying to store it in the trunk of a mid-size sedan. As the tester goes through the course, members of the MQP make observations and take notes about the operation of the accessory in the different conditions. The subjects would also have been asked to fill out the previous evaluation form for the wheelchair MQP and to comment on their experiences.

The course begins in the Rehab Lab (Higgins Labs 129) where the subject attempts to exit through the door and turn right toward the elevator. The subject then boards the elevator and rides it down to the bottom floor, exiting the building through the glass doors facing the Bartlett Center. The subject then goes toward the Campus Center and attempts to enter through the main glass doors. Once inside the Campus Center, the subject turns left before the main desk and moves toward the elevator, boarding and riding it to the bottom floor. On the bottom floor of the Campus Center, the subject attempts to maneuver through the food court and back to the elevator, riding it up to the main floor. The subject then exits the building and drives toward the ramp at the Fitness Center. The subject must go down the ramp, brake the wheelchair halfway down and hold the brake for five seconds, make a three-point turn at the bottom of the ramp, and then attempt to go back up the ramp. Finally, the subject re-enters the Higgins building and boards the elevator, riding up to the Rehab Lab where the test ends.

11.1.6 Additional Design Parameters

Tools Required for Installation

In the design specifications it was stated that the installation of the accessory would require only a Philips head screwdriver, flathead screwdriver, adjustable wrench, pliers, socket wrench, and hammer. This was decided in order to make the accessory as user-friendly and easy-to-install as possible, only requiring basic tools that most individuals have in their home.

This parameter can be tested by installing and uninstalling the accessory using only the aforementioned tools and recording the time it takes to do both. Installation instructions would be given to a subject who will install the accessory with no assistance from the team, aside from answering basic questions. This test was not conducted in precisely the aforementioned manner, as the design relied heavily on alternative types of fasteners (namely, socket-head screws). Instead, the accessory was assembled using as few tools as possible, and these tools were then noted.

Functionality Testing

In order to test whether the final product was successfully designed to do what it was intended, the team cross-checked the accessory with the original design specifications. The specifications range over four different categories; accessory installation, braking and propulsion, steering, and safety. Some of these tests cannot be numerically measured but simply tested by inspection; these items were evaluated using the checklist shown in Table 10. If the item did not comply with the specification then it was either fixed or a comment was made explaining why it could not be fixed. For further information on any of these parameters please refer to the design specifications in Chapter 4.

Design Parameter	Y/N	Comments
Only one arm for steering		
Accessory attachable to either side of wheelchair		
Propulsion system must move the wheelchair both in the forward and backward directions		
Brakes must be able to slow the wheelchair in addition to bringing it to a complete stop		
There will be a means of adjusting the mechanical advantage		
Actuating arm of the propulsion system must be able to be disengaged and locked into a secure stowed position while an attendant is pushing the chair		
Final assembly must have some means of locking the wheels to prevent rotation		
The user must be able to steer the chair at all times, unless an attendant is pushing the chair		
Accessory cannot interfere with an attendant’s ability to push/control the chair		
All mechanisms and wires must be encased or stored such that they do not interfere with use of the chair and its moving parts		
Moving parts and pinch points must be located and/or guarded such that they pose minimal risk of injury to users, attendants, and others in the area		

Table 10: Design Parameter Inspection Checklist

11.2 Testing Results

11.2.1 Stability Testing

For each of the three following stability tests, the wheelchairs were placed on a plywood ramp. The ramp was raised and lowered using a hydraulic piston.

Static Stability with Unlocked Brakes (ANSI/RESNA WC/01 1990)

Table 11 shows the results obtained from the static stability testing of the wheelchair, with its brakes unlocked. The 08-09 chair was more stable than both the 05-06 MQP chair and the Meyra chair in each of the five trials. This test was conducted with no passenger weight in the chair.

Wheelchair	**Minimum Angle of Instability**					**Mean**	**Std. Deviation**
08-09 MQP	44°	43°	44°	45°	45°	44.2°	0.8°
05-06 MQP	39°	41°	40°	38°	39°	39.4°	1.1°
Meyra	40°	42°	42°	42°	41°	41.4°	0.9°

Table 11: Static Stability Testing, Unlocked Brakes

Static Stability with Locked Brakes in the Transverse Direction (ANSI/RESNA WC/01 1990)

Table 12 shows the results of the static stability tests conducted with the brakes locked in the transverse direction, i.e. with the side of the wheelchair facing “downhill” on the testing ramp. For these tests, the side of the wheelchair with the accessory was the “downhill” side. Again, no additional weight was used. These tests showed that the 08-09 chair, while more stable than the 05-06 chair, tipped at a considerably smaller incline than the Meyra chair.

Wheelchair	**Minimum Angle of Instability**					**Mean**	**Std. Deviation**
08-09 MQP	21°	21°	20°	21°	21°	20.8°	0.4°
05-06 MQP	17°	18°	18°	18°	19°	18°	0.7°
Meyra	28°	29°	28°	27°	28°	28°	0.7°

Table 12: Static Stability Testing, Brakes Locked in Transverse Direction

Parking Brake Test (ANSI/RESNA WC/03 1990)

Table 13 shows the results of the parking brake testing. In these tests, 08-09 chair became unstable at a smaller angle than both the Meyra and the 05-06 wheelchairs.

Wheelchair	Minimum Angle of Instability					Mean	Std. Deviation
08-09 MQP	9°	10°	10°	9°	10°	9.6°	0.5°
05-06 MQP	13°	12°	12°	11°	12°	12°	0.7°
Meyra	11°	11°	11°	12°	11°	11.2°	0.4°

Table 13: Parking Brake Test

11.2.2 Dimensional Testing

Maximum Overall Dimensions (ANSI/RESNA WC/93 1991), Folded Wheelchair Width (ANSI/RESNA WC/05 1990), Mass of Wheelchair (ANSI/RESNA WC/05 1990)

The maximum dimensions and weight of the 08-09 wheelchair were measured and compared to those of the 05-06 and Meyra chairs. The results are shown in Table 14. Though some of the variation in size may have been due to the base wheelchair used in each design, the 08-09 wheelchair was shorter in length and a few inches taller in height than the other two models. It was only slightly wider than the Meyra, but still ½” narrower than the 05-06 MQP when unfolded. When the chairs were folded, the Meyra was the narrowest by only ½”. The 08-09 MQP was the next narrowest and still substantially narrower than the 05-06 MQP. Though the 08-09 MQP was eight pounds heavier than the 05-06 MQP chair, it was still two pounds lighter than the Meyra.

Dimensions	08-09 MQP	05-06 MQP	Meyra
Length	32”	42.5”	37.5”
Width	27.5"	28”	27”
Height	38”	36”	35.5”
Folded Width	15.5”	20.5”	15”
Total Weight	57 lbs	49 lbs	59 lbs

Table 14: Wheelchair Dimensions

Minimum Turning Radius (ANSI/RESNA WC/05 1990)
Turnaround Width Between Limiting Walls, B (ANSI/RESNA WC/05 1990)

The minimum turning radius and turnaround width between limiting walls was measured in the carpeted hallway of Higgins Labs in front of the Rehab Lab (Higgins Labs 129). The results of these tests are summarized in Table 15. The 08-09 chair had the median minimum turning radius in both directions out of all three wheelchairs, and the highest minimum turnaround width in both directions. The minimum turnaround width for the 08-09 chair while turning left exceeds the limit of 60” set by this ANSI/RESNA standard.

	08-09 MQP		05-06 MQP		Meyra	
	Right	**Left**	**Right**	**Left**	**Right**	**Left**
Minimum Turning Radius	29”	36”	30”	30.5”	28”	45.5”
Minimum Turnaround Width	58”	67”	56”	54”	51”	59”

Table 15: Turning Performance Tests

11.2.3 Operating Force Requirements

Measuring the Braking Operative Force (ANSI/RESNA WC/03 1990)

Measuring the Propulsion Operative Force

Operating force measurements (propulsion, braking, turning) were taken with both a 155 lb and 195 lb user in the chair. The results of these tests are shown in Table 16. In all cases, the 08-09 chair had the highest force requirement for turning. For the two MQP wheelchairs, the braking force did not change with user weight. More force was required to stop the Meyra chair with a heavier user, due to the Meyra’s unique braking mechanism. In general, greater force was required to propel and steer the wheelchairs with a heavier user.

	08-09 MQP		05-06 MQP		Meyra	
155 lb user	**Floor**	**Carpet**	**Floor**	**Carpet**	**Floor**	**Carpet**
Propulsive Force	4 lbs	5 lbs	4 lbs	4.5 lbs	3.8 lbs	6 lbs
Braking Force	16 lbs	16 lbs	20 lbs	20 lbs	9.5 lbs	5.75 lbs
Turning Force (Right)	31 lbs	22 lbs	5.5 lbs	11 lbs	4.5 lbs	8.5 lbs
Turning Force (Left)	19 lbs	26 lbs	5.6 lbs	8 lbs	5 lbs	9 lbs
195 lb user						
Propulsive Force	5 lbs	5.8 lbs	6 lbs	8.5 lbs	4.1 lbs	6 lbs
Braking Force	16 lbs	16 lbs	20 lbs	20 lbs	12 lbs	10.2 lbs
Turning Force (Right)	27 lbs	32 lbs	5.75 lbs	9 lbs	9 lbs	15 lbs
Turning Force (Left)	25 lbs	32 lbs	6.5 lbs	11 lbs	12 lbs	17 lbs

Table 16: Operating Force Testing

11.2.4 Subject Testing

Able-Bodied Student Testing and Rating

Eight students were asked to drive each of the three lever-operated wheelchairs around the first floor of Higgins Labs. The team chose to compare only the lever-operated models in this round of testing in order to focus on the differences between lever-operated chairs, as opposed to one-arm propelled chairs in general. Due to poor performance of the 08-09 chair in the three-point turning category during the first user's test run (the amount of force required to perform the task had the potential to break the accessory), three-point turns were eliminated from subsequent tests. This category was subsequently disregarded in the tabulation of results. After completing the test course, the students were asked to rate each chair on a scale of 1 (poor) to 5 (excellent) in several different categories. Resulting average scores are shown in Table 17, and the evaluations can be found in Appendix F. The total score was computed in addition to the average in order to give an overall comparison of how well the chairs did relative to each other.

Categories	**Meyra Chair**	**05-06 Wheelchair MQP**	**08-09 Wheelchair MQP**
Forward Propulsion	3.85	3.5	4.25
Backward Propulsion	4	3.63	3.4
Turning Right	4.29	3.13	3.13
Turning Left	4.29	3.13	2.25
Forward to Backward Shifting	4.14	2	2.43
Braking	2.57	4.25	3.75
Parking Brake	2.75	3.75	3.8
Force Required for Operation	3.86	2.88	3.63
Device Usage Comfort	4.43	2.75	3.13
Intuitiveness of Use	4.43	3.13	3.63
Overall Propulsion Mechanism	4	3.13	4.13
Overall Turning Mechanism	4.29	3.25	3.63
Overall Braking Mechanism	3.14	3.75	3.63
Average:	**3.85**	**3.25**	**3.32**
Standard Deviation:	**0.63**	**0.56**	**0.59**
Totals:	**50.04**	**42.28**	**43.16**

Table 17: User Testing Scores (n = 8)

Additional comments the students made included:

For the MQP chair, the handle makes it hard to turn left. Also grinding.

The chair was almost as easy to steer as the Meyra, but was easier to drive (less force needed to drive).
The MQP chair was feels a lot more comfortable to use, but turning is hard.

11.2.5 Performance Test Course

After the initial student testing in Higgins Labs, the team realized that there were several deficiencies in the 08-09 prototype; these included the constant need for steering cable tensioning, cables slipping, and extreme difficulty with left-hand turns. Despite the deficiencies, the team chose to continue with the outdoor performance course testing to obtain additional data. Instead of having unbiased users carry out the test, the team members decided to do it themselves.

The chair made it as far as the outside of Higgins Labs before any major complications arose. Twenty feet from the front entrance to the Labs, the chair got stuck in a large crack in the sidewalk. When attempting to propel out of the crack, the spokes connecting the accessory to the pushrim of the wheelchair sheared off along the threaded section of the spoke. This signaled the end of the performance test course, with the chair clearly unable to continue. No qualitative data was collected beyond the failure of the chair. This result was enough to judge the prototype unfit for full time use without further modification. The team observed that the failure (Figure 103) occurred along the thread of the spokes and hypothesized that stress concentrations introduced by threading, combined with the under-designing of the component, were likely the cause of the failure. The stress analysis in Appendix G helped support this hypothesis.

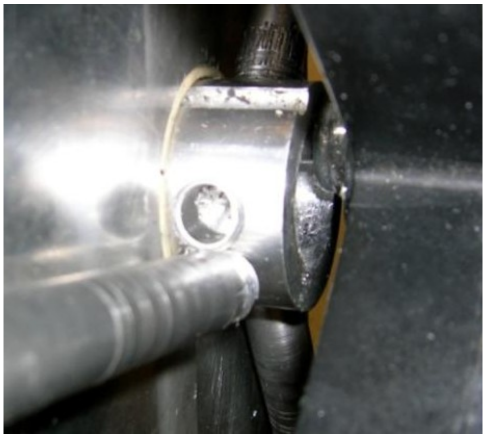


Figure 103: Spoke Failure

11.2.6 Additional Design Parameter Testing

Tools Required for Installation

The original goal was for the accessory to only require very simple tools which most people would either already have or be able to borrow or purchase at little cost. The final design relied heavily on socket-head screws, meaning Philips head and flat head screwdrivers were of little use. A hammer was not needed either. After the accessory had been installed the first time, the team uninstalled and reinstalled it in a timed trial while trying to use as few tools as possible. The following tools (Figure 104) were all that was necessary to install the accessory in its pre-assembled form: two pairs of pliers, an adjustable wrench, two open-end wrenches, two Allen keys, and a Philips head screwdriver. Many of these tools are still relatively common/easy to procure, except for the Allen keys, which could be provided with the accessory.

Figure 104: Assembly Tools

Functionality Testing

There were a number of design criteria for the 08-09 prototype that were not measureable on a varying scale; rather, the design either fulfilled the criteria or it did not. Table 18 shows these criteria as well as the results.

Design Parameter	Y/N	Comments
Only one arm for steering	Y	
Accessory attachable to either side of wheelchair	Y	The team did not actually try to attach it to both sides of the wheelchair; rather, by inspection it was confirmed that this was possible.
Propulsion system must move the wheelchair both in the forward and backward directions	Y	
Brakes must be able to slow the wheelchair in addition to bringing it to a complete stop	N/A	Conceptually the brakes work. However, on the final assembly there did not seem to be enough tension in the braking cables for them to work properly.
There will be a means of adjusting the mechanical advantage	Y	
Actuating arm of the propulsion system must be able to be disengaged and locked into a secure stowed position while an attendant is pushing the chair	Y	
Final assembly must have some means of locking the wheels to prevent rotation	Y	This feature was already on the chair, as it came standard with parking brakes.
The user must be able to steer the chair at all times, unless an attendant is pushing the chair	Y	
Accessory cannot interfere with an attendant's ability to push/control the chair	Y	This is true, however due to the steering system one caster only has a 90° range of motion, making it a bit difficult for the attendant to control the wheelchair while pulling it backwards.
All mechanisms and wires must be encased or stored such that they do not interfere with use of the chair and its moving parts	Y	
Moving parts and pinch points must be located and/or guarded such that they pose minimal risk of injury to users, attendants, and others in the area	Y	

Table 18: Functionality Test Results

11.2.7 Cost of Single-Arm Propulsion Accessory

Upon completion of the manufacturing and assembly of the chair, the total cost of materials, hardware, etc, was calculated. Table 19 breaks down the total expenditure into several different categories.

Clutches	2x $185.00	$370.00
Sprocket		$60.93
Stock Aluminum		$187.57
Disc Brakes	2x $52.00	$104.00
Cable Doubler		$39.99
Cables		$5.25
Assorted Hardware		$10.00
Assorted Bushings		$80.91
	Total:	**$858.65**

Table 19: Costs Associated with 08-09 Prototype

According to 2007 data from the United States Bureau of Labor Statistics, the hourly compensation rate for all employees in manufacturing is $30.56 (U.S. Dept. of Labor, 2009). The team estimated that a total of approximately 50 hours was spent on manufacturing and assembling this device. However, the process was extremely long because much of the time was spent trying to learn manufacturing and assembly practices for different components and doing multiple iterations. Assuming that a standardized manufacturing process is in place with skilled employees, the team estimates that the time for manufacturing and assembly can be reduced to approximately 10 hours. This figure was estimated by approximating the machining time for all machined parts and the time assembly would take given a set of standard instructions. A total of 10 hours of manufacturing and assembly would yield manufacturing costs of $305.60.

The total cost of making the accessory can be calculated by adding the cost of materials to the manufacturing and assembly costs. The final cost of making the accessory would then be $1,164.25. Assuming that profit to be made by the manufacturer is 100% above the cost, the final retail price of the accessory would be $2,328.50. This final retail price is higher than most of the other similar commercial products, which range mostly between $500 and $1000. A price point slightly above this range would be appropriate given that this product can perform the functions for which it was designed, does not compromise the trailing caster, does not compromise the foldability of the chair, and is versatile because it can be attached to different chairs on either side.

In order to make this product marketable and competitive with similar products the costs of manufacturing and materials need to be reduced. The propulsion subsystem housing was obviously overdesigned, and a large amount of aluminum was used to produce the cover and backplates. A significant amount of the purchased aluminum was wasted because it ended up as chips in the manufacturing process. Mass production and the use of cheaper materials could yield extensive cost savings and a significantly lower retail price. The use of a plastic such as high-density polyethylene and an injection molding process to manufacture the part can reduce the manufacturing costs. Using an injection molding cost estimator and entering the desired material and combined dimensions of the two parts, it was estimated that producing 1000 cover/backplate units would cost approximately $30 per unit, including the costs of material, tooling, and production ("Injection Molding Cost Estimator", 2009). This is opposed to the approximately $160 worth of aluminum used to manufacture the two parts, which does not including tooling or production costs. The team also ordered about double the amount of bushings that were needed for the accessory; however, many of the bushings broke during assembly due to improper practices. This means that the $80.91 amount spent on bushings could potentially be reduced to $40 and even less if they are bought in bulk. By changing the material, process of making the gear housing and reducing the breaking of the bushings there could be savings of $175.46 per unit. Another means of savings would be manufacturing the accessory in another country where the manufacturing costs are lower. Additional savings can be achieved by purchasing the clutches, sprockets, brakes, cable doubler, cables, and hardware in bulk. The goal for the price point for making this accessory a competitive product on the market would be on the higher end of the range of similar products. Given all the added functionality of this accessory, an appropriate price point would be around $1,200.00.

12. Discussion

12.1 Test Results

The team successfully achieved the primary goal of creating an accessory to convert a manual wheelchair into a one-arm manually propelled and controlled wheelchair. The prototype was tested using the methods outlined in Section 11.1.

In static stability testing, the 2008-09 chair had a higher angle of instability when facing uphill than both the 2005-06 MQP prototype and the Meyra wheelchair (Table 11), meaning it tips backward at a steeper angle than the other two wheelchairs and can thus go up steeper inclines without running the risk of tipping backward. The 08-09 chair had only the second-highest angle of instability in the transverse direction (Table 12), likely due to the unbalanced weight added by the propulsion subassembly. The 08-09 chair also had the lowest angle of instability when facing downhill with its parking brakes engaged (Table 13). Though the parking brakes were successful at preventing rotation of the wheels after being properly adjusted, the tread on the wheels is very worn, making it more difficult for the wheel to grip the ramp. The standard deviations for the angle of instability measurements were all between 0.4° and 1.1°, meaning there was little error in measurements and that the measurements were highly repeatable. Since the standard deviations and the results do not appear to be random and are highly repeatable, it is not necessary to conduct additional tests to determine the statistical significance of this data. The team considers this data to be statistically valid.

Due to greater attention to user-environment interaction, the 2008-09 design is 0.5” narrower than the 2005-06 MQP prototype, making it easier to maneuver through doorways. It fulfills the design specification governing size, which states that the chair could not exceed dimensions of 51” x 27.5” x 43” (L x W x H). The chair, when unfolded, measures 32” x 27.5” x 38”. It also maintains the ability to fold, increasing the portability of the wheelchair onto which the accessory is installed. The folded dimensions of the chair are 32” x 15.5” x 38”, which allows the chair to fit easily into the trunk of a mid-size sedan. The 05-06 chair was 5” wider when folded, making the decreased width of the 08-09 chair a significant improvement. The 08-09 chair weighed 57 pounds, a 22-pound increase over the original weight of approximately 35 pounds. This was eight pounds heavier than the 05-06 MQP prototype, but two pounds lighter than the Meyra. Such a large increase in weight is highly undesirable, but can be easily remedied by using lighter materials and different manufacturing techniques, as will be discussed in Section 14.

Several tests were run to evaluate the 2008-09 prototype's maneuverability and compare it to the 05-06 MQP chair and the Meyra chair. The 2008-09 chair had the second smallest (out of the three models tested) minimum turning radius in both the right and left directions, meaning it was capable of making sharper right turns than the 05-06 MQP and sharper left turns than the Meyra. The minimum turnaround width, or the minimum corridor width in which the chair can make a complete 180° turn using only one backing motion, was also measured for each of the chairs. In these tests, the 08-09 MQP required the largest turnaround width in both right and left turns. It had the highest right turn requirement by only two inches, but the highest left turn requirement by eight inches. This difficulty is due to steering pulley issues, which will be discussed in greater detail in later sections. The operational force data suggests that the propulsive force required for all three chairs is very similar, since the standard deviation is less than one with an average of 4.55lbs for the 155lb user, and less than 1.5lbs with an average of 5.9lbs for the 195lb user.

Operating force requirements for braking and propulsion on the 2008-09 chair were well within the limits set in the design specifications. The limit for braking force was 35 pounds, and testing of the chair showed that the actual average braking force requirement was 16 pounds. The maximum limit for the propulsive force was 18 pounds; the 08-09 chair had an average required force of 4.9 pounds for propulsion. These figures were obtained by testing the chair on both a tile and a carpeted surface, with two users; one weighed approximately 155 pounds and the other approximately 195 pounds. In both cases, the 08-09 chair required considerably more force to turn than either of the other two chairs, though it required less force to brake than the 05-06 chair and was within the range of propulsive force requirements measured on the 05-06 chair and the Meyra, i.e. its requirements were comparable to the two other chairs. Both users also had to exert greater force to propel the chairs on the carpet than on the floor. With one exception (the 155-lb user turning right) all of the chairs generally required more force to turn on the carpet than on the floor, as might be expected from the greater friction the carpeted surface provides. Since there was only the one exception to this trend out of 12 trials (two users turning both right and left on three different chairs), the team believes it may be due to problems with the steering system and cable tensioning rather than an actual reflection of the force requirement. After propulsion, the next category in which the chairs were closest in performance was braking, with average braking forces of about 15lbs and standard deviations of less than 6lbs for both users. The chairs measured most differently in turning forces for different directions and on different surfaces, with most standard deviations on the order of 10lbs.

These results suggest that all three chairs perform similarly in propulsion and braking but that the major difference between them lies in the steering. One can explain this difference because the Meyra chair has linkage steering as opposed to the cable steering of the two other chairs. The 08-09 chair's steering system did not work properly, therefore there was a wider range of performance between the three chairs in this category.

The 2008-09 prototype performed very well in the comparative user testing. Eight individuals were asked to evaluate the performance of the two (08-09, 05-06) MQP wheelchairs and the Meyra chair against each other after driving each chair around a test course in Higgins Labs. The testers gave each chair a score on a scale of 1 (poor) to 5 (excellent) in thirteen different categories. Originally there were fourteen categories; however, three-point turning was eliminated very early in the testing because it became apparent that the force required to perform this task with the 08-09 chair had the potential to snap the steering cable and deform the handle. The 08-09 chair had a higher average score (3.32/5) than the 05-06 chair (3.25/5), though the Meyra had a higher average (3.85/5) than both. This would be expected, as the Meyra is a refined commercial product and the two MQP chairs are prototypes. The 08-09 chair had the highest score in three out of the thirteen categories: forward propulsion, parking brake (i.e. ease of operation of the brake), and overall propulsion. It had the lowest score in two out of the thirteen categories: backward propulsion and turning left. Of greatest importance to the team, however, was the 08-09 chair's success in scoring higher than the 05-06 chair in five out of the remaining eight categories and tying it in one, marking noticeable design improvements. These categories included: turning right (tie), forward to reverse shifting, force required for operation, usage comfort, intuitiveness of use, and overall turning. The overall greater ease and comfort of use of the 08-09 chair compared to the 05-06 chair make it an even more attractive and desirable product. The 08-09 chair also scored higher than the Meyra chair in braking (i.e. effectiveness of brakes) and overall braking mechanism (i.e. operation of the brakes), though lower than the 05-06 chair in both categories. Seeing that the averages for both the 05-06 and 08-09 MQP chairs are very similar, a t-test was carried out to determine if the difference between both means was statistically significant. The probability that the team could have gotten these results by chance was 44%, meaning that the difference between both averages is not statistically significant. These results suggest that the differences and changes made on the 08-09 chair on average did not result in notable improvement from the 05-06 chair. It is recommended that a larger sample size of subjects be used for testing the chair in order to obtain better results on statistical significance

The team originally intended to have three additional testers take the prototype on a more extensive test course around the WPI campus. After the initial user testing, however, the prototype showed signs of wear and it was decided that the team would conduct these tests rather than outside test subjects. As noted in Section 11.2.5, the chair made it outside of Higgins Labs before getting stuck in a crack in the sidewalk. The force applied to try to dislodge the wheelchair caused the spokes to shear off at the threaded portion at the axle, rendering the chair unfit for further testing. Before the stress analysis had been performed, a design was proposed without accounting for the diameter reduction produced by threading the pipe. The threads, while only .03937 inches deep, tripled the stress in the pipe at the location of the threads. Additionally, the threads represented an area of stress concentration, further heightening the stress in the spoke. This oversight, combined with the fact that the official stress analysis was not completed until after manufacturing, set up an inevitable failure of the part. The original calculations do prove the concept of the design, and with only slight modifications, the spokes could perform as intended.

Several other criteria were used to evaluate the 2008-09 prototype. Originally, one of the design specifications for the accessory was that it only require a specified set of common, easily-accessible tools to install; however, this list of tools was set prior to formally designing the accessory. The final design used different fasteners than originally anticipated, meaning several of the tools in the preliminary list were not correct. Rather than try to install the accessory using these tools, the team conducted a time trial for installation of the accessory while trying to use as few tools as possible. Two team members were able to install the accessory in 51 minutes using only two pairs of pliers, an adjustable wrench, two open-end wrenches, two Allen keys, and a Philips head screwdriver. Many of these tools are still very common and easy to procure, thus the original intention of the design specification has been satisfied. The only unusual tools were the Allen keys, which could be combined into a single tool that is provided with the accessory. The team members were able to install the accessory relatively quickly due to prior experience with it. It is almost certain that the installation process would take longer for individuals with no experience with the accessory, but because most of the accessory has been pre-assembled, the additional time is not likely to be extensive.

In addition to the timed installation trial, the accessory was evaluated against several of the original design specifications. As stated in Section 11.2.6, these specifications were either fulfilled or not fulfilled; there was no basis for scoring. The accessory fulfilled all of these specifications, with the exception of the brakes. The specification stated that the brakes needed to be able to both slow the chair and bring it to a complete stop. Despite repeated attempts to properly tension the cables for the disc brakes, full use of the brakes could not be achieved. Squeezing the brake lever did produce some response from the calipers, however, which helped slow the chair. When the accessory was removed from the wheelchair, the brakes worked perfectly, leading the team to believe that the cable routing may have inhibited brake function as well.

12.2 General Results

In addition to the results obtained by testing using the procedures in Section 11.1, the team made several observations about the prototype design and operation.

The propulsion system (cover and backplates as well as the shifter/pawl assembly) is primarily aluminum, with steel clutches and toothed wheels, making the whole system heavier than desired. Figure 105 and Figure 106 show the majority of the propulsion assembly.

Figure 105: Propulsion System (Backplate, Toothed Wheels, & Clutches)

Figure 106: Pawl Assembly

Additionally, the press-fit between the reverse clutch and the axle was looser than desired, resulting in slipping during high-load conditions. This meant that a portion of the propulsion stroke in the reverse direction was wasted.

The cable-based steering system was prone to stretching and slipping, requiring constant re-tensioning and adjustments to maintain the required tension for proper functioning of the system. The team believes the root of this problem was the use of a trailing caster, though this was one of the most important design specifications because it allows an attendant to push the chair. The point of contact of the caster with the floor was not vertically aligned with the center of rotation of the steering system (Figure 107), which created a mechanical disadvantage, meaning a larger input force was required for a small turning response at the caster.

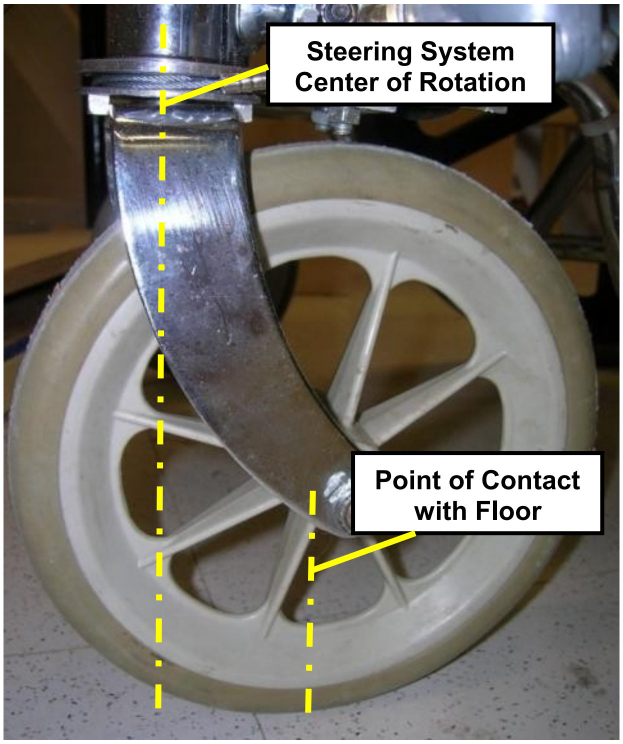


Figure 107: Trailing Caster Alignment

In addition, the overall sizing of the steering system components was insufficient for the force requirements of this arrangement. The pulleys used for steering were 2” in diameter, meaning there was only a 1” moment arm to transmit the torque to turn the wheel. As a result, most of the force to supply the required torque had to come from the user. Despite these difficulties, the trailing caster made the chair much easier for an attendant to push, fulfilling the design specification.

Due to incorrect assumptions about how the wheelchair, axle, and wheel interacted, the braking system had to be redesigned late in the project, resulting in a less-developed final design. Rather than mounting the rotor to the axle, it had to instead be mounted right onto the wheelchair's wheel. The fixturing required to mount the rotors to the wheel greatly reduced the amount of space available on the axle to adjust the rotor's alignment inside the caliper (Figure 108).

Figure 108: Brake Mounting

The disc brakes were designed to be mounted onto a bike with a certain fitting, and as such the calipers had to be mounted in a very specific orientation in order for the rotors to fit into the slot in the caliper. Drilling into or otherwise modifying the wheelchair frame was not an option, and so the original caliper bracket design had to be slightly modified. Though the team developed a workable solution for the caliper mounting (Figure 109), there was still some friction between the rotor and the caliper due to slight misalignment, which over time would cause unnecessary wear on both the rotor and the caliper.

Figure 109: Actual Caliper Bracket

13. Conclusions

At the end of this approximately 28-week project, the team achieved its primary goal of designing, manufacturing/assembling, and testing a prototype of a one-arm propulsion accessory for a manual wheelchair. This design can be removed for installation on either side of a wheelchair, and requires no structural modifications or alterations to the original chair. It allows steering and propulsion to be performed simultaneously, and includes a neutral configuration which allows an attendant to propel the chair. The accessory consists of a lever-operated propulsion system in which the user chooses the desired direction of motion (i.e. forward or reverse) by moving a shifter to cause a pawl to engage one of two unidirectional clutches. The clutches are oriented in opposite directions on the accessory axle such that one allows forward propulsion and the other allows reverse propulsion. Steering is accomplished by rotating the handle, which is attached to a cable-based pulley system, in order to rotate the caster. The disc brakes used in this accessory are operated by squeezing the brake handle, also at the lever.

As this accessory is a third-generation prototype, many improvements have been made over prior designs. Its primary advantage is that it is a removable accessory as opposed to a permanent modification of the wheelchair, creating a larger potential market for the accessory. The trailing caster feature has been maintained, which allows the attendant to steer the chair. In previous designs, attendant propulsion was not possible because neither of these features were present. The use of unidirectional clutches instead of a ratchet-pawl system means the propulsion system is completely silent. Finally, the 2008-09 design is much more user-friendly, as sharp edges have been eliminated, moving parts eliminated or enclosed, and cables stowed more securely.

There were a number of deficiencies in the 2008-09 prototype. Several of these were manufacturing-related, including the excessive weight of many of the components because they were made out of aluminum. The geometry of some of the pieces was dictated by manufacturing constraints, causing them to be larger than necessary. Slipping occurred at the press-fit between the axle and reverse clutch, resulting in wasted force input during the propulsive stroke. In addition, maintaining cable tension was a constant concern, as the bike cables used were prone to stretching. Finally, the disc brakes were difficult to mount in perfect alignment, as the calipers had to be oriented in a specific direction and there was not a great deal of room underneath the chair. These and other deficiencies, as well as possible solutions, are discussed in Section 14.

14. Recommendations

Though the 2008-09 design was a success in many ways and satisfied many of the design specifications, there is considerable room for improvement in each of the three subsystems: propulsion, steering, and braking.

First and foremost, the enclosed drive system alone is extremely heavy (14 pounds), as it is made almost entirely of aluminum and steel. The size and shape of the housing were dictated primarily by the fixturing constraints of the manufacturing resources available in Washburn Shops. Large portions of the propulsion mechanism are overdesigned, with safety factors of 5 or more. To save on weight, the housing should be made using as little material as possible. A manufacturing technique which does not require fixturing, such as casting or injection molding as described in section 11.2.7, would save a considerable amount of material, weight, and cost. Using high-density polyethylene in a mass-production (1000+ units) injection molding process to make the propulsion housing (cover & backplates) would cost $30/unit. The housing unit required approximately 5 hours of machine time, bringing the total material and labor cost of producing a unit to $312.80 (using the labor rate specified in Section 11.2.7). Using the injection molding process yields a 90% decrease in production cost, which would substantially reduce the retail price of the accessory. For the 08-09 prototype, weight reduction can be accomplished by removing the current coverplate and replacing it with a new Plexiglas design. The new coverplate's inner pocket dimensions would match the outer dimensions of the current backplate so that it fits over the backplate with an inch of overlap, meaning its depth would be 2.25". The back and side pieces of the new coverplate can be joined using either methylene chloride (dichloromethane) solvent cement, which is commonly used to fuse Plexiglas without seams, or cyanoacrylate cement ("Superglue") (The Chemistry Encyclopedia, 2007). The new coverplate would have holes for the backplate shaft and axle rather than pockets. To prevent the coverplate from sliding off these shafts, small circular Plexiglas plates would be screwed into the open end of both the axle and backplate shafts. Figure 110 shows a sketch of the new coverplate, which is identical in shape to the existing coverplate, though the new one would have thinner walls and holes (shown in the sketch).

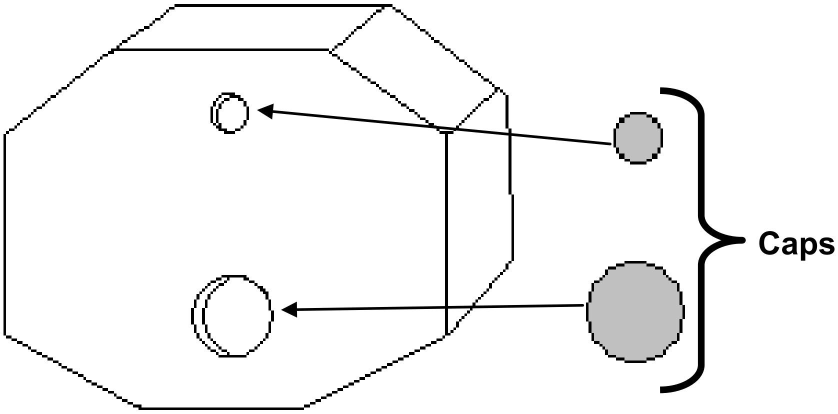


Figure 110: New Coverplate

Another goal of the propulsion design was to avoid any wasted movement in the propulsion stroke due to play between engaged components. The pawls were designed and machined for a custom gear (Figure 111), but the final design used a purchased part (Figure 112) with teeth that did not exactly match the profile of the pawl.

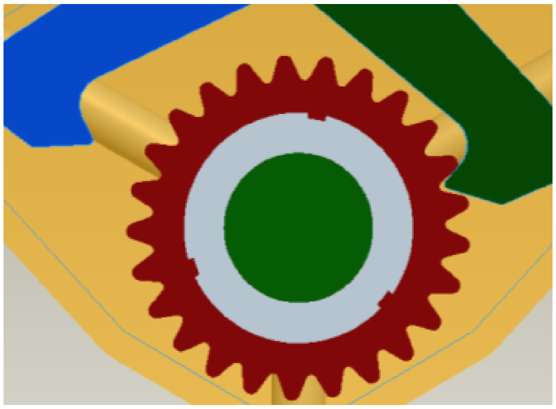


Figure 111: Custom Gear Design

Figure 112: Purchased Toothed Wheel

To address this problem, the pawls should be redesigned for the purchased part using drawings which should be requested from the manufacturer (U.S. Tsubaki). Alternatively, the current pawls could be sanded and filed down so that they match the contours of the toothed wheel.

The next major deficiency in the propulsion subsystem was the amount of slipping due to reliance on press-fits, namely between the clutch and accessory axle. It is extremely difficult to press a soft metal (aluminum axle) into a hardened metal (steel clutch) and maintain tolerances any tighter than those used for a loose press-fit. To address this issue, the clutches should be purchased with a keyway. The manufacturer (Formsprag) offers the same clutches used in the propulsion assembly with a keyway pre-cut. By keying the interaction between the clutch and accessory axle, the tendency to slip will be eliminated. A possible fix for the current prototype would be to press a wedge-shaped, rounded bottom piece of key stock into the rounded keyway cut in the axle. The added pressure from wedging the key stock into the keyway would help to tighten the press-fit and reduce slipping. In conjunction with this operation, the axle should be disassembled and Loctite retaining compound applied to the inner race of the clutch before reassembly for added security.

During testing, the selector mechanism used to shift between forward, reverse, and neutral would occasionally disengage. Mechanical interference at the groove walls was used to keep the shifter in gear, but operational forces and slight misalignment issues caused deflection of the shifter from the secured position. To prevent this from occurring, a latch should be added to the housing attachment link which holds the shifter in place. The latch should pivot at one end and have a means of locking in place at the opposite end so that it is easily operable with one hand, but will not disengage due to the deflection of the shifter. In addition, it should span the width of the housing attachment link so that only one latch is needed to hold the shifter in any of its three positions. Figure 113 shows one possible example of such a latch.

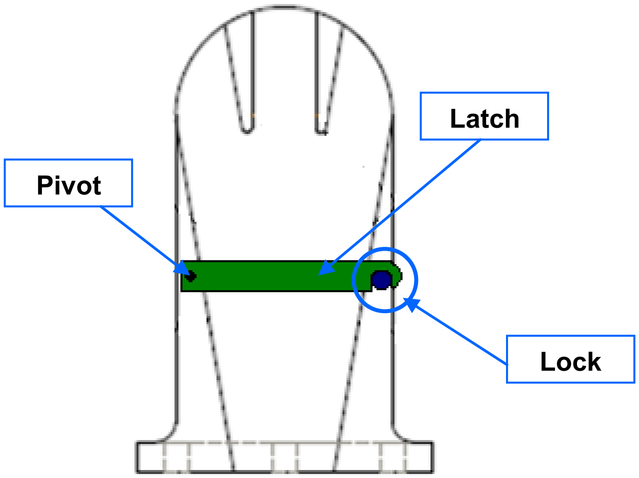


Figure 113: Shifter Latch

The final major problem with the propulsion subsystem was the stress failure of the handrim-attachment spokes during testing (Figure 114). Based on calculations in the stress analysis (Appendix G), these spokes were under-designed for their intended function.

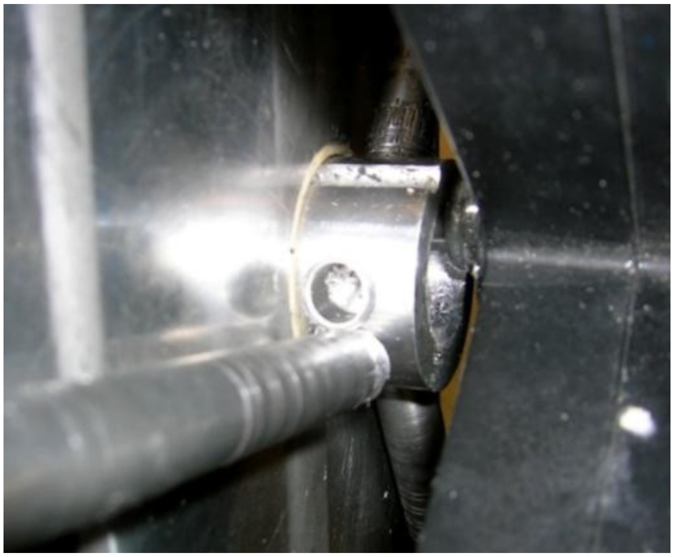


Figure 114: Spoke Stress Failure

External threads added to the pipe during manufacturing decreased the effective diameter of the pipe and left areas of stress concentration which were not taken into account during the design process. During peak-load testing, all three spokes sheared simultaneously at virtually identical locations on their threads. Instead of using external threads, the pipe should be press-fit into the axle holes, as there is no added benefit to using threads. The current prototype can be easily fixed by removing the threaded sections of the pipe and drilling out the threads in the axle so that the hole's diameter matches the diameter of the pipe. This should decrease the stresses to a safety factor of 2; however, this does not fully account for secondary forces or stress concentrations created by the interface of the hole and pipe. An identically-dimensioned pipe made from steel would increase the safety factor to 6, and increase the weight of the chair by an additional 0.38 pounds.

The steering subsystem had a similar design to the well-received steering in the 2005-06 MQP. The primary changes made in the 2008-09 design were the removal of over-steer and the use of a trailing caster. The over-steer was removed by utilizing a 1:1 diameter ratio of the pulleys at the caster and steering handle. Due to space limitations at the caster mounting point, the diameter of the caster pulley had to be significantly decreased from 4" down to 2". This translated to less mechanical advantage for the user because there was a smaller moment arm converting the cable tension to wheel rotation. In addition, the fact that the caster is a trailing caster means that the caster pulley axle is not directly over the point at which the caster touches the ground, creating a mechanical disadvantage. There was also some friction between the caster pulley and wheelchair frame sitting on top of it, as this was a direct metal-on-metal interface. These three factors all combined to create excessive user input force requirements to operate the steering. To alleviate the excess friction, a bushing and/or lubricant should be placed at the metal-on-metal interface between the caster pulley and wheelchair frame. Also, a caster yoke with a less-severe trail should be used, which will bring the point of contact with the floor and the caster pulley axle into closer vertical alignment. Reintroducing the over-steer from the 05-06 MQP by increasing the diameter of the handle pulley to make up for the mechanical disadvantage at the caster would also help alleviate the excessive force required to operate the steering. The cable used in the steering subsystem had a tendency to stretch, meaning it constantly had to be adjusted to maintain proper tension. Thicker, sturdier cable should be used in place of the bike cable, along with an in-line cable tensioning device, to fix this problem.

Despite the advantageously decreased profile of the disc brakes, they suffered from the same tensioning issues as the steering cable. The original design called for mounting the rotors to the axle on the inside of the frame, but because the wheelchair's main wheels have bearings which allow them to rotate independently of the axle, the rotors had to be directly attached to the wheel. Space constraints on the axle made this extremely difficult, and compounding the difficulties was the fact that the brake calipers had to be mounted such that the rotor fit into a narrow slot in the caliper. These issues were put to the side in favor of redesigning and modifying the steering and propulsion systems, and were not given the full attention they required. As a result, the implementation of the final design was not fully representative of the original design concept. The rotors could be mounted directly to the accessory axle, which rotates with the wheelchair wheel. This would provide more potential locations for fixturing the calipers and the opportunity to house the brakes to protect them from damage.

Though the overall assembly functioned reasonably well, there were additional improvements that could be made to improve its performance as a whole. The attachment points for the coupler link between the propulsion housing and lever were not aligned, subjecting the coupler to out-of-plane forces. Figure 115 shows the coupler with arrows to indicate how it should be aligned.

Figure 115: Coupler Alignment

Though this did not affect the overall performance of the accessory, it is certainly not an optimal condition. The misalignment should be addressed simply by decreasing the bearing length on the lever attachment point or moving the location of the propulsion housing attachment so it is aligned with the lever attachment point.

Another assembly issue was slipping of the pieces attaching the lever pivot to the wheelchair frame. To avoid this problem, the current mounting system should be modified with inserts such as rubber. The slot cut into the lever-frame attachment pipe was intended to act in conjunction with a screw to serve as a mechanical stop for the lever. Since the attachment pipe was threaded into the attachment plate (which attaches to the frame), forces from interference at one extreme of the lever motion tended to unscrew the pipe, though forces at the other extreme would screw the pipe back into place. This meant the slot-screw arrangement ceased to serve as a stop for the lever. Fusing the lever-frame attachment pipe to the attachment plate using fasteners or welding (or manufacturing them together as one piece) will prevent the unscrewing and allow this feature to function as intended.

Finally, though considerable attention was paid to tolerances in the accessory, redesigns and modifications during the manufacturing process meant many of these tolerances were not adhered to. Any additional modification to the accessory should pay close attention to tolerances, especially tolerances after fitting or fixturing of parts.

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16. Appendices

Appendix A: Raw Evaluation Data (Preliminary Testing)

The following appendix contains the raw data from the preliminary wheelchair assessments in the form of evaluations filled out by the individuals testing the chairs.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

Categories	**Meyra Chair** ✓	**Quickie (dual pushrim)**	**WPI MQP Prototype**
Forward Propulsion	5	5	3
Backward Propulsion	5	5	3
Turning Right Forward	5	4	3
Turning Left Forward	5	4	3
Turning Right Backward	5	4	3
Turning Left Backward	5	4	3
Forward to Backward Switch	5	5	3
Braking	4	5	4
Device Usage Comfort	5	4 need footrests	5
Intuitiveness of Use	4	5	3
Aesthetics	4	4	3
Overall Propulsion Mechanism	5	5	3
Overall Turning Mechanism	5	4	3
Overall Braking Mechanism	4	5	4
Totals:	66/70	63/70	46/70

Additional Comments:

Meyra was great. Easy to use mostly all around.

Quickie was a bit hard to turn. Turned left alot when going straight (pushing both wheels)

MQP was harder to use than Meyra. Turning was very sensitive. Braking was tough. Reverse was hard to get to.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

Categories	**Meyra Chair**	**Quickie (dual pushrim)**	**WPI MQP Prototype**
Forward Propulsion	5	3	2
Backward Propulsion	5	3	2
Turning Right Forward	5	2	3
Turning Left Forward	5	2	3
Turning Right Backward	4	2	3
Turning Left Backward	4	2	3
Forward to Backward Switch	4	5	2
Braking	3	4	3
Device Usage Comfort	4	5	3
Intuitiveness of Use	5	3	3
Aesthetics	5	5	2
Overall Propulsion Mechanism	5	3	2
Overall Turning Mechanism	4	2	3
Overall Braking Mechanism	3	4	3
Totals:	61/70	45/70	37/70

Additional Comments:

Quichie very little effort required compared to other two, Turning on Meyra chair is awsome, Turning on WPI MQP Proto is horrible, can't go straight

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

✓ **1= Poor 5= Good**

Categories	**Meyra Chair**	**Quickie (dual pushrim)**	**WPI MQP Prototype**
Forward Propulsion	3	3	4
Backward Propulsion	4	3	5
Turning Right Forward	5	3	4
Turning Left Forward	5	3	4
Turning Right Backward	4	3	4
Turning Left Backward	4	3	4
Forward to Backward Switch	5	3	2
Braking	5	2	2 (cable too tight)
Device Usage Comfort	3	3	3
Intuitiveness of Use	5	5	4
Aesthetics	5	5	4
Overall Propulsion Mechanism	3.5	3	3.5
Overall Turning Mechanism	4	2	4
Overall Braking Mechanism	5	3	4
Totals:	60.5	44/70	51.5/70

Additional Comments:

Angle of steering is more extreme turning right compare to left

Occasionally forward/reverse slipped into natural

Multi-gear ~~not~~ would be helpful, feels like moment is lost too fast, add flywheel?

Reverse breaking doesn't feel comfortable

Simple Design allows for easier fix ~~it~~ broken

If there is a limit of turning radius, might help with handeling.

braking is poor.

when going straight, the handle is angle at about 45° which feel weird as I expect 90° (straight) would go straight.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good ✓

Categories	Meyra Chair	Quickie (dual pushrim)	WPI MQP Prototype
Forward Propulsion	3	5	4
Backward Propulsion	3	5	4
Turning Right Forward	4	4	4
Turning Left Forward	4	3	4
Turning Right Backward	4	4	4
Turning Left Backward	4	4	4
Forward to Backward Switch	5 (but the range of the button is very large)	5	1
Braking	2 if I try to go forward fast it brakes	4	3
Device Usage Comfort	5	2	4
Intuitiveness of Use	5	5	3
Aesthetics	5	5	1
Overall Propulsion Mechanism	3	4	3
Overall Turning Mechanism	5	3	4
Overall Braking Mechanism	3	4	4
Totals:	55	57	47

Additional Comments:

Quickie - I had trouble going straight for an extended Period of time (> 2sec)

MQP - a bit bulky, the arm gets in the way while going through doors

Meyra - easy to learn + use. braking is a bit difficult

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

Categories	Meyra Chair	[✓ Quickie (dual pushrim)]	WPI MQP Prototype
Forward Propulsion	3	3	3
Backward Propulsion	3	3	3
Turning Right Forward	4	5	3
Turning Left Forward	2	5	5
Turning Right Backward	2	5	5
Turning Left Backward	4	5	3
Forward to Backward Switch	5	5	1
Braking	3	2	2
Device Usage Comfort	2	1	~~3~~ 2
Intuitiveness of Use	3	4	3
Aesthetics	~~4~~ 5	3	2
Overall Propulsion Mechanism	3	3	3
Overall Turning Mechanism	2	5	4
Overall Braking Mechanism	3	2	1
Totals:	44/70	51/70	40/70

Additional Comments:

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

✓

Categories	Meyra Chair	Quickie (dual pushrim)	WPI MQP Prototype
Forward Propulsion	4	4	4
Backward Propulsion	4	4	4
Turning Right Forward	4	5	4
Turning Left Forward	4	3	4
Turning Right Backward	4	4	4
Turning Left Backward	4	4	4
Forward to Backward Switch	2	5	~~0~~ 1
Braking	3	3	~~0~~ 1
Device Usage Comfort	2	4	2
Intuitiveness of Use	4	~~4~~ 3	4
Aesthetics	4	4	1
Overall Propulsion Mechanism	3	4	3
Overall Turning Mechanism	5	4	5
Overall Braking Mechanism	4	3	~~0~~ 1
Totals:	51/70	54/70	42/70

Additional Comments:

- Switching btwn back/forward on MQP prototype is dangerous. ~~I~~ You could totally cut yourself.
- Pushing the lever thing is a pain.
- The brake on MQP prototype is waayy too tight.
- On quickie, it's easier to turn right than left.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

✓ **1= Poor 5= Good**

Categories	Meyra Chair	Quickie (dual pushrim)	WPI MQP Prototype
Forward Propulsion	3	2	2
Backward Propulsion	3	1	2
Turning Right Forward	3	3	3
Turning Left Forward	4	3	1
Turning Right Backward	4	1	3
Turning Left Backward	3	1	2
Forward to Backward Switch	5	4	1
Braking	4	1	2
Device Usage Comfort	4	2	2
Intuitiveness of Use	4	3	2
Aesthetics	5	5	1
Overall Propulsion Mechanism	4	3	2
Overall Turning Mechanism	4	2	2
Overall Braking Mechanism	4	1	3
Totals:	54/70	33/70	28/70

Additional Comments:

Quickie: ~~I was afraid of m~~ My fingers were getting caught.
It was very fatiguing.

Prototype: Physically taxing, switch from front to back is dangerous, because of alot of sharp edges and location of switch, steering was hard the chair wouldnt stay straight, brakes were hard.

Meyra: Too much pumping for so little propulsion, steering was by far the best. Most easy to use.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

Categories	Meyra Chair	Quickie (dual pushrim)	WPI MQP Prototype
Forward Propulsion	4	3	2
Backward Propulsion	4	3	2
Turning Right Forward	5	4	4
Turning Left Forward	5	4	4
Turning Right Backward	5	4	3
Turning Left Backward	5	4	3
Forward to Backward Switch	3	5	2
Braking	5	5	3
Device Usage Comfort	2	2	1
Intuitiveness of Use	3	4	2
Aesthetics	4	5	2
Overall Propulsion Mechanism	2	3	4
Overall Turning Mechanism	5	5	5
Overall Braking Mechanism	5	5	4
Totals:	57/70	56/70	41/70

Additional Comments:

For a person that has been in a wheelchair before: It seems really hard to propel forward in astraight line. If I were to go ~~Strai~~ into a supermarket I would hit everything.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 5= Good

Categories	**Meyra Chair**	**Quickie (dual pushrim)**	**WPI MQP Prototype**
Forward Propulsion	2	3	4
Backward Propulsion	2	3	4
Turning Right Forward	4	3	2
Turning Left Forward	4	3	2
Turning Right Backward	4	3	2
Turning Left Backward	4	3	2
Forward to Backward Switch	5	4	5
Braking	5	4	4
Device Usage Comfort	5	3	3
Intuitiveness of Use	4	4	3
Aesthetics	5	5	4
Overall Propulsion Mechanism	4	3	4
Overall Turning Mechanism	5	3	1
Overall Braking Mechanism	4	2	4
Totals:	57	46	41

Additional Comments:

Appendix B: Anthropometric Data

The following appendix contains anthropometric data and diagrams the team used as references for the accessory design.

Measurement Diagrams

Upper Torso

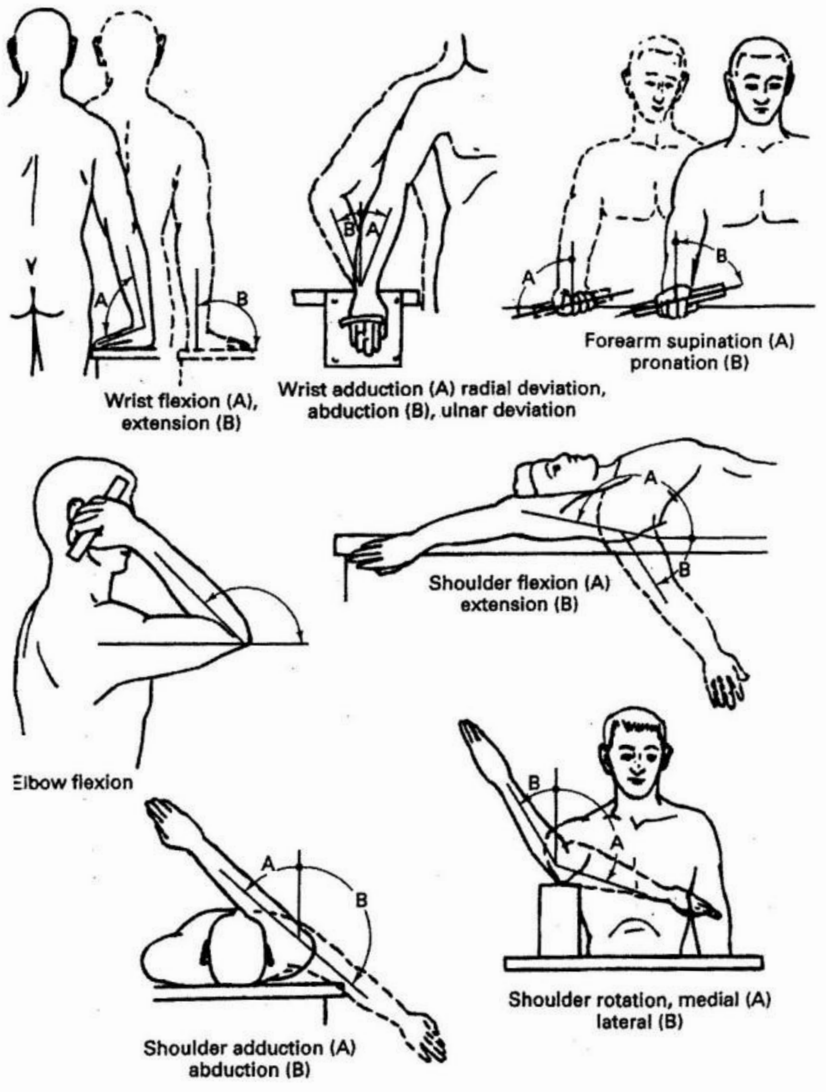


FIGURE 4.1 Displacements in body joints (continued on page 82). (Adapted from *Human Engineering Guide to Equipment Design,* by H. P. Van Cott and R. G. Kinkade, 1972, Washington, DC: U.S. Government Printing Office.)

(From Kroemer p. 81)

Hips/Legs

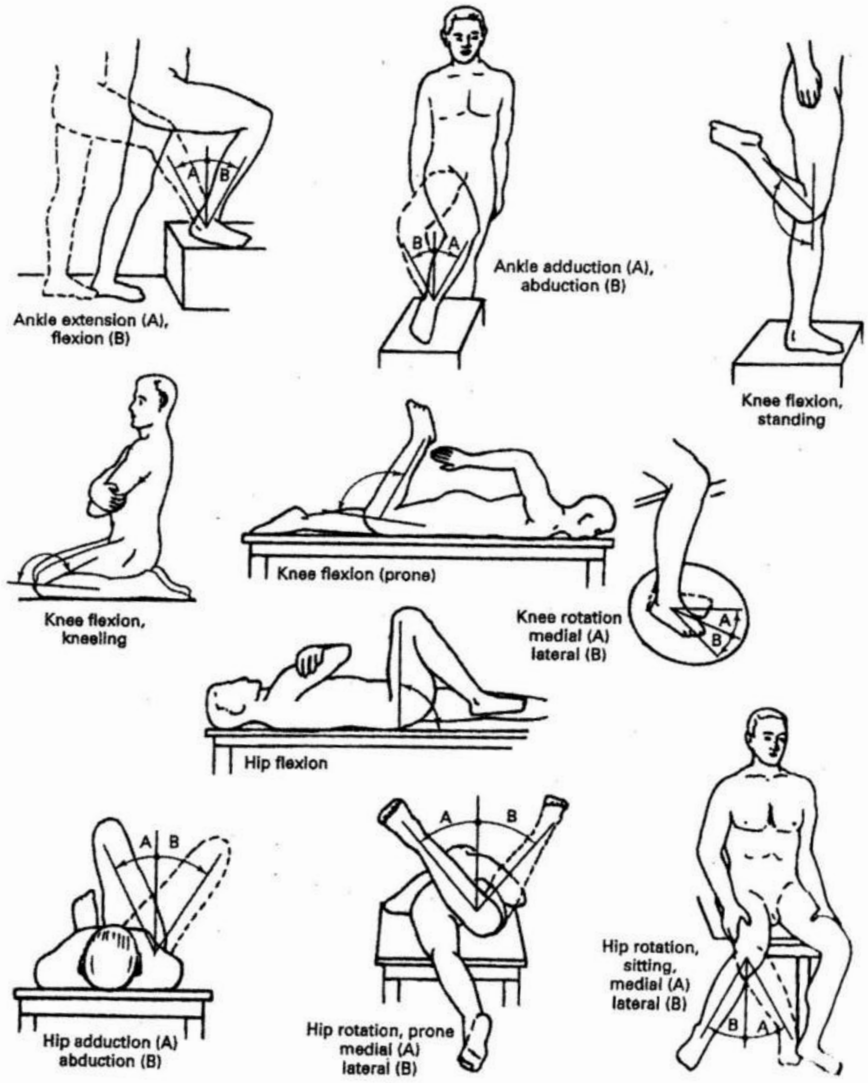
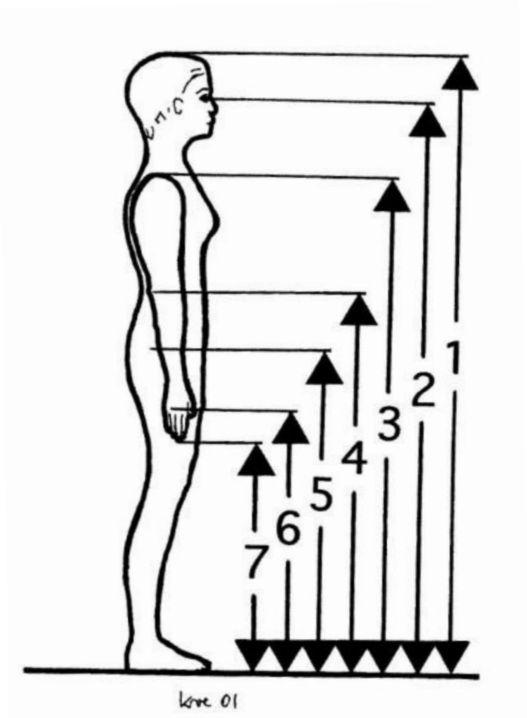


FIGURE 4.1 (continued) Displacement in body joints.

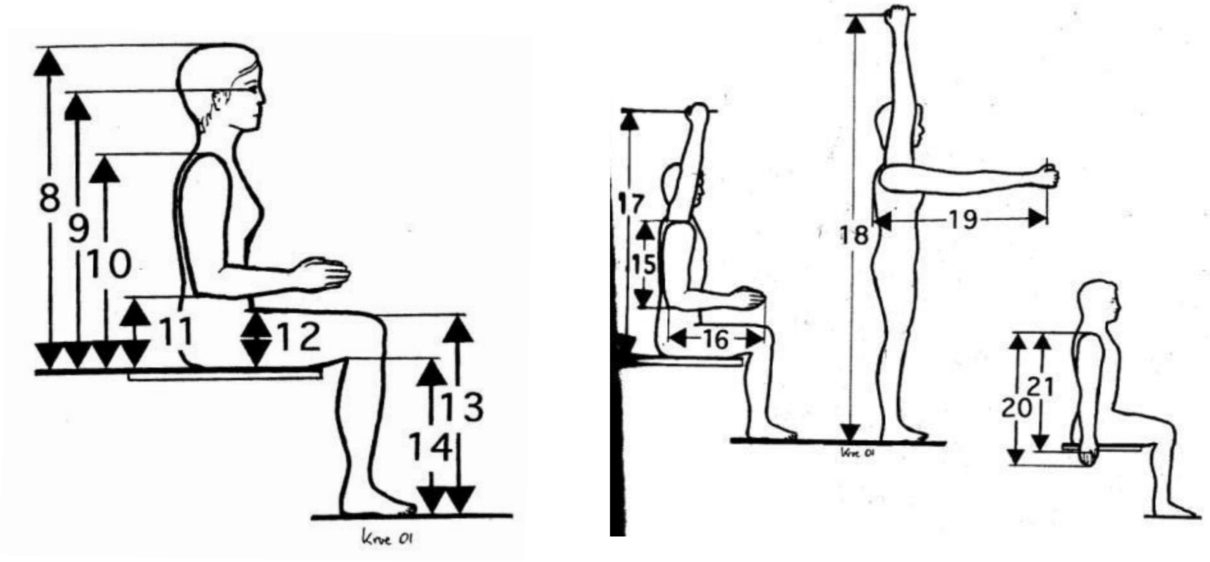
(From Kroemer p. 82)

Heights



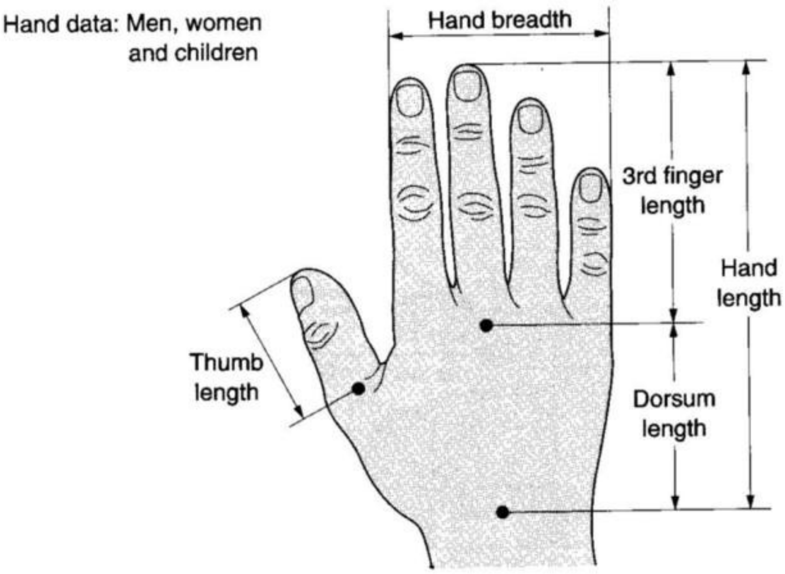
Heights measured on a person standing upright.

(From Kroemer p. 89)



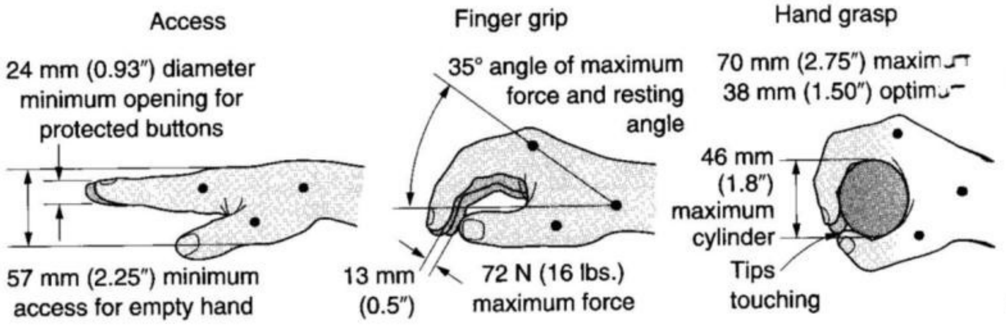
(From Kroemer pp. 90-91)

Hand Grip



Hand data	Men			Women			Children			
	2.5% tile	50.0% tile	97.5% tile	2.5% tile	50.0% tile	97.5% tile	6 yr.	8 yr.	11 yr.	14 yr.
Hand length	173 mm (6.8″)	191 mm (7.5″)	208 mm (8.2″)	157 mm (6.2″)	175 mm (6.9″)	191 mm (7.5″)	130 mm (5.1″)	142 mm (5.6″)	160 mm (6.3″)	[illegible]
Hand breadth	81 mm (3.2″)	89 mm (3.5″)	97 mm (3.8″)	66 mm (2.6″)	74 mm (2.9″)	79 mm (3.1″)	58 mm (2.3″)	64 mm (2.5″)	71 mm (2.8″)	[illegible]
3rd finger lg.	102 mm (4.0″)	114 mm (4.5″)	127 mm (5.0″)	91 mm (3.6″)	100 mm (4.0″)	112 mm (4.4″)	74 mm (2.9″)	81 mm (3.2″)	89 mm (3.5″)	102 [illegible]
Dorsum lg.	71 mm (2.8″)	75 mm (3.0″)	81 mm (3.2″)	66 mm (2.6″)	74 mm (2.9″)	79 mm (3.1″)	56 mm (2.2″)	61 mm (2.4″)	71 mm (2.8″)	[illegible]
Thumb length	61 mm (2.4″)	69 mm (2.7″)	75 mm (3.0″)	56 mm (2.2″)	61 mm (2.4″)	66 mm (2.6″)	46 mm (1.8″)	51 mm (2.0″)	56 mm (2.2″)	[illegible]

Additional data: Average man



(From Fries p. 306)

Anthropometric Data

Mobility Data of College Students

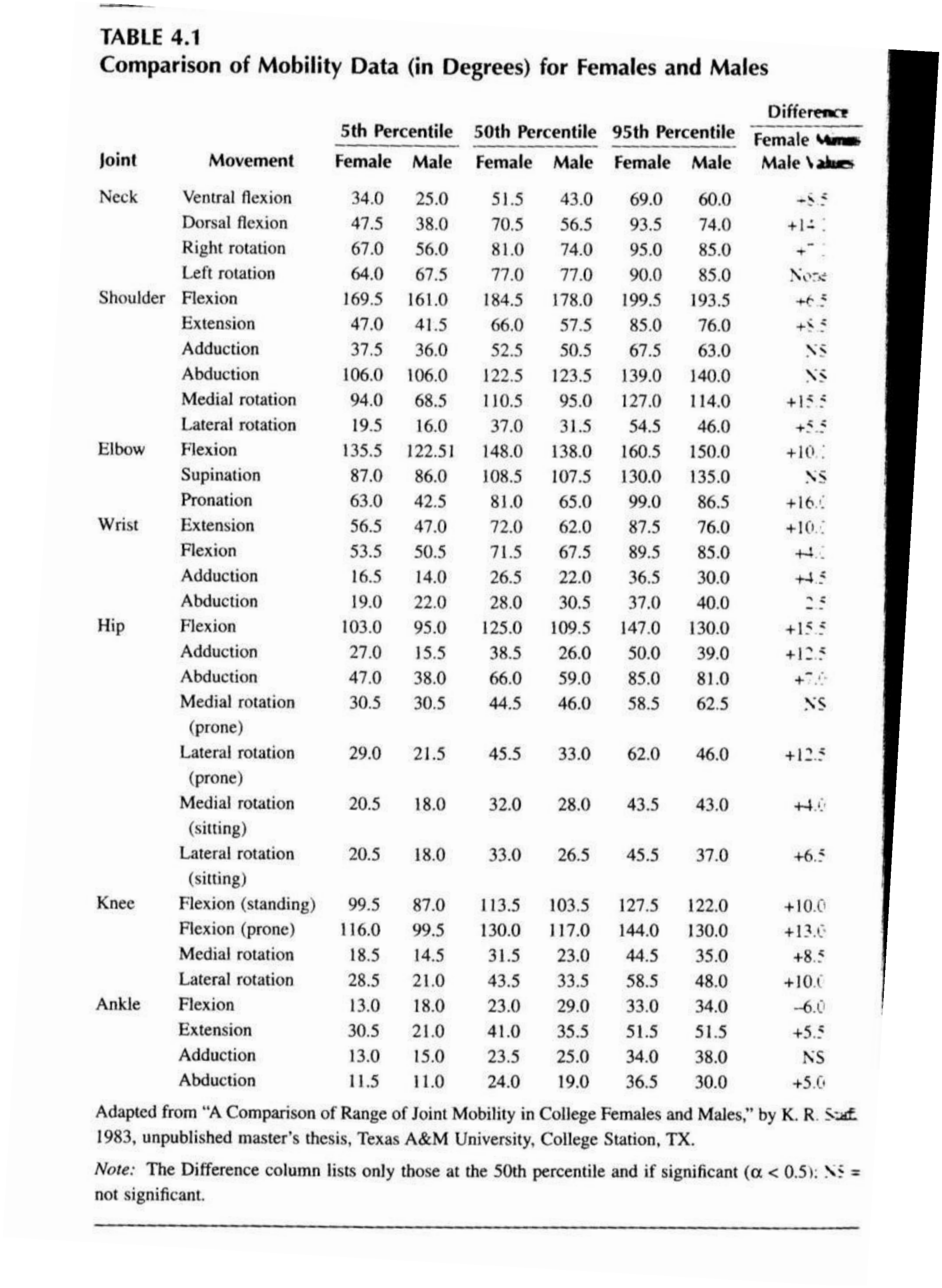


TABLE 4.1
Comparison of Mobility Data (in Degrees) for Females and Males

Joint	Movement	5th Percentile		50th Percentile		95th Percentile		Difference
		Female	Male	Female	Male	Female	Male	Female Minus Male Values
Neck	Ventral flexion	34.0	25.0	51.5	43.0	69.0	60.0	+8.5
	Dorsal flexion	47.5	38.0	70.5	56.5	93.5	74.0	+14.0
	Right rotation	67.0	56.0	81.0	74.0	95.0	85.0	+7.0
	Left rotation	64.0	67.5	77.0	77.0	90.0	85.0	None
Shoulder	Flexion	169.5	161.0	184.5	178.0	199.5	193.5	+6.5
	Extension	47.0	41.5	66.0	57.5	85.0	76.0	+8.5
	Adduction	37.5	36.0	52.5	50.5	67.5	63.0	NS
	Abduction	106.0	106.0	122.5	123.5	139.0	140.0	NS
	Medial rotation	94.0	68.5	110.5	95.0	127.0	114.0	+15.5
	Lateral rotation	19.5	16.0	37.0	31.5	54.5	46.0	+5.5
Elbow	Flexion	135.5	122.51	148.0	138.0	160.5	150.0	+10.0
	Supination	87.0	86.0	108.5	107.5	130.0	135.0	NS
	Pronation	63.0	42.5	81.0	65.0	99.0	86.5	+16.0
Wrist	Extension	56.5	47.0	72.0	62.0	87.5	76.0	+10.0
	Flexion	53.5	50.5	71.5	67.5	89.5	85.0	+4.0
	Adduction	16.5	14.0	26.5	22.0	36.5	30.0	+4.5
	Abduction	19.0	22.0	28.0	30.5	37.0	40.0	2.5
Hip	Flexion	103.0	95.0	125.0	109.5	147.0	130.0	+15.5
	Adduction	27.0	15.5	38.5	26.0	50.0	39.0	+12.5
	Abduction	47.0	38.0	66.0	59.0	85.0	81.0	+7.0
	Medial rotation (prone)	30.5	30.5	44.5	46.0	58.5	62.5	NS
	Lateral rotation (prone)	29.0	21.5	45.5	33.0	62.0	46.0	+12.5
	Medial rotation (sitting)	20.5	18.0	32.0	28.0	43.5	43.0	+4.0
	Lateral rotation (sitting)	20.5	18.0	33.0	26.5	45.5	37.0	+6.5
Knee	Flexion (standing)	99.5	87.0	113.5	103.5	127.5	122.0	+10.0
	Flexion (prone)	116.0	99.5	130.0	117.0	144.0	130.0	+13.0
	Medial rotation	18.5	14.5	31.5	23.0	44.5	35.0	+8.5
	Lateral rotation	28.5	21.0	43.5	33.5	58.5	48.0	+10.0
Ankle	Flexion	13.0	18.0	23.0	29.0	33.0	34.0	–6.0
	Extension	30.5	21.0	41.0	35.5	51.5	51.5	+5.5
	Adduction	13.0	15.0	23.5	25.0	34.0	38.0	NS
	Abduction	11.5	11.0	24.0	19.0	36.5	30.0	+5.0

Adapted from "A Comparison of Range of Joint Mobility in College Females and Males," by K. R. Staff, 1983, unpublished master's thesis, Texas A&M University, College Station, TX.

Note: The Difference column lists only those at the 50th percentile and if significant ($\alpha < 0.5$); NS = not significant.

(Kroemer, 2006)

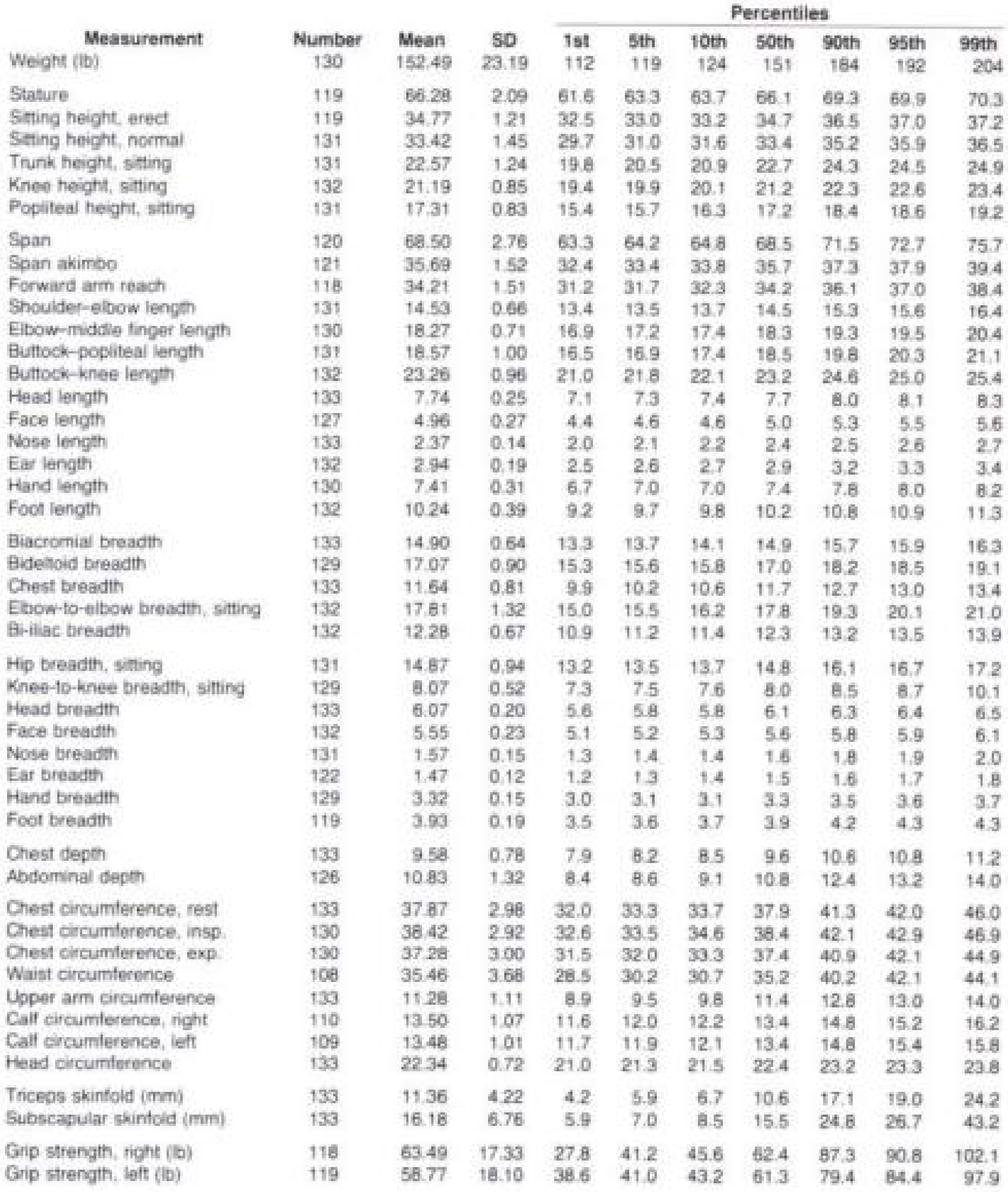
US Army Personnel Ages 17-55

	Men				Women			
Dimension	5th Percentile	Mean	95th Percentile	SD	5th Percentile	Mean	95th Percentile	SD
Stature	1647	1756	1867	67	1528	1629	1737	64
Eye height, standing	1528	1634	1743	66	1415	1516	1621	63
Shoulder height (acromion), standing	1342	1443	1546	62	1241	1334	1432	58
Elbow height, standing	995	1073	1153	48	926	998	1074	45
Hip height (trochanter)	853	928	1009	48	789	862	938	45
Knuckle height, standing	-	-	-	-	-	-	-	-
Fingertip height, standing	591	653	716	40	551	610	670	36
Sitting height	855	914	972	36	795	852	910	35
Sitting eye height	735	792	848	34	685	739	794	33
Sitting shoulder height (acromion)	549	598	646	30	509	556	604	29
Sitting elbow height	184	231	274	27	176	221	264	27
Sitting thigh height (clearance)	149	168	190	13	140	160	180	12
Sitting knee height	514	559	606	28	474	515	560	26
Sitting popliteal height	395	434	476	25	351	389	429	24
Shoulder-elbow height	340	369	399	18	308	336	365	17
Elbow-fingertip length	448	484	524	23	406	443	483	23
Overhead grip reach, sitting	1221	1310	1401	55	1127	1212	1296	51
Overhead grip reach, standing	1958	2107	2260	92	1808	1947	2094	87
Forward grip reach	693	751	813	37	632	686	744	34
Arm length, vertical	729	790	856	39	662	724	788	38
Downward grip reach	612	666	722	33	557	700	664	33
Chest depth	210	243	280	22	209	239	279	21
Abdominal depth, sitting	199	236	291	28	185	219	271	26
Buttock-knee depth, sitting	569	616	667	30	542	589	640	30
Buttock-popliteal depth, sitting	458	500	546	27	440	482	528	27
Shoulder breadth (biacromial)	367	397	426	18	333	363	391	17
Shoulder breadth (bideltoid)	450	492	535	26	397	433	472	23
Hip breadth, sitting	329	367	412	25	343	385	432	27
Span	1693	1823	1960	82	1542	1672	1809	81
Elbow span	-	-	-	-	-	-	-	-
Head length	185	197	209	7	176	187	198	6
Head breadth	143	152	161	5	137	144	153	5
Hand length	179	194	211	10	165	181	197	10
Hand breadth	84	90	98	4	73	79	86	4
Foot length	249	270	292	13	224	244	265	12
Foot breadth	92	101	110	5	82	90	98	5
Weight (kg)	62	79	98	11	50	62	77	8

***Measurements in mm unless otherwise noted.**

(Kroemer, 2006)

Elderly Men

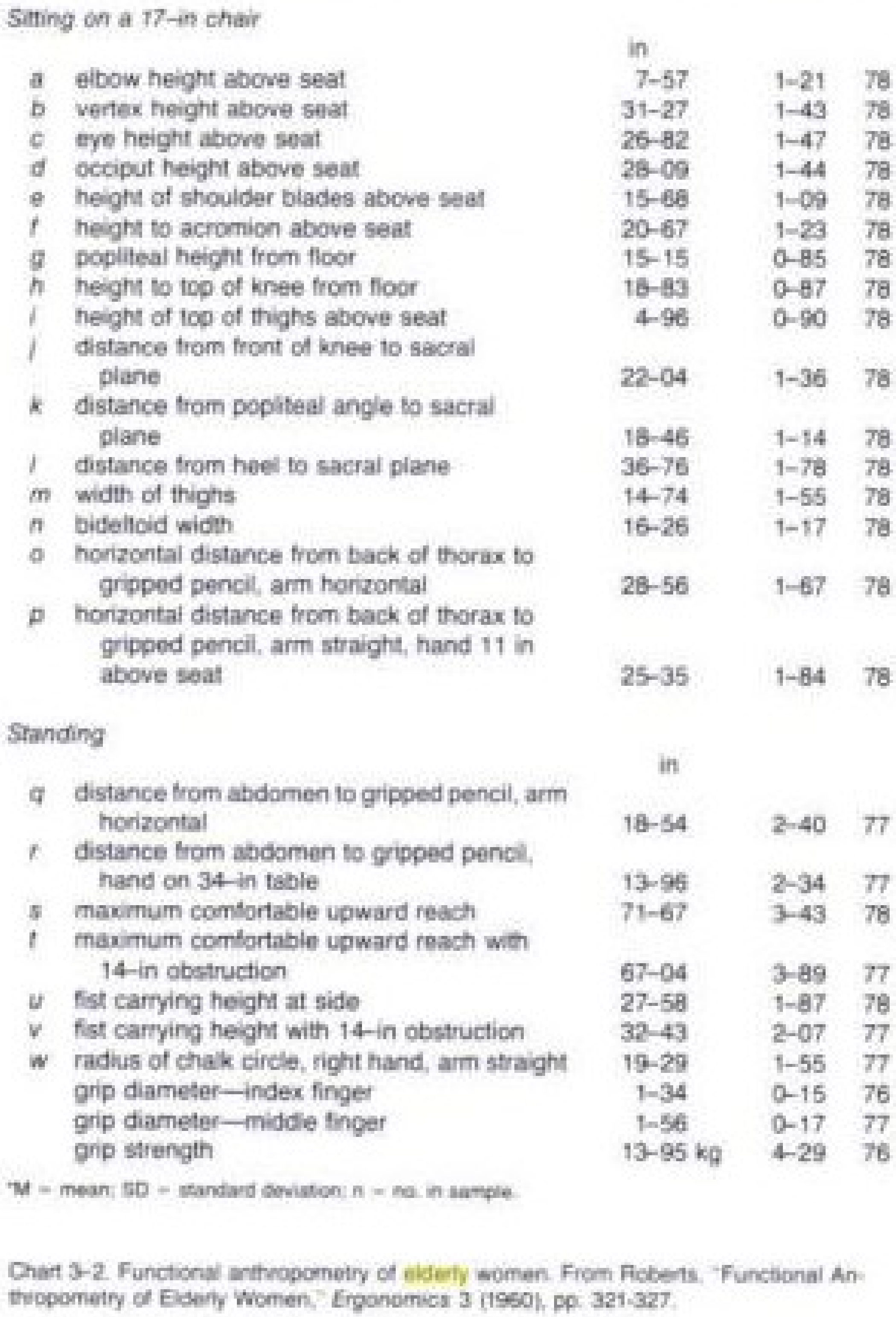


				Percentiles						
Measurement	**Number**	**Mean**	**SD**	**1st**	**5th**	**10th**	**50th**	**90th**	**95th**	**99th**
Weight (lb)	130	152.49	23.19	112	119	124	151	184	192	204
Stature	119	66.28	2.09	61.6	63.3	63.7	66.1	69.3	69.9	70.3
Sitting height, erect	119	34.77	1.21	32.5	33.0	33.2	34.7	36.5	37.0	37.2
Sitting height, normal	131	33.42	1.45	29.7	31.0	31.6	33.4	35.2	35.9	36.5
Trunk height, sitting	131	22.57	1.24	19.8	20.5	20.9	22.7	24.3	24.5	24.9
Knee height, sitting	132	21.19	0.85	19.4	19.9	20.1	21.2	22.3	22.6	23.4
Popliteal height, sitting	131	17.31	0.83	15.4	15.7	16.3	17.2	18.4	18.6	19.2
Span	120	68.50	2.76	63.3	64.2	64.8	68.5	71.5	72.7	75.7
Span akimbo	121	35.69	1.52	32.4	33.4	33.8	35.7	37.3	37.9	39.4
Forward arm reach	118	34.21	1.51	31.2	31.7	32.3	34.2	36.1	37.0	38.4
Shoulder–elbow length	131	14.53	0.66	13.4	13.5	13.7	14.5	15.3	15.6	16.4
Elbow–middle finger length	130	18.27	0.71	16.9	17.2	17.4	18.3	19.3	19.5	20.4
Buttock–popliteal length	131	18.57	1.00	16.5	16.9	17.4	18.5	19.8	20.3	21.1
Buttock–knee length	132	23.26	0.96	21.0	21.8	22.1	23.2	24.6	25.0	25.4
Head length	133	7.74	0.25	7.1	7.3	7.4	7.7	8.0	8.1	8.3
Face length	127	4.96	0.27	4.4	4.6	4.6	5.0	5.3	5.5	5.6
Nose length	133	2.37	0.14	2.0	2.1	2.2	2.4	2.5	2.6	2.7
Ear length	132	2.94	0.19	2.5	2.6	2.7	2.9	3.2	3.3	3.4
Hand length	130	7.41	0.31	6.7	7.0	7.0	7.4	7.8	8.0	8.2
Foot length	132	10.24	0.39	9.2	9.7	9.8	10.2	10.8	10.9	11.3
Biacromial breadth	133	14.90	0.64	13.3	13.7	14.1	14.9	15.7	15.9	16.3
Bideltoid breadth	129	17.07	0.90	15.3	15.6	15.8	17.0	18.2	18.5	19.1
Chest breadth	133	11.64	0.81	9.9	10.2	10.6	11.7	12.7	13.0	13.4
Elbow-to-elbow breadth, sitting	132	17.81	1.32	15.0	15.5	16.2	17.8	19.3	20.1	21.0
Bi-iliac breadth	132	12.28	0.67	10.9	11.2	11.4	12.3	13.2	13.5	13.9
Hip breadth, sitting	131	14.87	0.94	13.2	13.5	13.7	14.8	16.1	16.7	17.2
Knee-to-knee breadth, sitting	129	8.07	0.52	7.3	7.5	7.6	8.0	8.5	8.7	10.1
Head breadth	133	6.07	0.20	5.6	5.8	5.8	6.1	6.3	6.4	6.5
Face breadth	132	5.55	0.23	5.1	5.2	5.3	5.6	5.8	5.9	6.1
Nose breadth	131	1.57	0.15	1.3	1.4	1.4	1.6	1.8	1.9	2.0
Ear breadth	122	1.47	0.12	1.2	1.3	1.4	1.5	1.6	1.7	1.8
Hand breadth	129	3.32	0.15	3.0	3.1	3.1	3.3	3.5	3.6	3.7
Foot breadth	119	3.93	0.19	3.5	3.6	3.7	3.9	4.2	4.3	4.3
Chest depth	133	9.58	0.78	7.9	8.2	8.5	9.6	10.6	10.8	11.2
Abdominal depth	126	10.83	1.32	8.4	8.6	9.1	10.8	12.4	13.2	14.0
Chest circumference, rest	133	37.87	2.98	32.0	33.3	33.7	37.9	41.3	42.0	46.0
Chest circumference, insp.	130	38.42	2.92	32.6	33.5	34.6	38.4	42.1	42.9	46.9
Chest circumference, exp.	130	37.28	3.00	31.5	32.0	33.3	37.4	40.9	42.1	44.9
Waist circumference	108	35.46	3.68	28.5	30.2	30.7	35.2	40.2	42.1	44.1
Upper arm circumference	133	11.28	1.11	8.9	9.5	9.8	11.4	12.8	13.0	14.0
Calf circumference, right	110	13.50	1.07	11.6	12.0	12.2	13.4	14.8	15.2	16.2
Calf circumference, left	109	13.48	1.01	11.7	11.9	12.1	13.4	14.8	15.4	15.8
Head circumference	133	22.34	0.72	21.0	21.3	21.5	22.4	23.2	23.3	23.8
Triceps skinfold (mm)	133	11.36	4.22	4.2	5.9	6.7	10.6	17.1	19.0	24.2
Subscapular skinfold (mm)	133	16.18	6.76	5.9	7.0	8.5	15.5	24.8	26.7	43.2
Grip strength, right (lb)	118	63.49	17.33	27.8	41.2	45.6	62.4	87.3	90.8	102.1
Grip strength, left (lb)	119	58.77	18.10	38.6	41.0	43.2	61.3	79.4	84.4	97.9

Chart 3-1. Functional anthropometry of elderly men. From Damon and Stoudt, "The Functional Anthropometry of Old Men," *Human Factors*, 1963, p. 488.

(Panero, 1979)

Elderly Women



Sitting on a 17–in chair

		in		
a	elbow height above seat	7–57	1–21	78
b	vertex height above seat	31–27	1–43	78
c	eye height above seat	26–82	1–47	78
d	occiput height above seat	28–09	1–44	78
e	height of shoulder blades above seat	15–68	1–09	78
f	height to acromion above seat	20–67	1–23	78
g	popliteal height from floor	15–15	0–85	78
h	height to top of knee from floor	18–83	0–87	78
i	height of top of thighs above seat	4–96	0–90	78
j	distance from front of knee to sacral plane	22–04	1–36	78
k	distance from popliteal angle to sacral plane	18–46	1–14	78
l	distance from heel to sacral plane	36–76	1–78	78
m	width of thighs	14–74	1–55	78
n	bideltoid width	16–26	1–17	78
o	horizontal distance from back of thorax to gripped pencil, arm horizontal	28–56	1–67	78
p	horizontal distance from back of thorax to gripped pencil, arm straight, hand 11 in above seat	25–35	1–84	78

Standing

		in		
q	distance from abdomen to gripped pencil, arm horizontal	18–54	2–40	77
r	distance from abdomen to gripped pencil, hand on 34–in table	13–96	2–34	77
s	maximum comfortable upward reach	71–67	3–43	78
t	maximum comfortable upward reach with 14–in obstruction	67–04	3–89	77
u	fist carrying height at side	27–58	1–87	78
v	fist carrying height with 14–in obstruction	32–43	2–07	77
w	radius of chalk circle, right hand, arm straight	19–29	1–55	77
	grip diameter—index finger	1–34	0–15	76
	grip diameter—middle finger	1–56	0–17	77
	grip strength	13–95 kg	4–29	76

*M = mean; SD = standard deviation; n = no. in sample.

Chart 3-2. Functional anthropometry of elderly women. From Roberts, "Functional Anthropometry of Elderly Women," *Ergonomics* 3 (1960), pp. 321-327.

(Panero, 1979)

Appendix C: Tolerance Study

The following appendix contains a tolerance study conducted on the attach plate and the two parts mating to it: the attach plate cable plate and attach plate shaft.

In any professional drawing, dimensions have tolerances which give the allowable deviation from the nominal dimension shown. On some parts of the wheelchair accessory, certain types of fits are required (i.e. press fits), and the appropriate tolerances are given on the drawings for those parts. For all other dimensions, the tolerances are given in the drawing's tolerance block. There is no set standard for choosing tolerances, and as such the tolerances for this project were chosen based on input from individuals with experience in drafting and manufacturing, as well as the following analysis.

For parts that are modeled using inches as the linear dimension unit, ProEngineer drawings have default values for general tolerances, as shown in Figure 116.

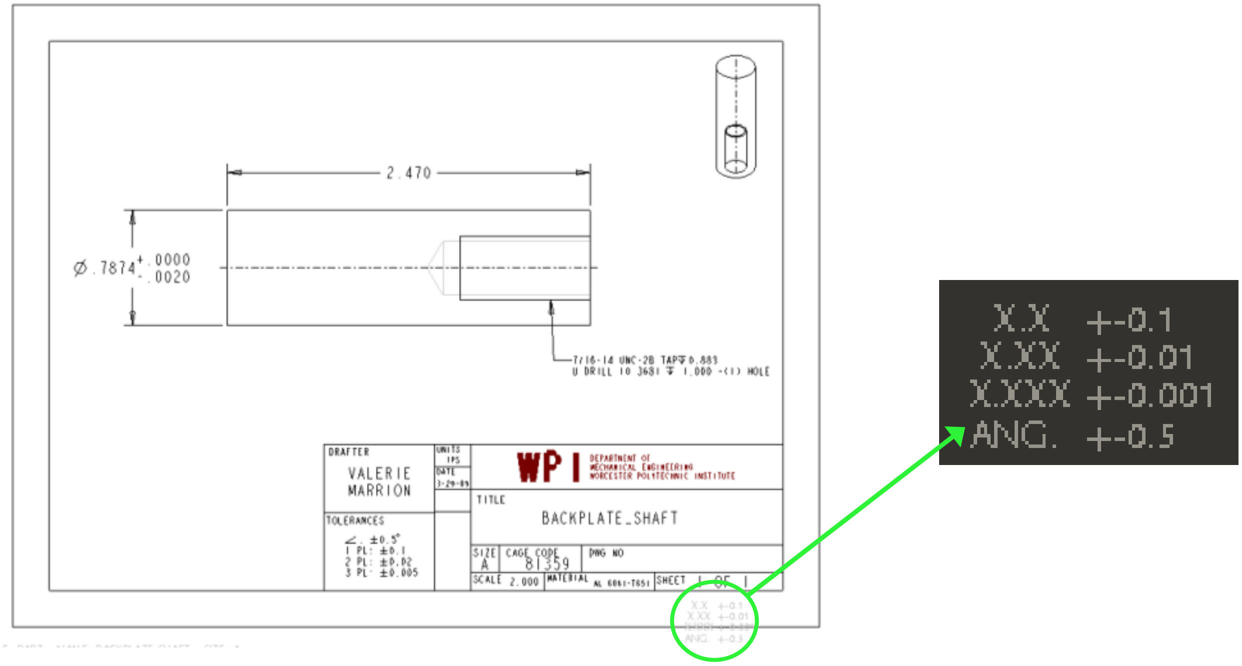


Figure 116: ProEngineer Default Tolerances

These tolerances mean, for example, that a nominal dimension of 3.5 inches would have a tolerance of ±0.1 inches, meaning the allowable range is 3.4-3.6 inches. A nominal dimension of 2.125 inches would only have an allowable range of 2.124-2.126 inches. While precision is ideal in a part, it makes machining the part much more difficult, time-consuming, and expensive. After speaking with the staff in Washburn Shops on multiple occasions, as well as a design engineer with experience in the defense industry (Marrion, 2009), two more possible tolerance sets were determined based on their input and tolerances currently used in the manufacturing and defense industries. They are shown in Table 20.

	Set #2 (based on engineer input)	Set #3 (based on defense industry)
Angle	±0.5°	±1°
X.X	±0.1	±0.1
X.XX	±0.02	±0.03
X.XXX	±0.005	±0.010

Table 20: Alternate Tolerance Sets

Set #2 was chosen as the final tolerance scheme because it held the dimensions close to their nominal values while remaining within the manufacturing capabilities of the machines in Washburn Shops. The next step, after choosing the tolerance scheme, was to apply it to the parts to determine whether it will ensure the parts were appropriately designed. For the purposes of this analysis, a few sample parts were chosen from the final assembly.

The first part to be analyzed was "ATTACH_PLATE_FOR_DWGV1," shown below in Figure 117:

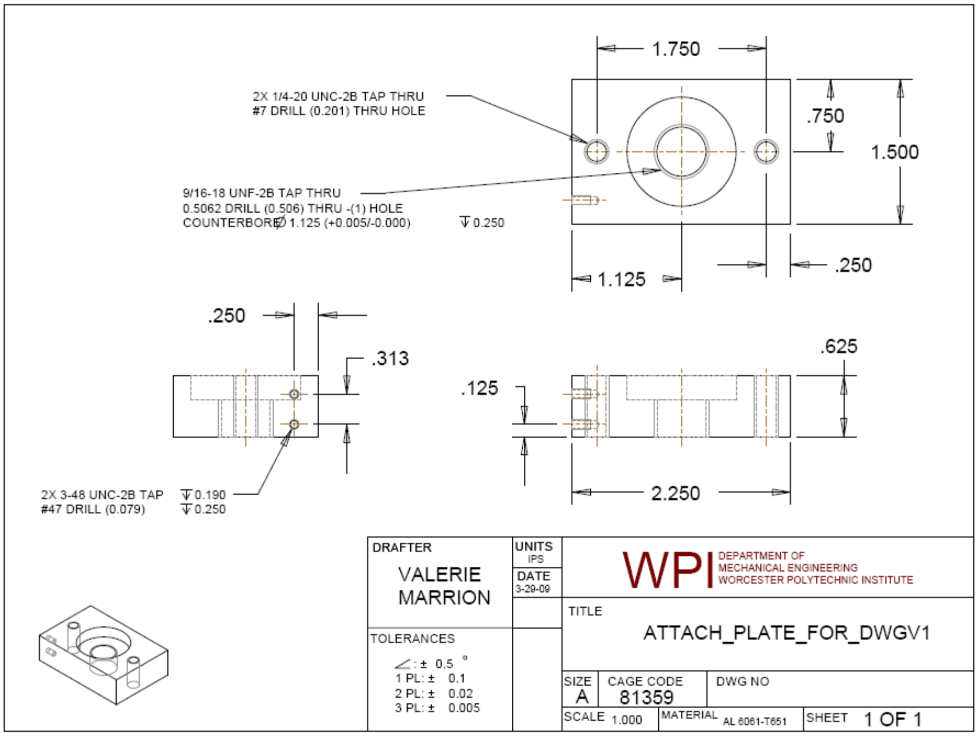


Figure 117: Attach Plate Drawing

The allowable range for each dimension was determined using the method described in Fischer's *Mechanical Tolerance Stackup and Analysis*, pp 62-67. It will be outlined using the following example. Given a part like the one below in Figure 118, positive and negative dimension directions are defined. The zero position for the positive direction in this particular case is the bottom edge, while for the negative direction it is the top edge. In the analysis, the dimensions essentially make a loop up (positive direction) and down (negative direction) to arrive at the initial starting point (the bottom edge of the part).

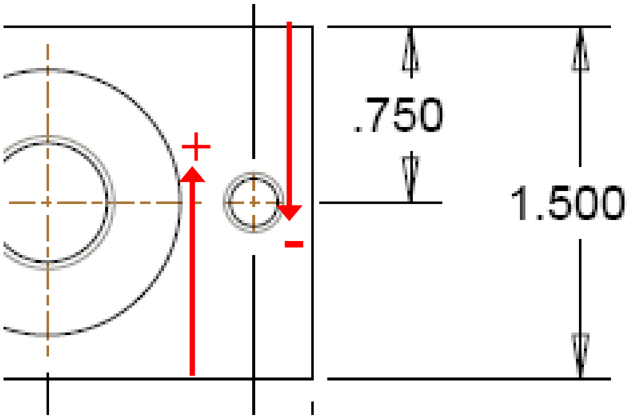


Figure 118: Range Determination Example

The given dimensions are then tabulated, with their corresponding directions and tolerances (Table 21):

Positive (+)	Negative (-)	Tolerance
1.500		±0.005
	0.750	±0.005
Total: 1.500	0.750	±0.010

Table 21: Dimensions & Tolerances

The “missing” dimension is obtained by subtracting the negative total from the positive total. The individual tolerances each of the positive and negative dimensions are summed to obtain the total tolerance. For the above case, the missing nominal dimension was 0.750 inches, ±0.010 inches. Adding and subtracting the tolerance for each dimension gives the maximum and minimum value, respectively, of that dimension as specified by the particular tolerance set. This particular dimension had a range of 0.740-0.760 inches. This process was repeated for each of the dimensions on the drawing. Once all of the dimensions on the part have been analyzed, the results can be examined to determine whether the variations will still allow the part to function as intended, or if it will have to be redesigned and/or tighter tolerances added. The results are also examined in conjunction with the results from identical analyses on mating parts to determine whether everything will fit together appropriately.

The two parts mating to the plate analyzed above are a shaft with a threaded end, which will screw into the threaded hole at the center of the plate, and a small rectangular piece with holes which will attach to the side of the plate and act as a guide for steering cables. These pieces must be analyzed in a similar fashion to determine whether any design changes are necessary prior to manufacturing. The drawing of the first of these parts, the shaft, is shown in Figure 119.

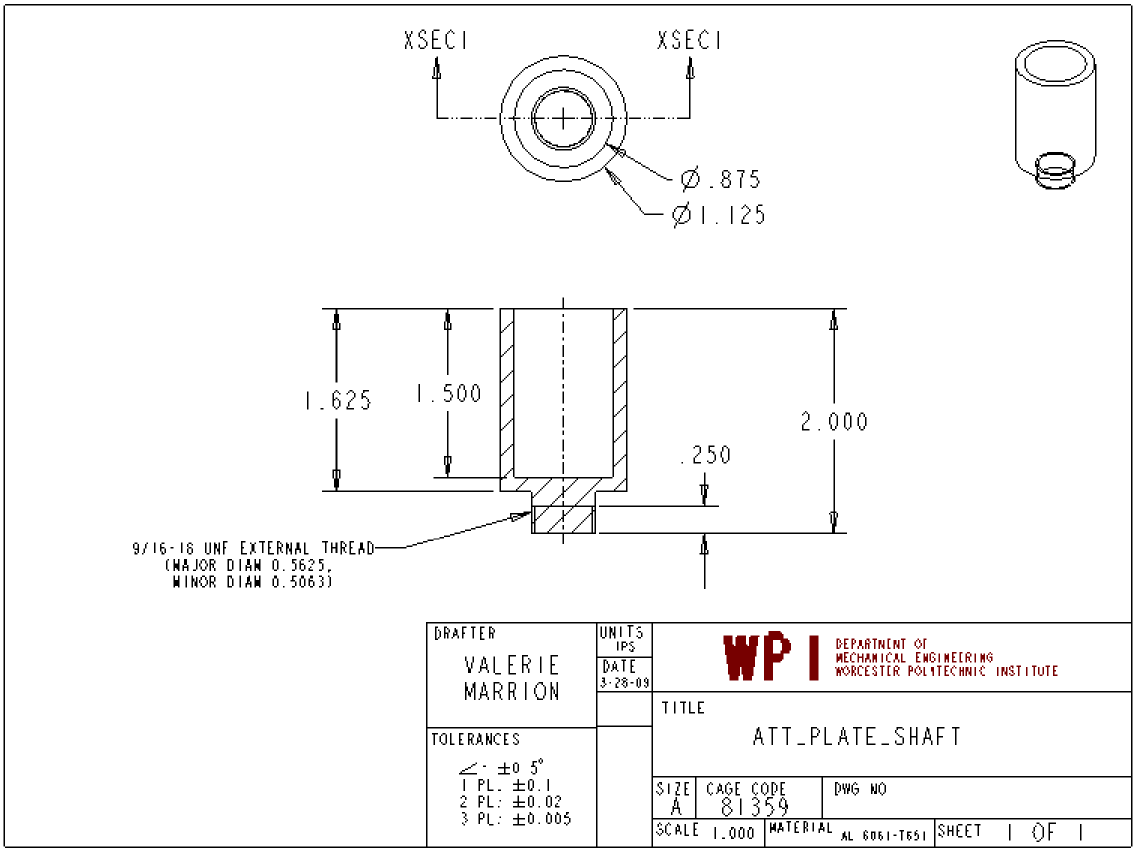


Figure 119: Attach Plate Shaft

The two primary dimensions of concern are the threaded bottom portion and the outermost diameter of the shaft, because these two features must be able to fit inside the holes of the attach plate. There is very little chance that the threaded portion will not fit into the corresponding threaded hole on the attach plate, because both are the same standard size (9/16-18). The outer diameter of the shaft is the same size as the counterbore hole into which it is being inserted, though the tolerance on the shaft stock is ±0.012 inches according to the distributor's website (www.onlinemetals.com, 2009). This gives an allowable counterbore hole diameter range of 1.125-1.130 inches, and an allowable shaft diameter range of 1.113-1.137 inches. Problems could occur if the hole is at its smaller limit and the shaft is at its larger limit, i.e. the two pieces would not fit together. Since the manufacturing of the attach plate preceded the procurement of material for the shaft, the attach plate was manufactured before the stock aluminum rod for the shaft arrived. As such, the shaft diameter must be measured and turned down to size so that it will fit in the hole. Had this not happened, the hole would have been resized so that its smallest diameter would still be larger than the maximum diameter of the shaft; i.e. nominal diameter of 1.140 inches with a +0.005/-0.000 inch tolerance.

The other part to be analyzed is the cable plate, which will be screwed into the side of the attach plate. The drawing of the original part is shown in Figure 120.

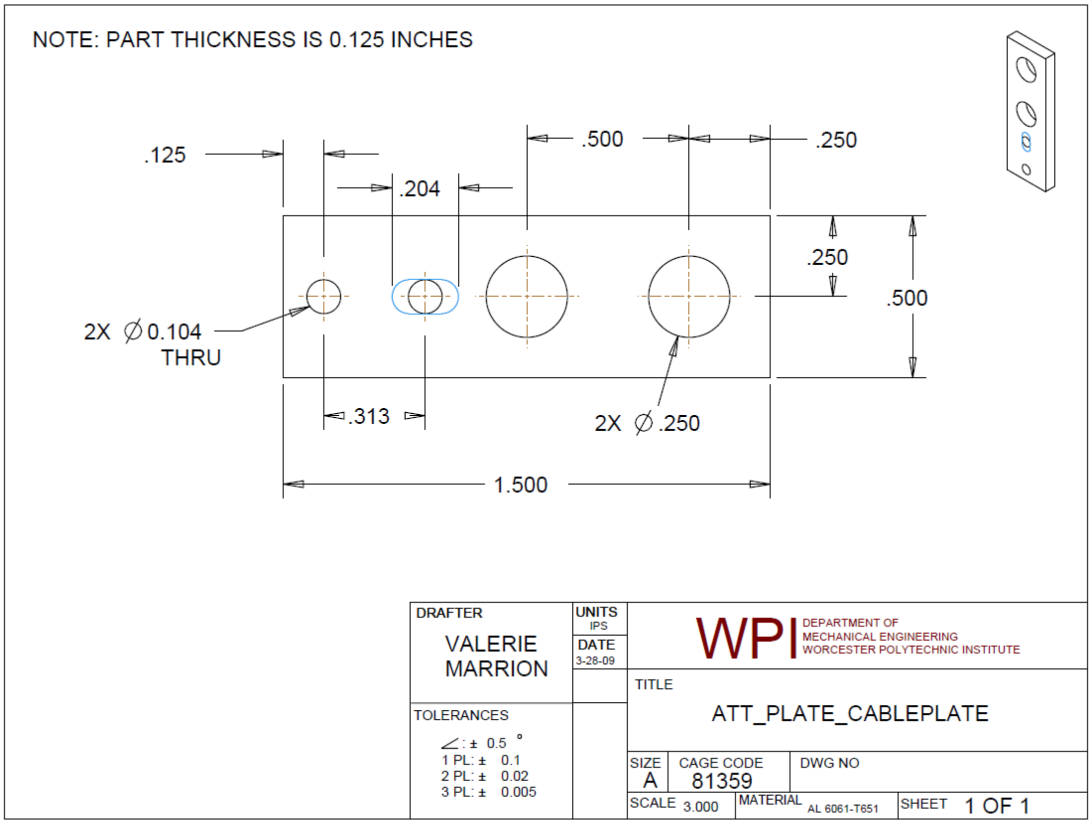


Figure 120: Cable Plate

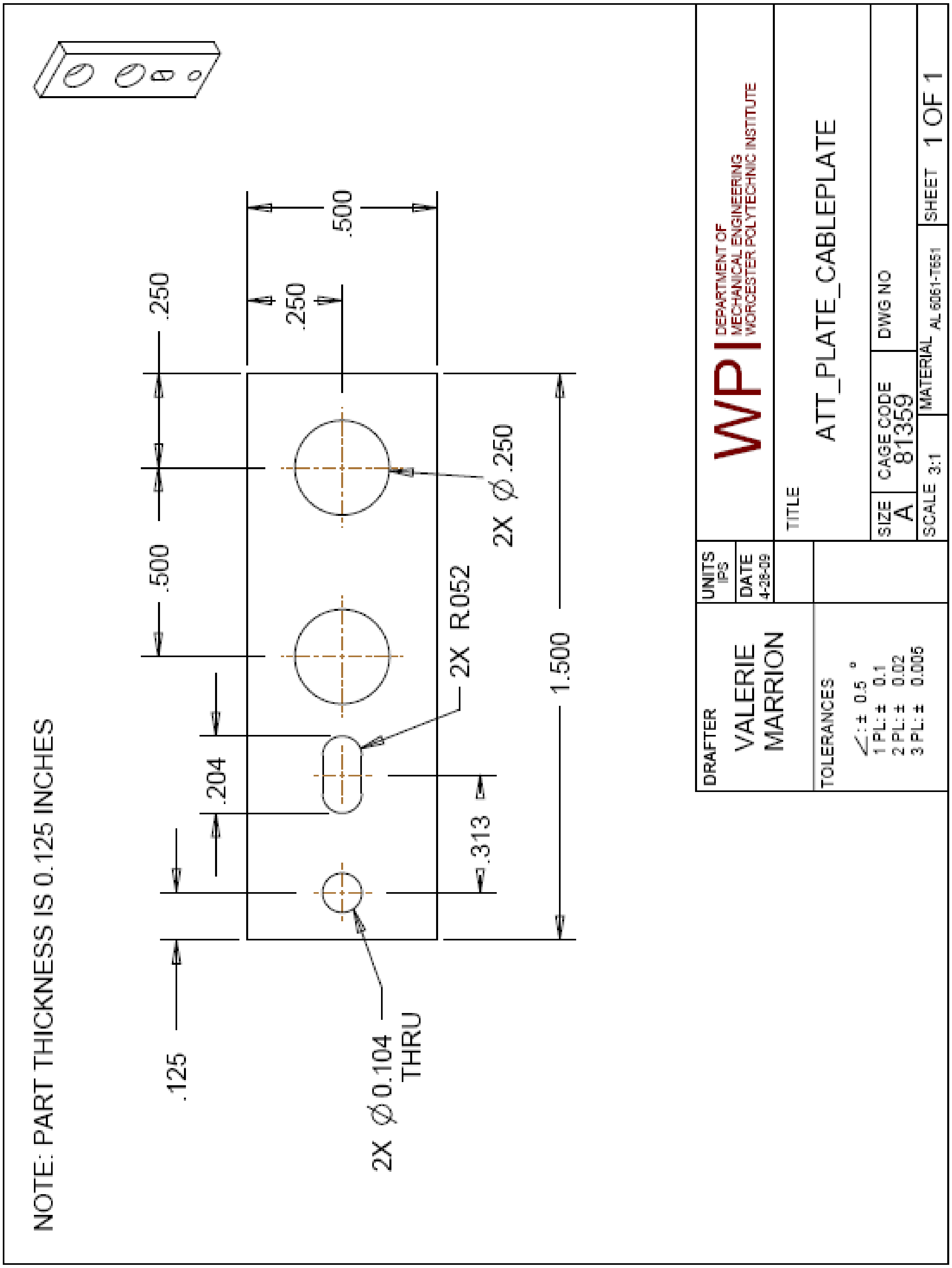
The holes on the attach plate are standard-size threaded holes (UNC 3-48). The clearance holes on the attach plate are to be drilled with a #37 drill so that they have a diameter of 0.104 inches, which is the diameter for a close fit with a 3-48 screw (Henderson, 2009). This nominal value gives an allowable range of 0.099-0.109 inches. The screws to be used for this particular set of holes were ordered from McMaster-Carr (www.mcmaster.com, 2009) and have a major thread diameter of 0.099 inches, thus even the smallest hole should still be equal to the maximum screw diameter. According to the McMaster-Carr website, “many manufacturers consider tolerance information proprietary” and do not provide it, making it very difficult to design the holes based on hardware tolerances. The head diameter of the screw is 0.161 inches, meaning the maximum hole size is still small enough that the screw will hold the plate down.

The nominal distance between the holes is the same on both parts, 0.313 inches, with a toleranced range of 0.308-0.318 inches. One set of holes can be lined up exactly to align the two parts. However, this means that one pair of mating holes has a chance of not lining up if the distances between the holes on the two parts do not match up exactly (maximum possible distance between them is 0.318-0.308 = 0.010 inches). Should this happen, it would be impossible for the screw to be inserted. To avoid this issue, the top of these two holes can be made into a slot with the same 0.104-inch diameter (which will become the width of the slot), but with an addition of +0.005 inches on either side of the original hole, making the slot 0.204 inches long. This option is shown as a blue outline in Figure 120.

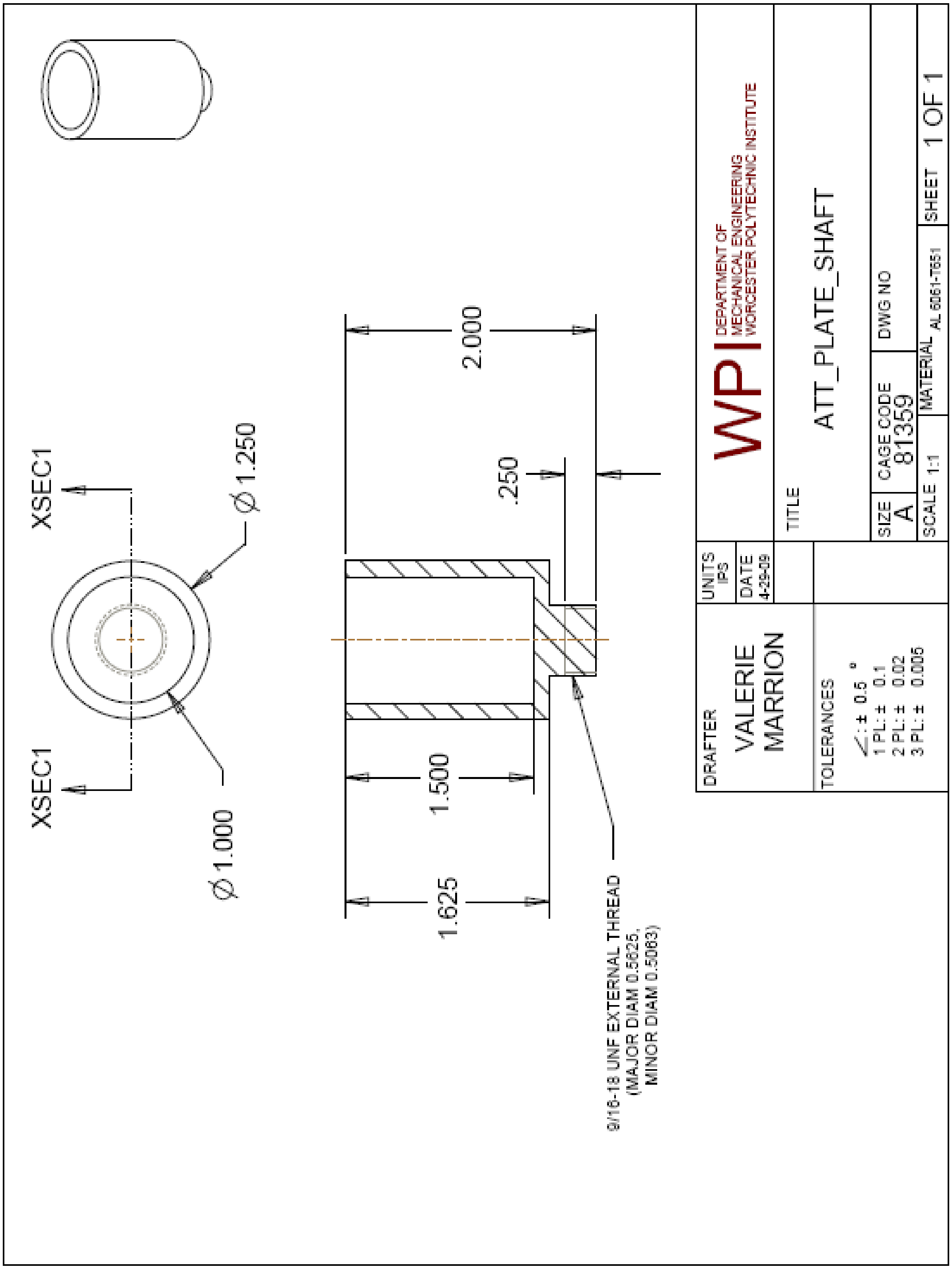
Appendix D: Part Drawings for Manufactured Pieces

The following appendix contains the drawings for all parts manufactured by manual and CNC machines in Higgins Labs and Washburn Shops. They are intended as stand-alone drawings which would allow an individual to reproduce the parts exactly.

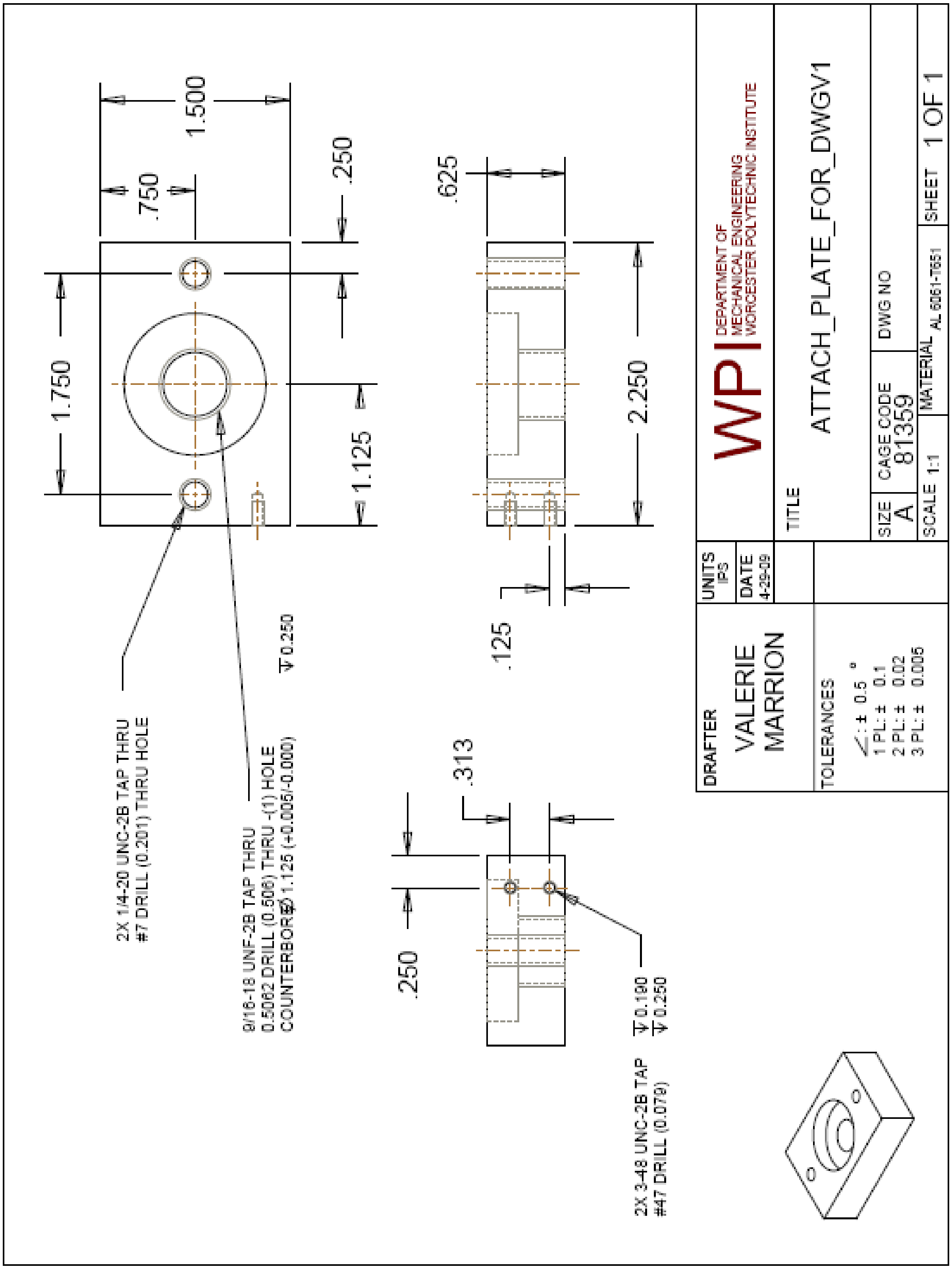
Drawing 1: Attach Plate Cable Plate



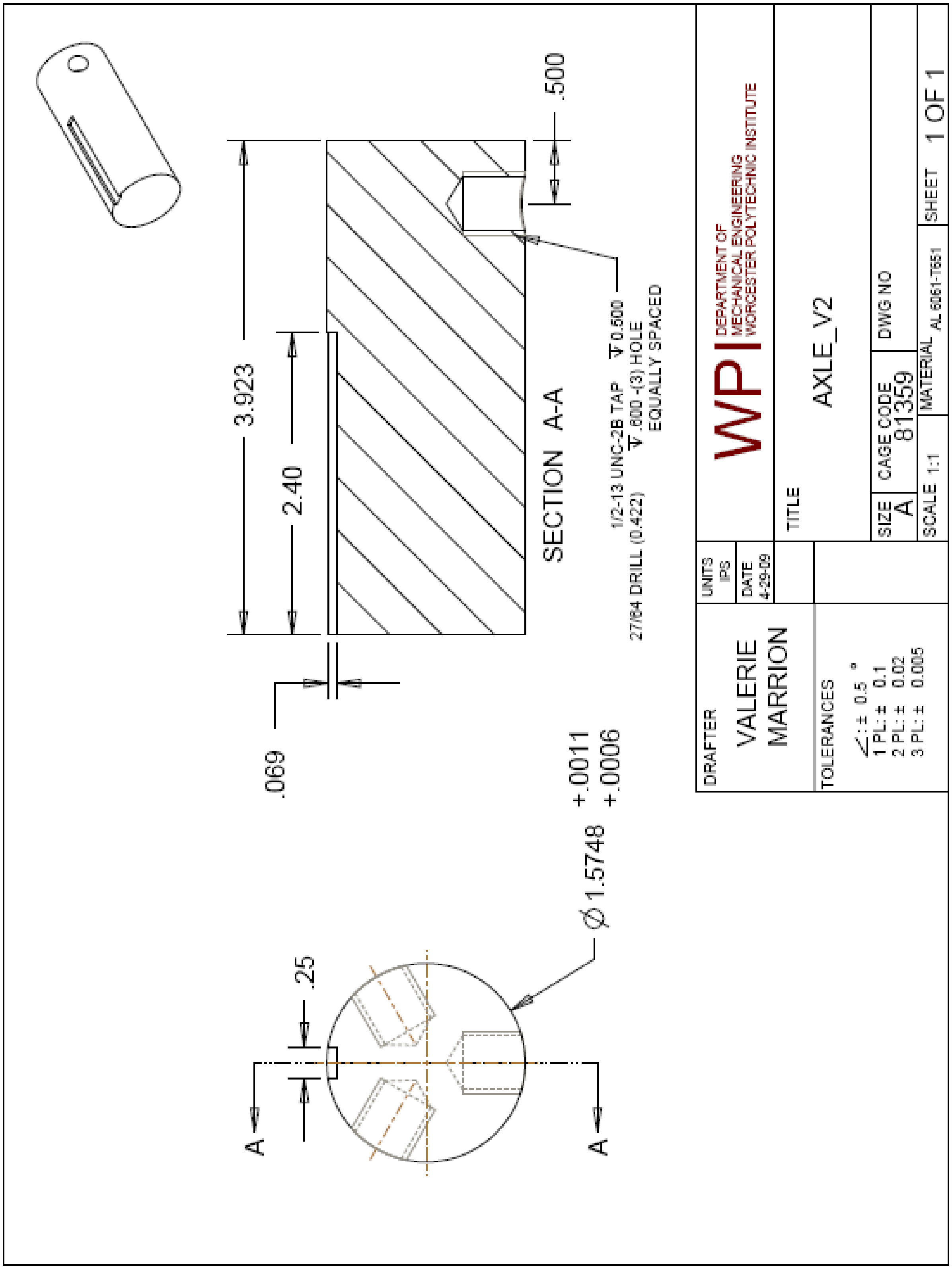
Drawing 2: Attach Plate Shaft



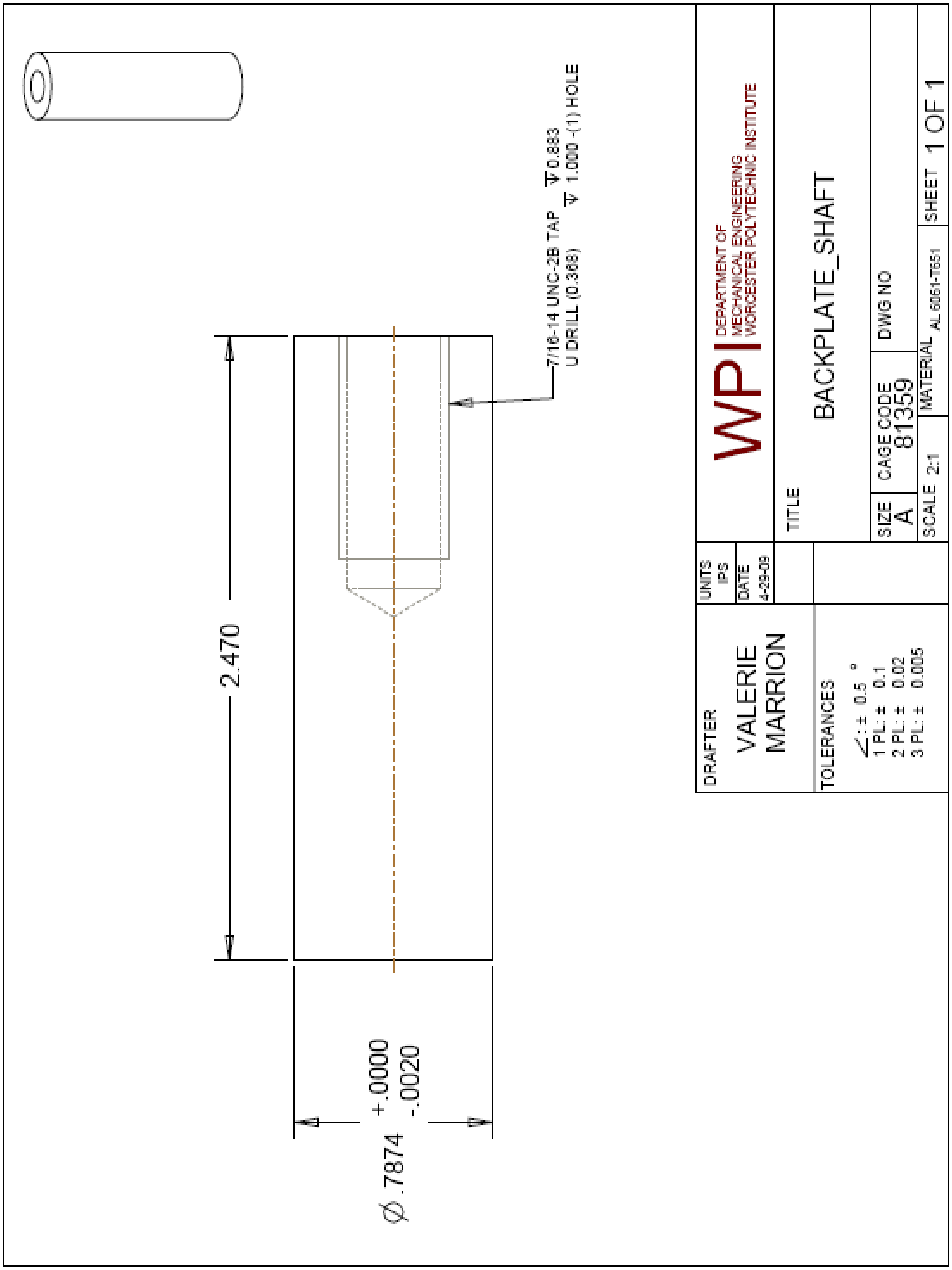
Drawing 3: Attach Plate



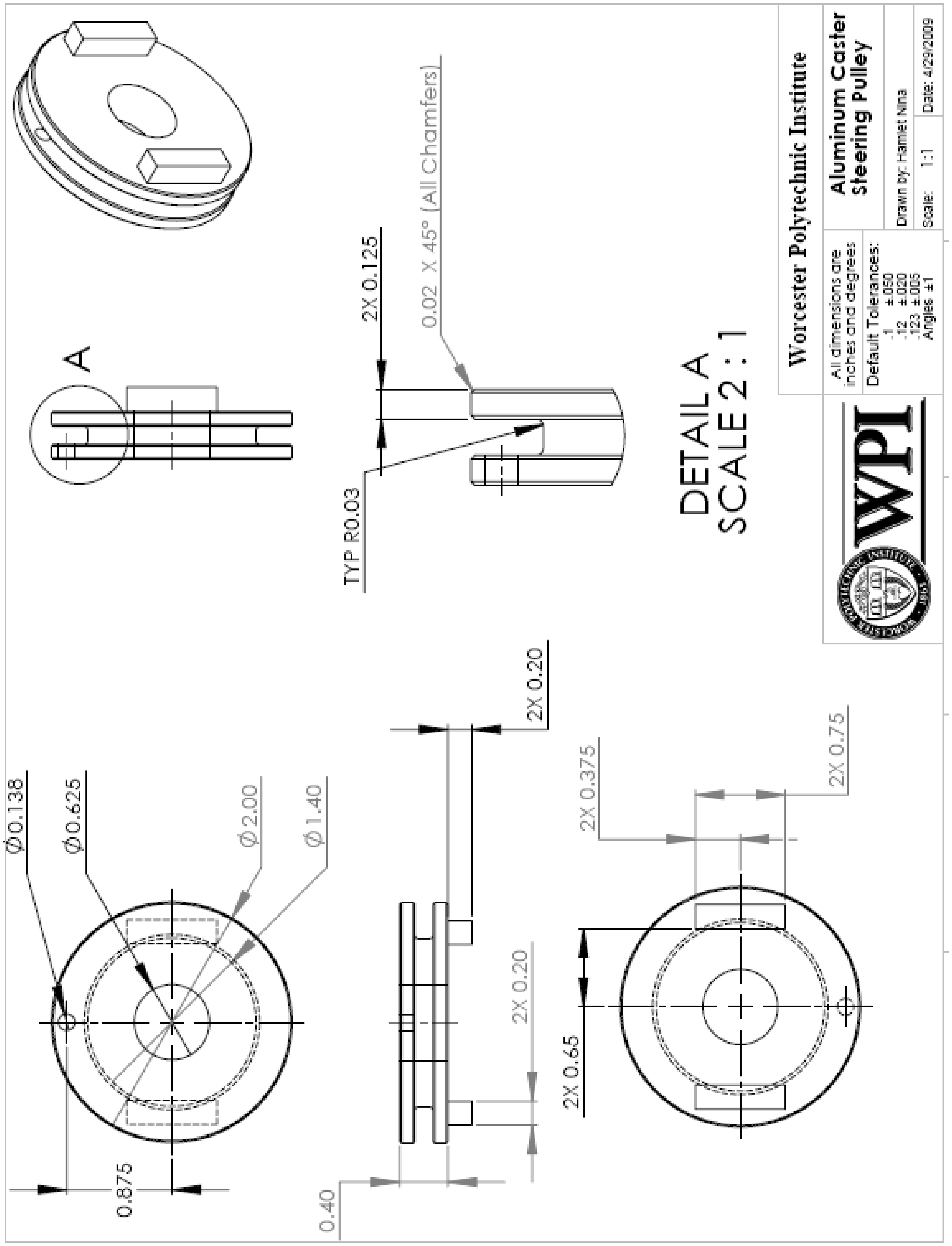
Drawing 4: Axle



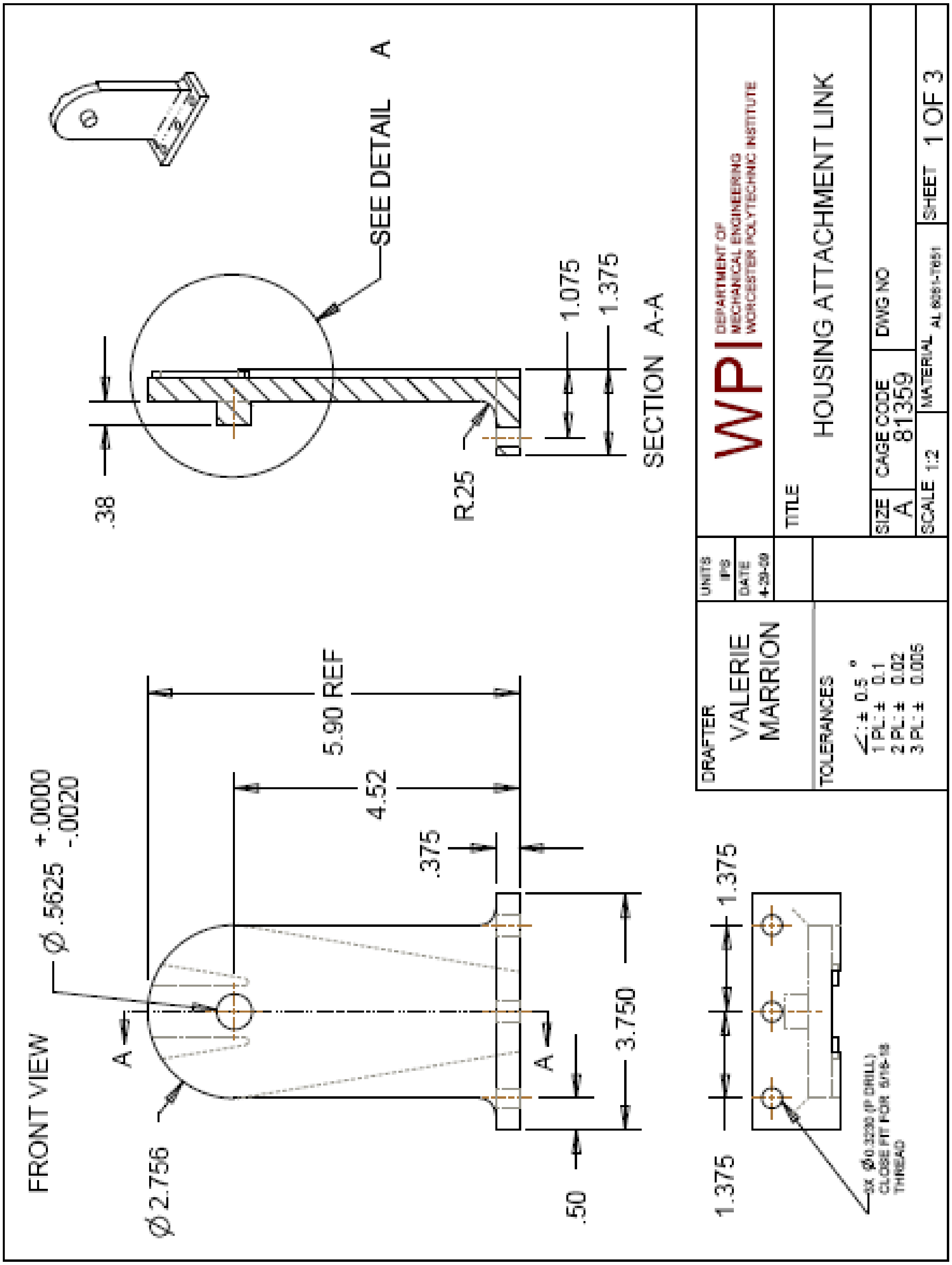
Drawing 5: Backplate Shaft



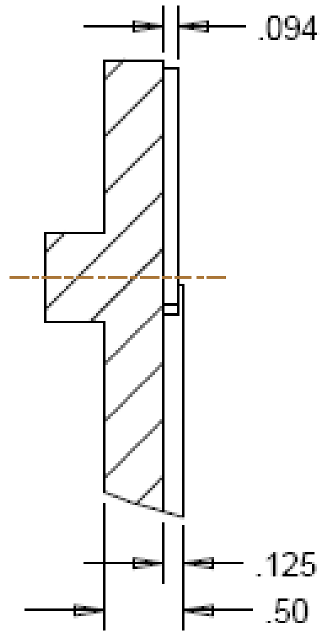
Drawing 6: Caster Pulley



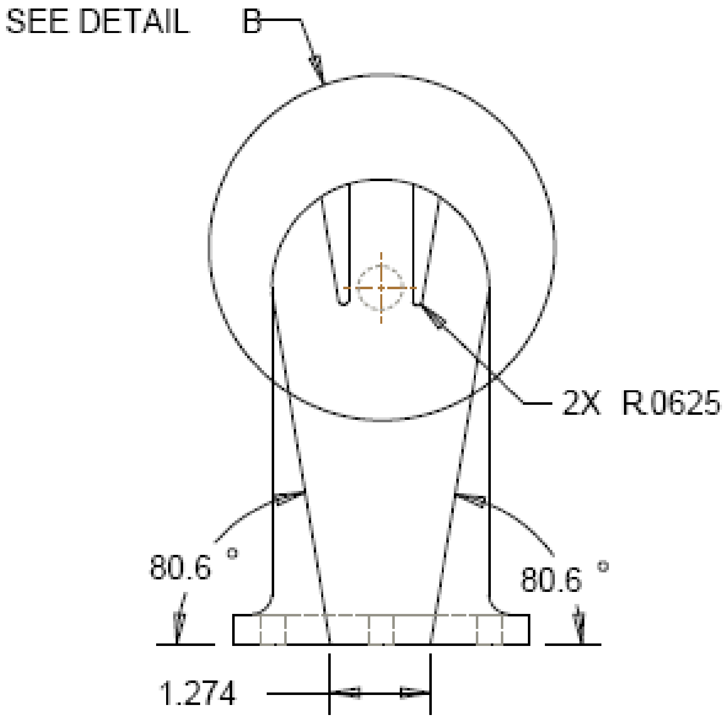
Drawing 7: Housing Attachment Link



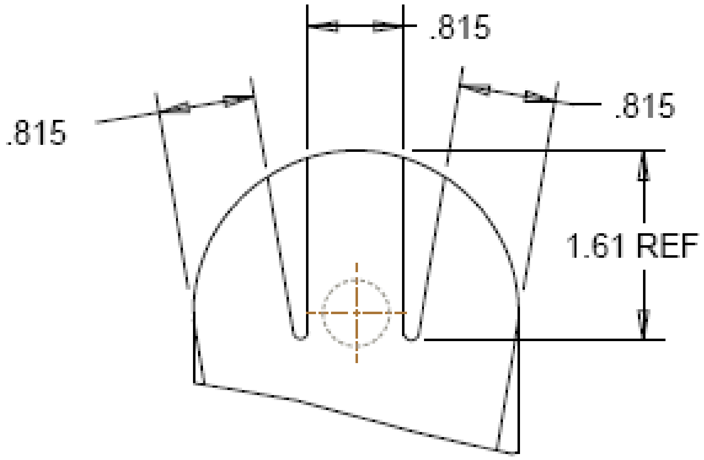
DETAIL A



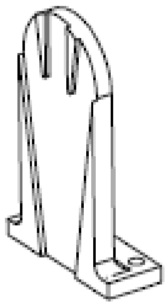
DRAFTER VALERIE MARRION	UNITS IPS DATE 4-29-09	WPI DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE
TOLERANCES ∠: ± 0.5 ° 1 PL: ± 0.1 2 PL: ± 0.02 3 PL: ± 0.005		TITLE HOUSING ATTACHMENT LINK
		SIZE A · CAGE CODE 81359 · DWG NO
		SCALE 1:1 · MATERIAL AL 6061-T651 · SHEET 2 OF 3



BACK VIEW



DETAIL B
SCALE 0.750



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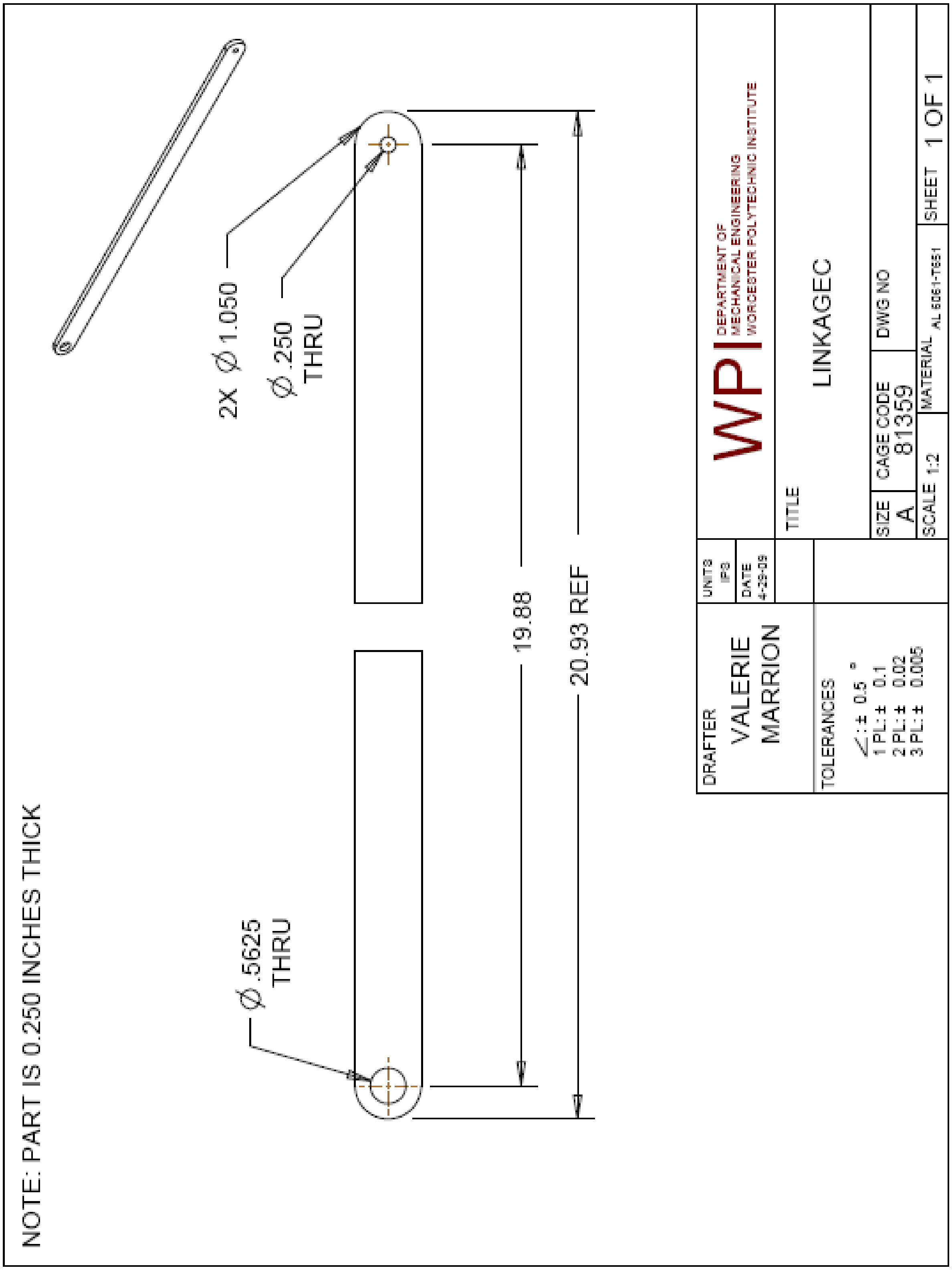
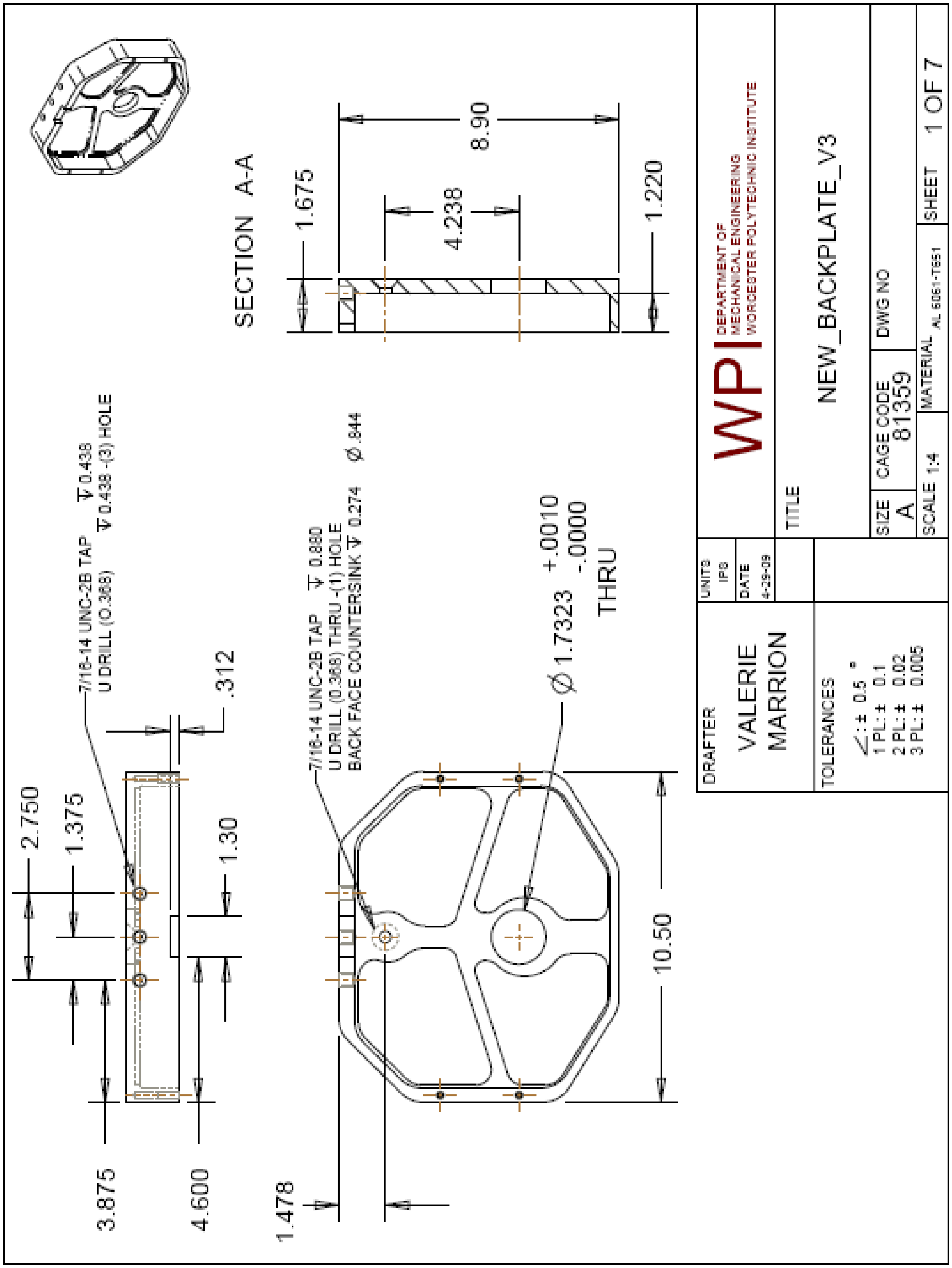
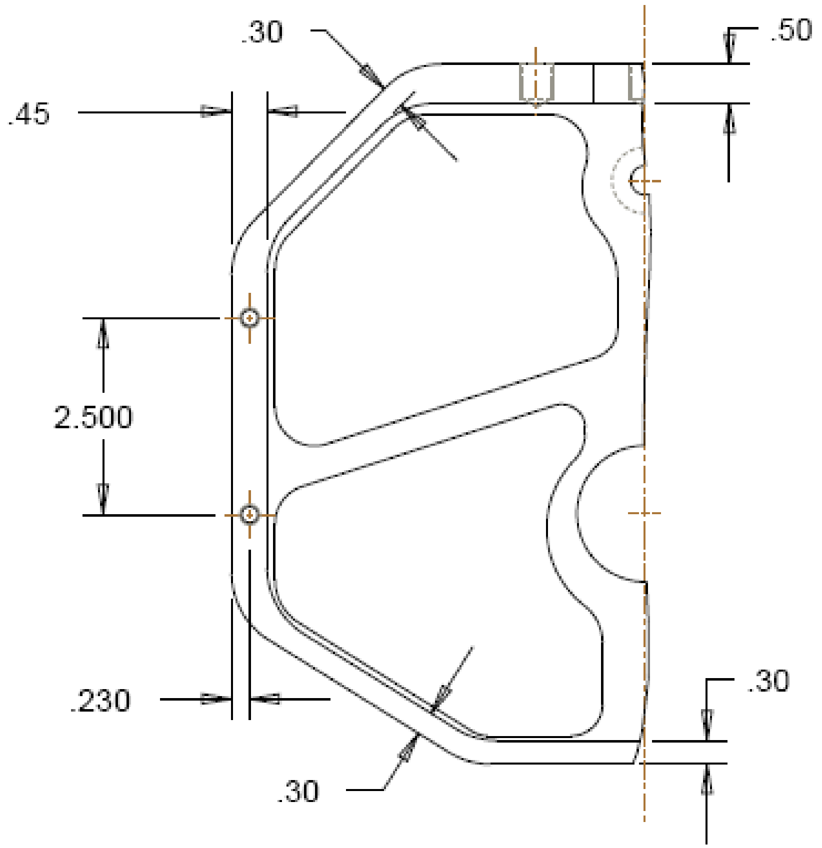
	DATE 4-29-09		
TOLERANCES ∠: ± 0.5 ° 1 PL: ± 0.1 2 PL: ± 0.02 3 PL: ± 0.005		TITLE HOUSING ATTACHMENT LINK	
		SIZE A	CAGE CODE 81359
		DWG NO	
		SCALE 1:2	MATERIAL AL 6061-T651
		SHEET 3 OF 3	

Drawing 8: Coupler



Drawing 9: Backplate





NOTE: SKETCH IS MIRROR IMAGE
ACROSS VERTICAL CENTERLINE;
ONLY ONE SIDE WILL BE DIMENSIONED

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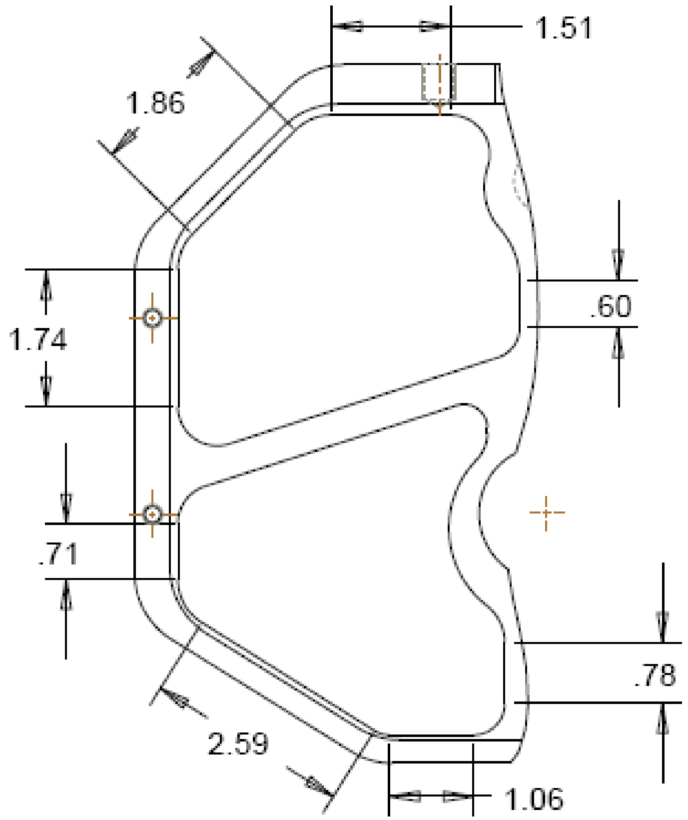
2 PL: ± 0.02
3 PL: ± 0.005

TITLE
NEW_BACKPLATE_V3

SIZE A
CAGE CODE 81359
DWG NO
SCALE 1:2
MATERIAL AL 6061-T651
SHEET 2 OF 7



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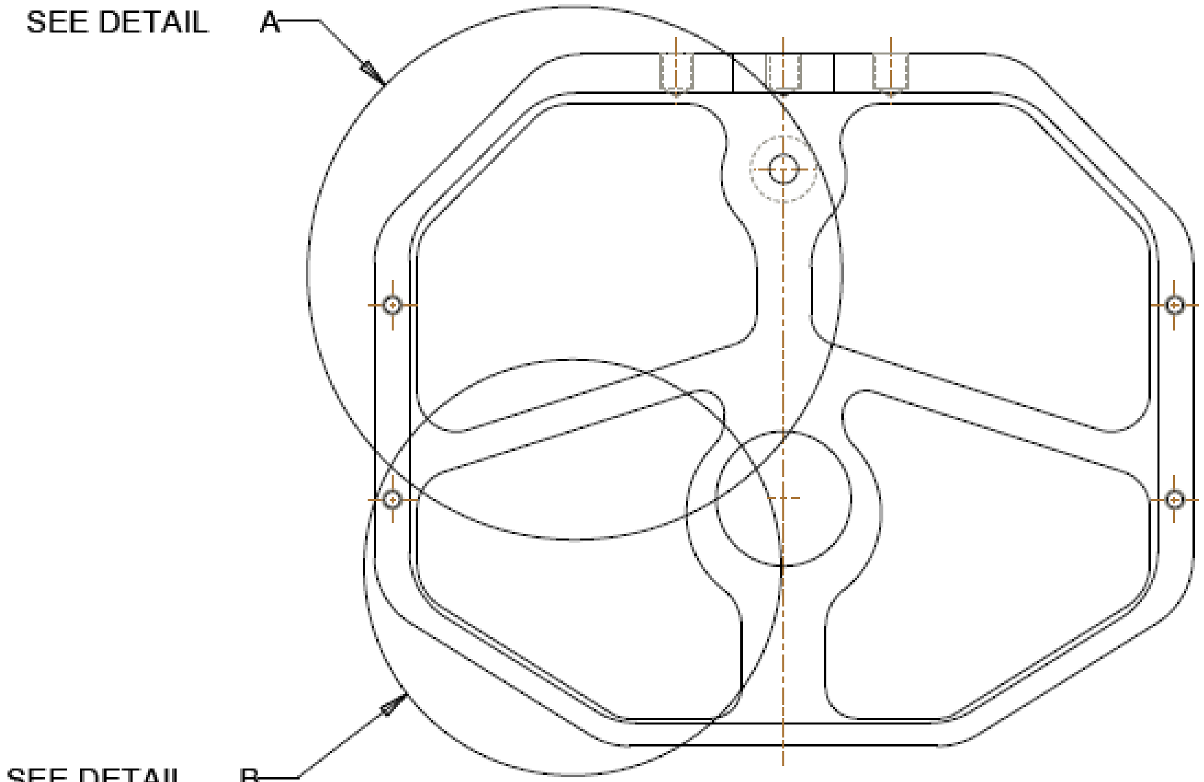
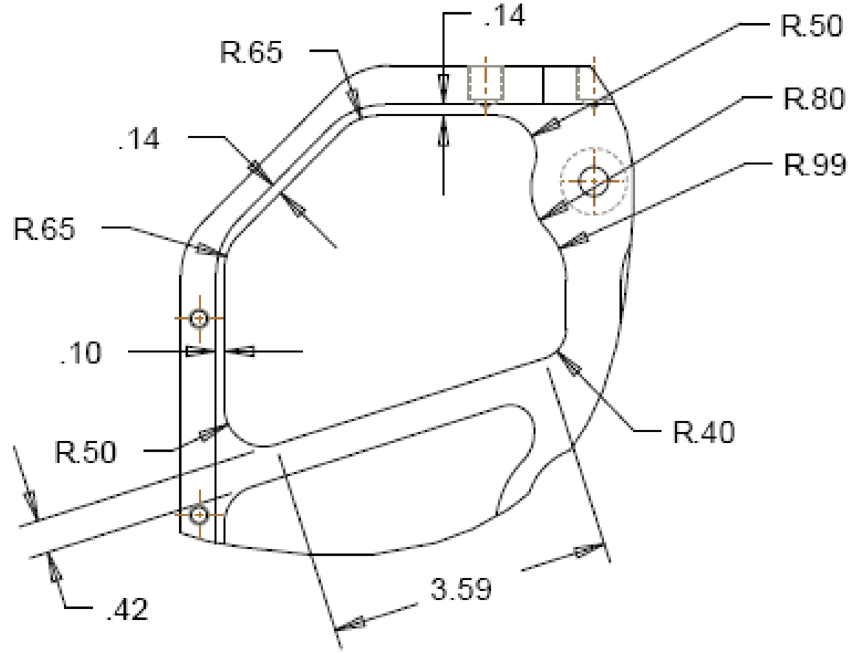
TOLERANCES
∠: ± 0.5 °
1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

SIZE A
CAGE CODE 81359
DWG NO
SCALE 1:2
MATERIAL AL 6061-T651
SHEET 3 OF 7



DRAFTER VALERIE MARRION	UNITS IPS DATE 4-29-09	WPI DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE	
TOLERANCES ∠: ± 0.5 ° 1 PL: ± 0.1 2 PL: ± 0.02 3 PL: ± 0.005		TITLE NEW_BACKPLATE_V3	
		SIZE A	CAGE CODE 81359	DWG NO
		SCALE 1:2	MATERIAL AL 6061-T651	SHEET 4 OF 7



DETAIL A

DRAFTER VALERIE MARRION	UNITS IPS	WPI DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE	
	DATE 4-29-09		
TOLERANCES ∠: ± 0.5 ° 1 PL: ± 0.1 2 PL: ± 0.02 3 PL: ± 0.005		TITLE NEW_BACKPLATE_V3	
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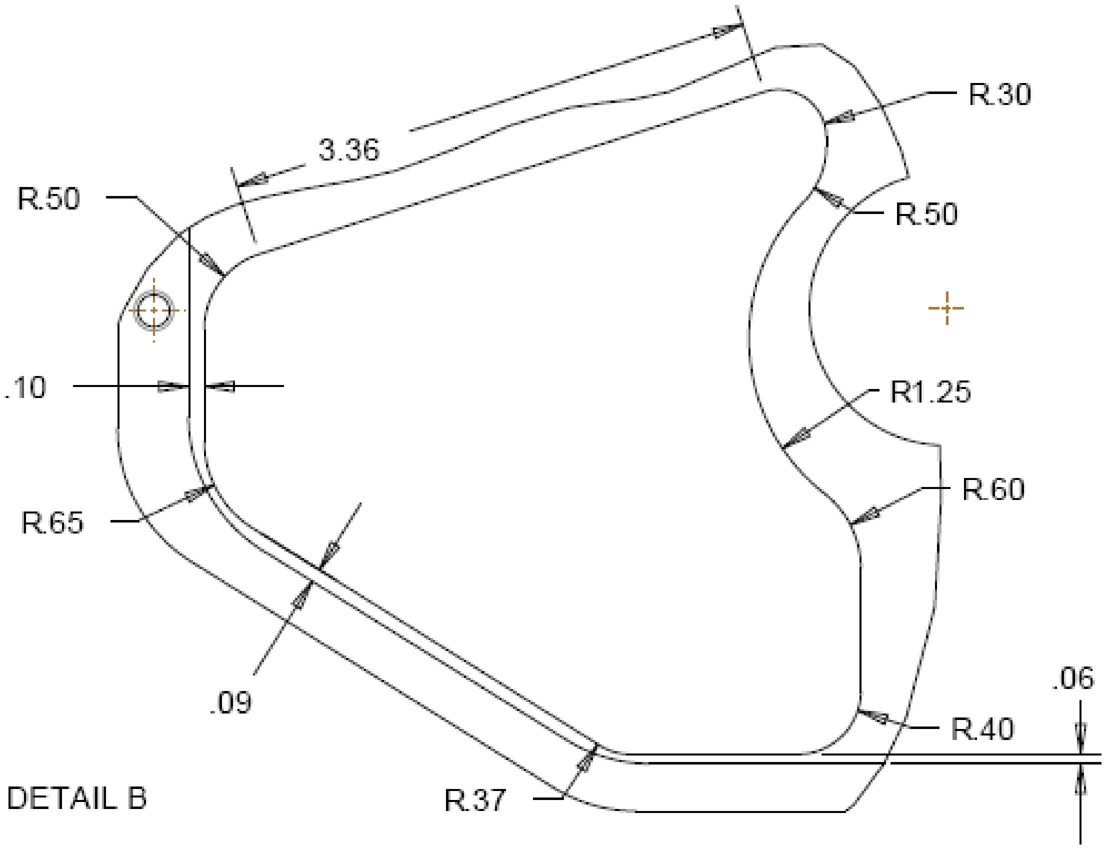
		DWG NO	
		SCALE 1:2	MATERIAL AL 6061-T651
		SHEET 5 OF 7	



DETAIL B

DRAFTER VALERIE MARRION	UNITS IPS DATE 4-29-09	WPI DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE		
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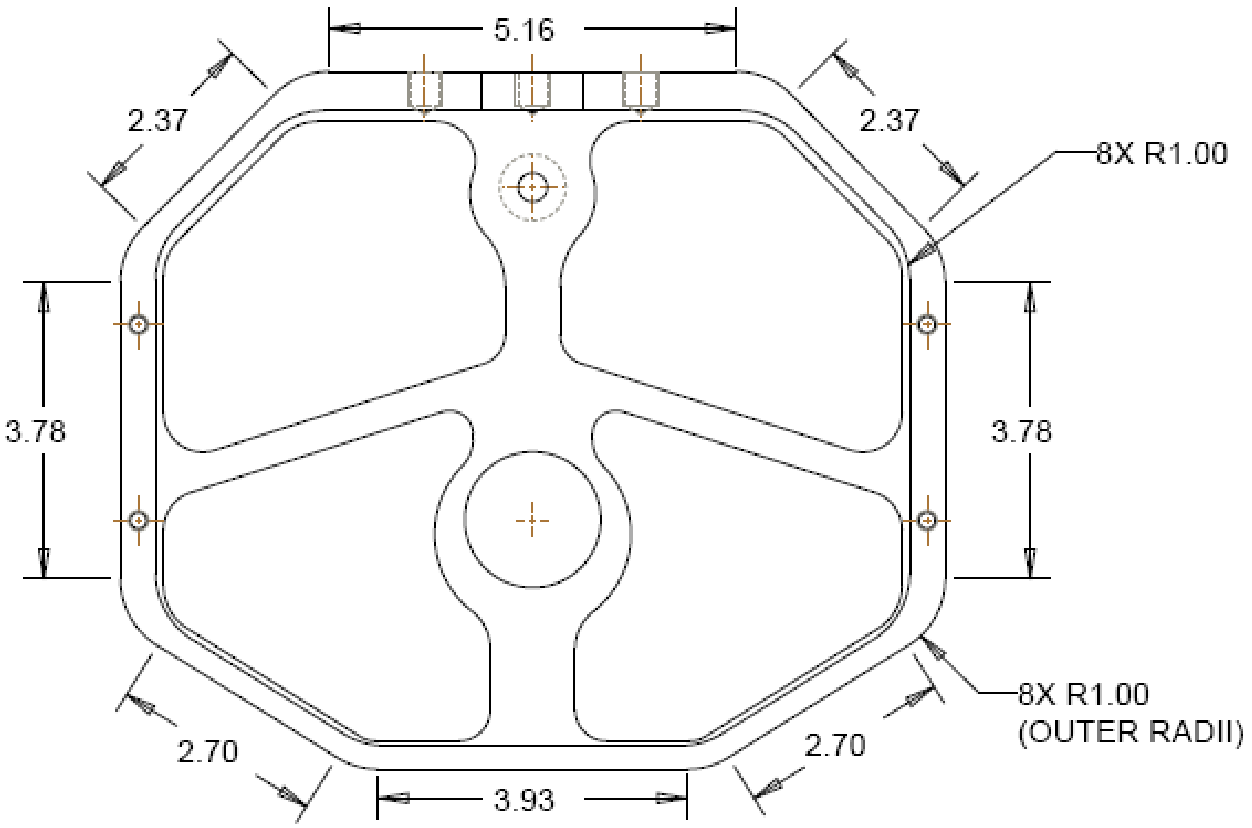
		SIZE A	CAGE CODE 81359	DWG NO
		SCALE 1:1	MATERIAL AL 6061-T651	SHEET 6 OF 7



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2 PL: ± 0.02
3 PL: ± 0.005

TITLE
NEW_BACKPLATE_V3

SIZE
A

CAGE CODE
81359

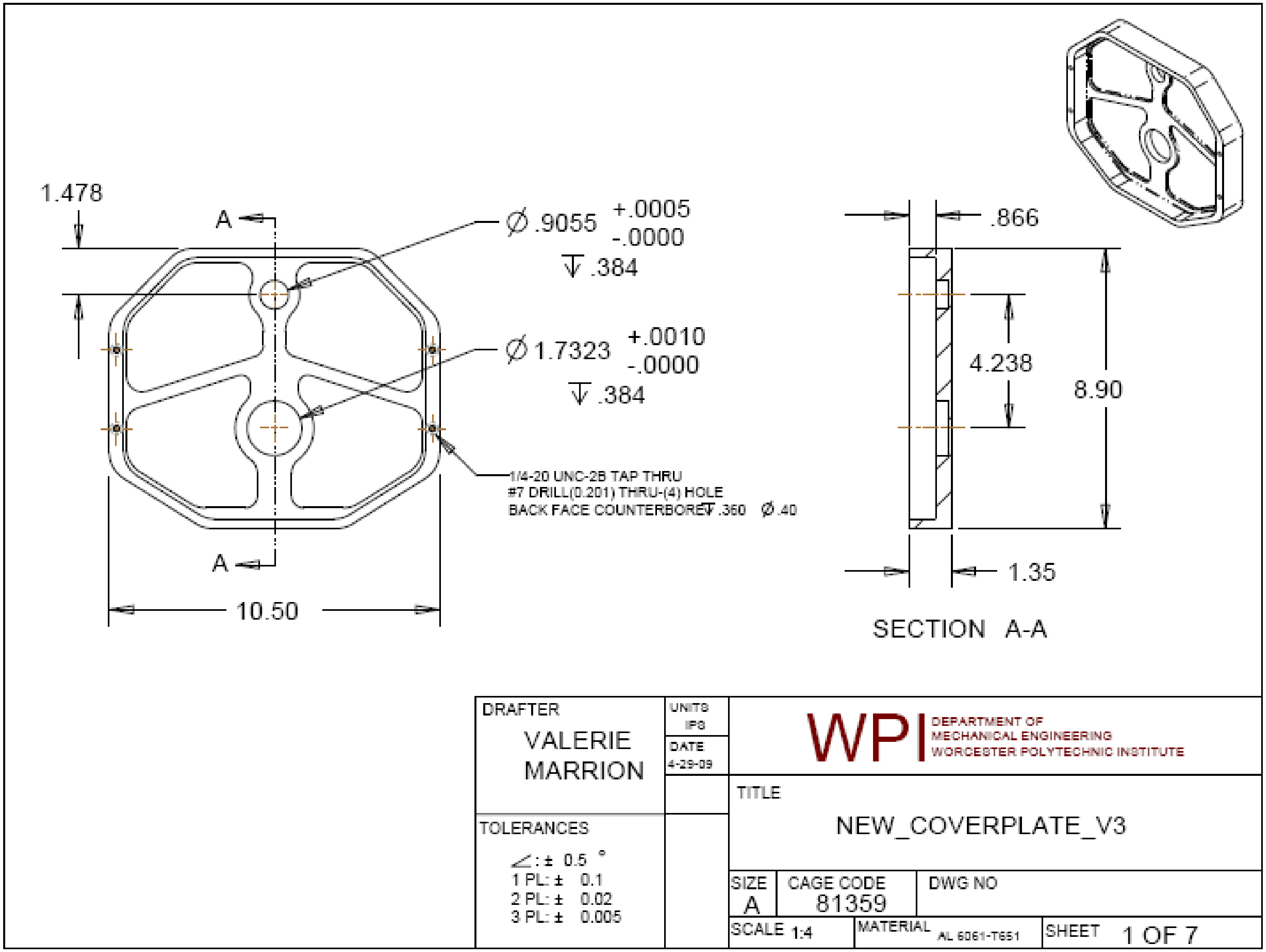
DWG NO

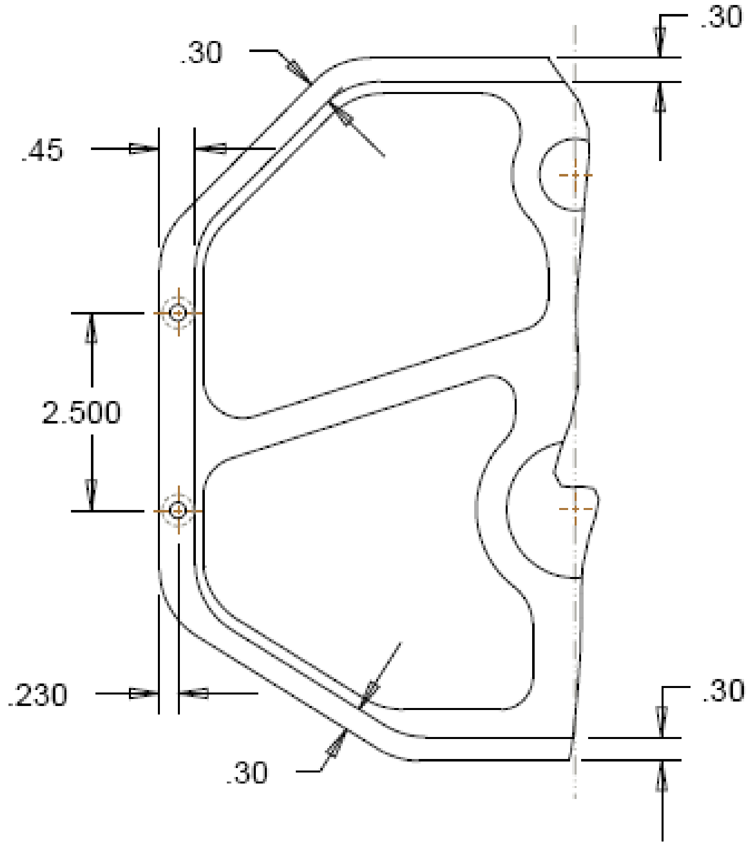
SCALE 1:2

MATERIAL AL 6061-T651

SHEET 7 OF 7

Drawing 10: Coverplate





NOTE: SKETCH IS MIRROR IMAGE
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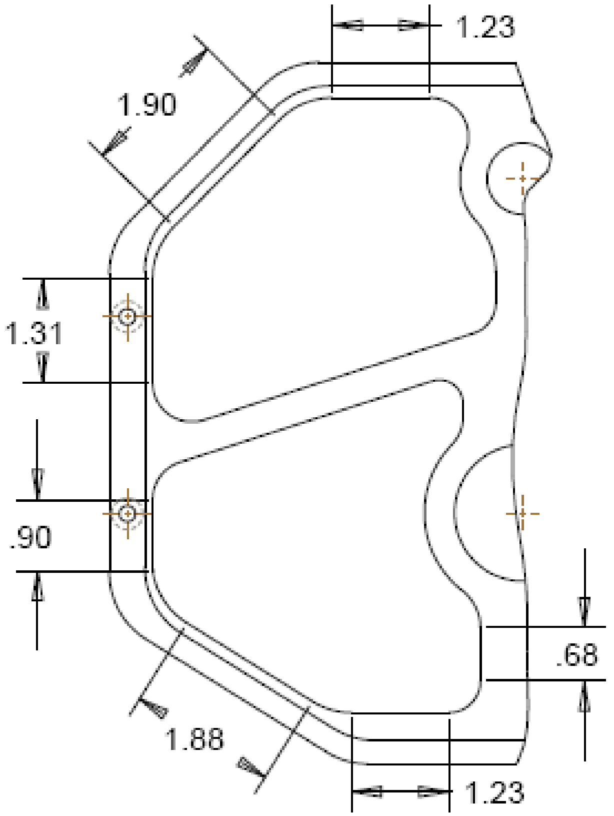
∠: ± 0.5 °
1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

TITLE
NEW_COVERPLATE_V3

SIZE A
CAGE CODE 81359
DWG NO

SCALE 1:2
MATERIAL AL 6061-T651
SHEET 2 OF 7



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1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

SIZE A

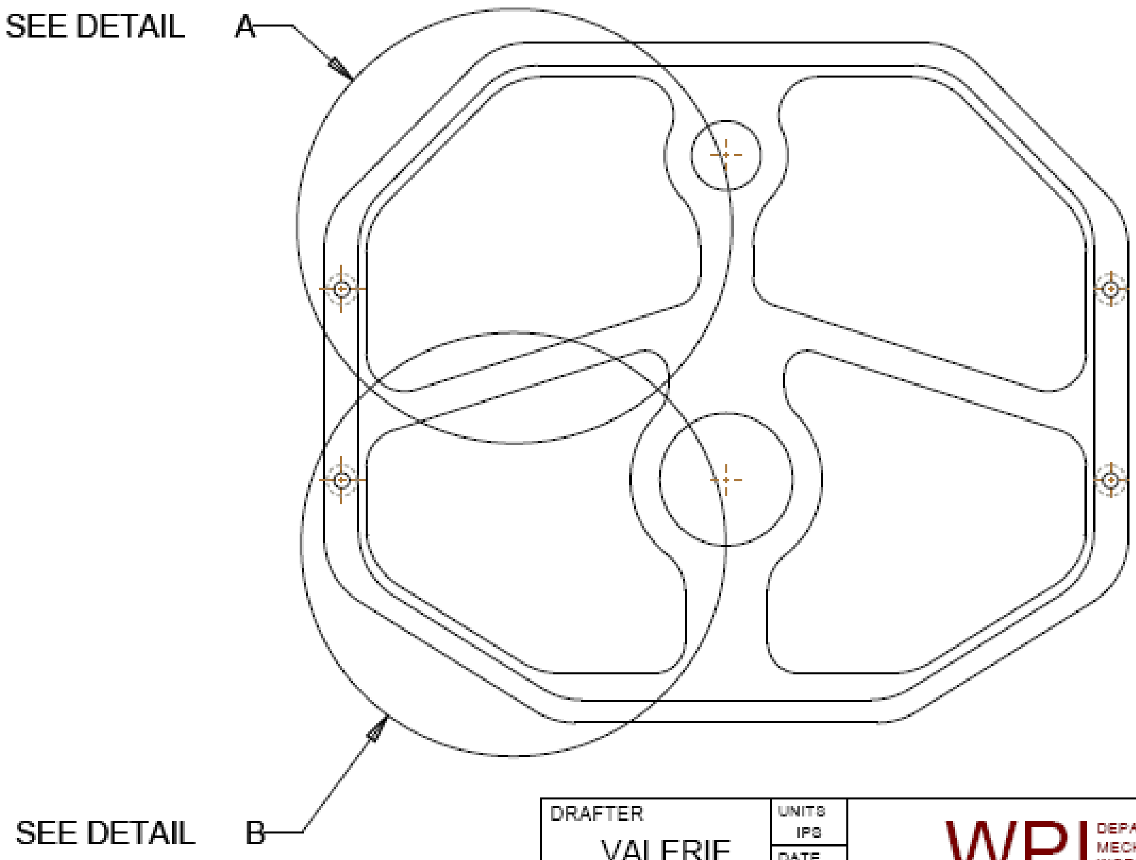
CAGE CODE 81359

DWG NO

SCALE 1:2

MATERIAL AL 6061-T651

SHEET 3 OF 7



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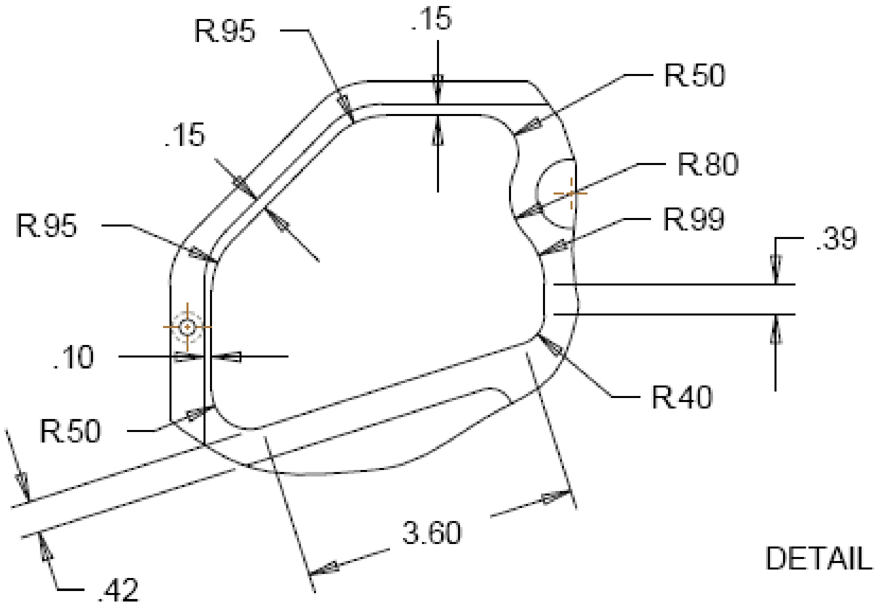
TITLE
NEW_COVERPLATE_V3

TOLERANCES
∠: ± 0.5 °
1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

SIZE	CAGE CODE	DWG NO
A	81359	

SCALE	MATERIAL	SHEET
1:2	AL 6061-T651	4 OF 7



DETAIL A

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TOLERANCES
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1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

TITLE
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SIZE
A

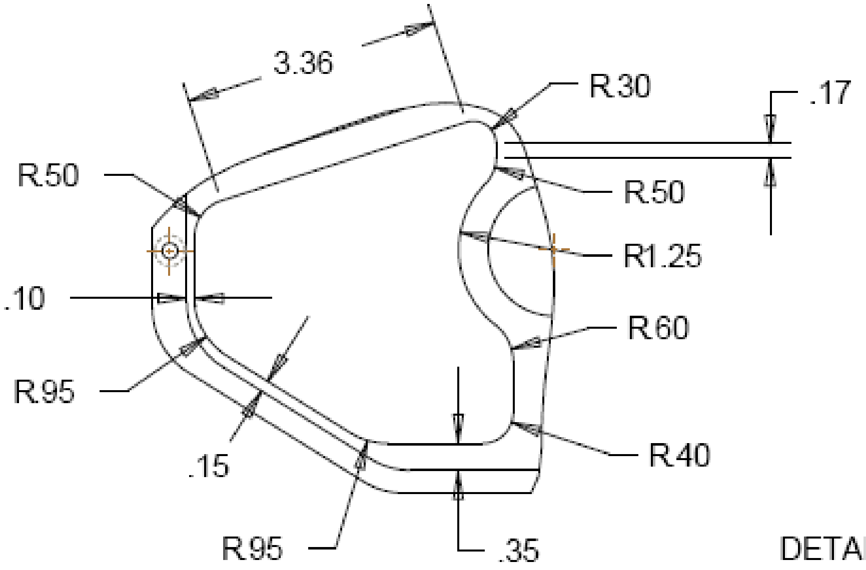
CAGE CODE
81359

DWG NO

SCALE 1:2

MATERIAL AL 6061-T651

SHEET 5 OF 7



DETAIL B

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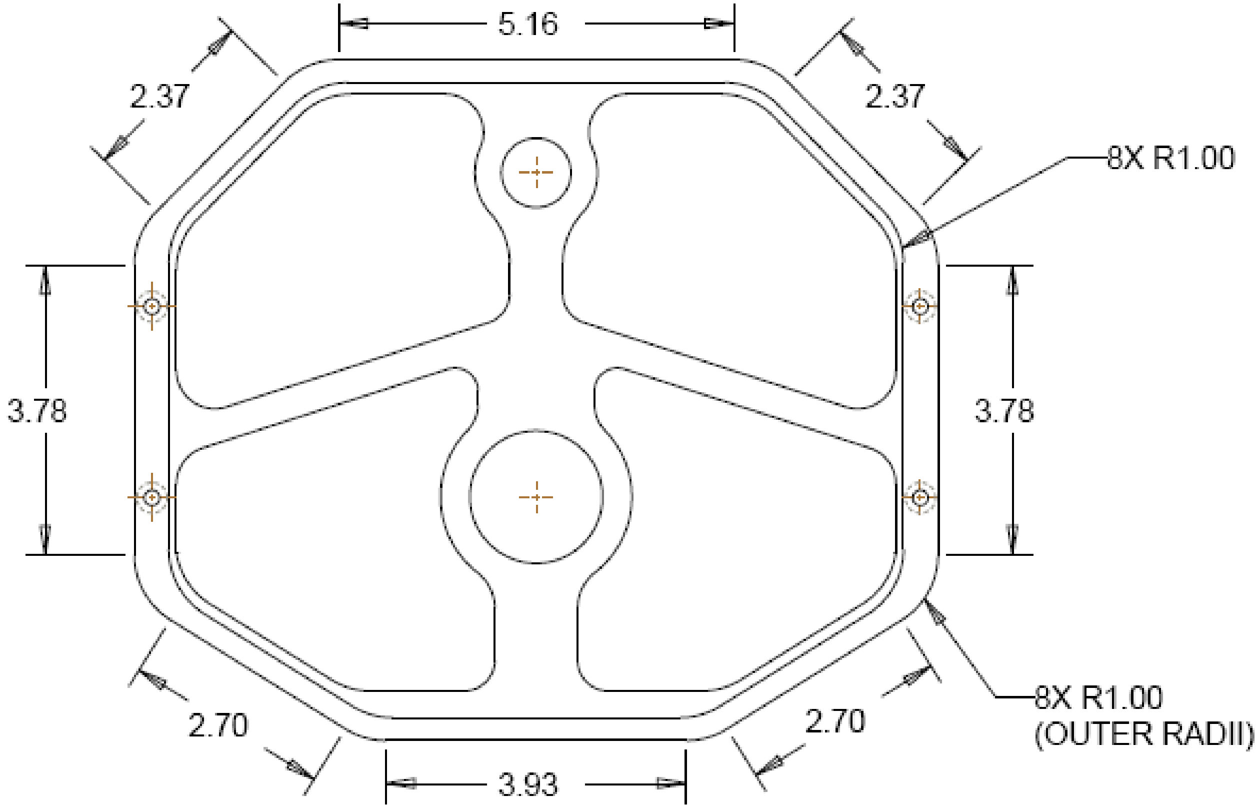
TOLERANCES
∠: ± 0.5 °
1 PL: ± 0.1
2 PL: ± 0.02
3 PL: ± 0.005

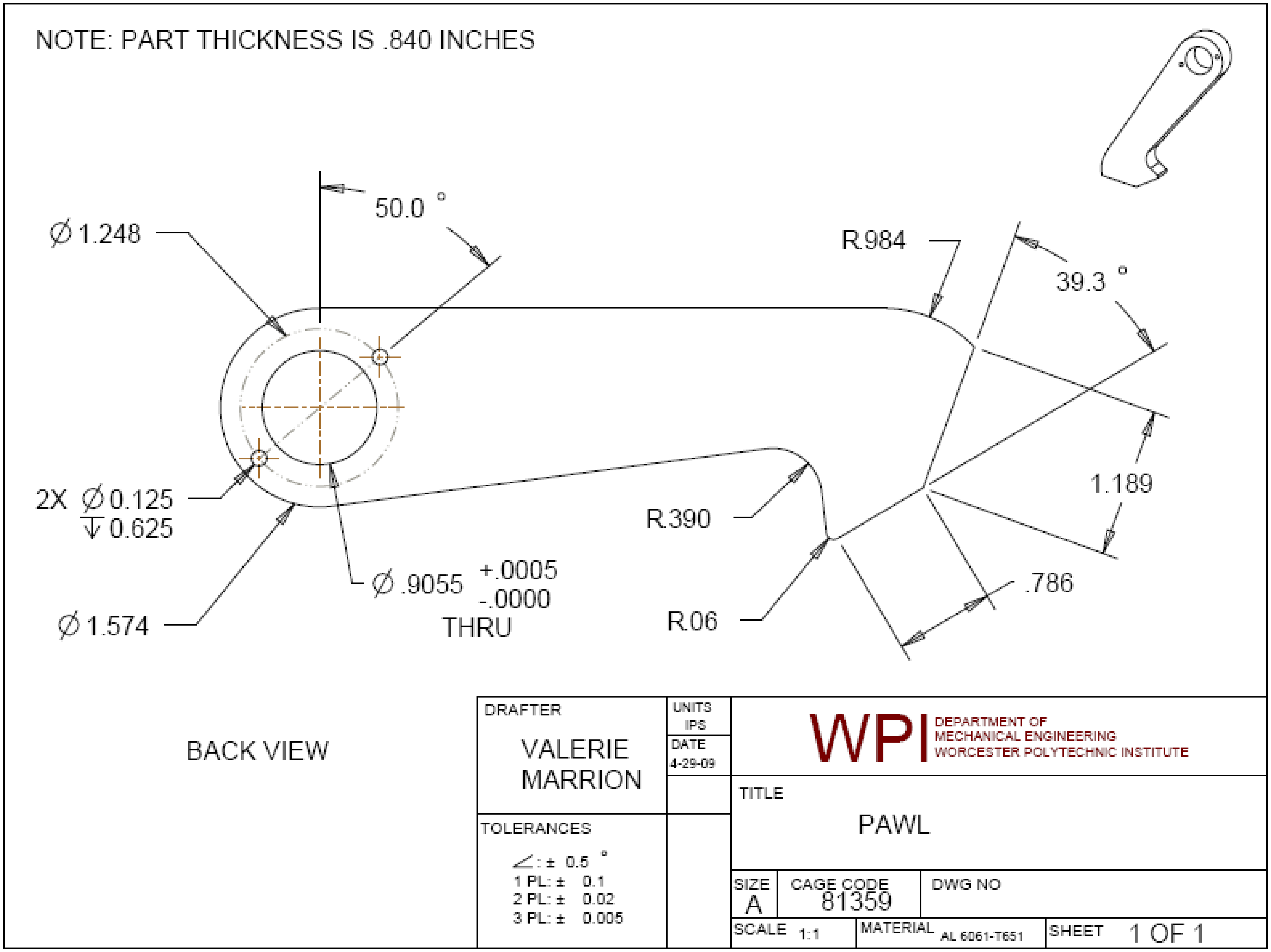
SIZE A
CAGE CODE 81359
DWG NO

SCALE 1:2
MATERIAL AL 6061-T651
SHEET 6 OF 7

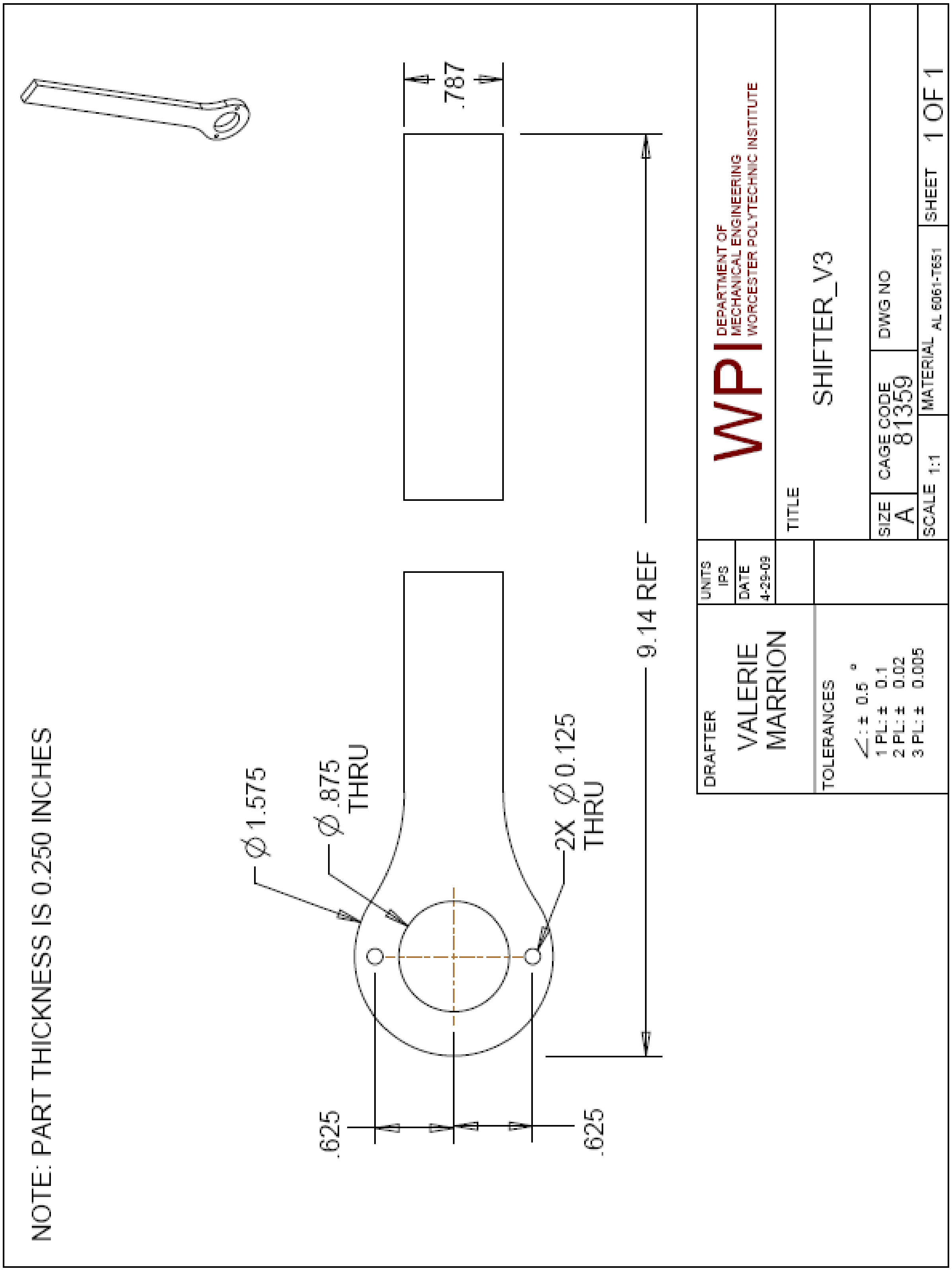


DRAFTER VALERIE MARRION	UNITS IPS DATE 4-29-09	WPI DEPARTMENT OF MECHANICAL ENGINEERING WORCESTER POLYTECHNIC INSTITUTE
		TITLE NEW_COVERPLATE_V3
TOLERANCES ∠: ± 0.5 ° 1 PL: ± 0.1 2 PL: ± 0.02 3 PL: ± 0.005		SIZE A · CAGE CODE 81359 · DWG NO SCALE 1:2 · MATERIAL AL 6061-T651 · SHEET 7 OF 7

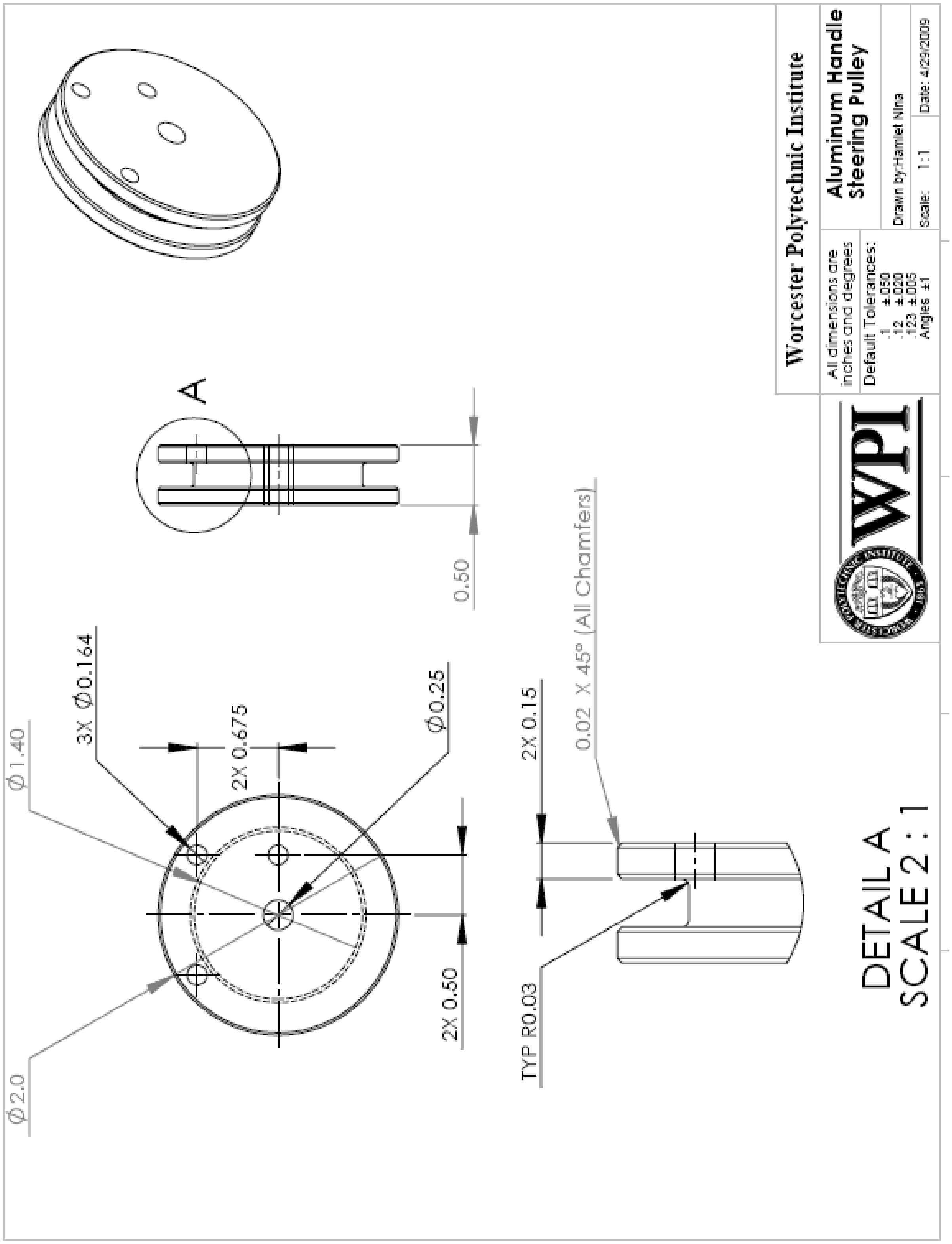
Drawing 11: Pawl



Drawing 12: Shifter



Drawing 13: Steering Pulley



Appendix E: Prototype Photos

The following appendix contains photographs of the prototype during its assembly and testing phases.

Figure 121: Entire Wheelchair Assembly

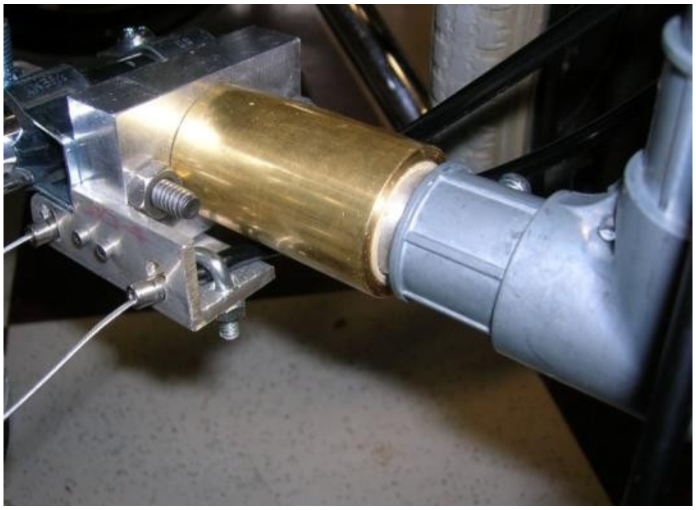


Figure 122: Lever-Frame Attachment

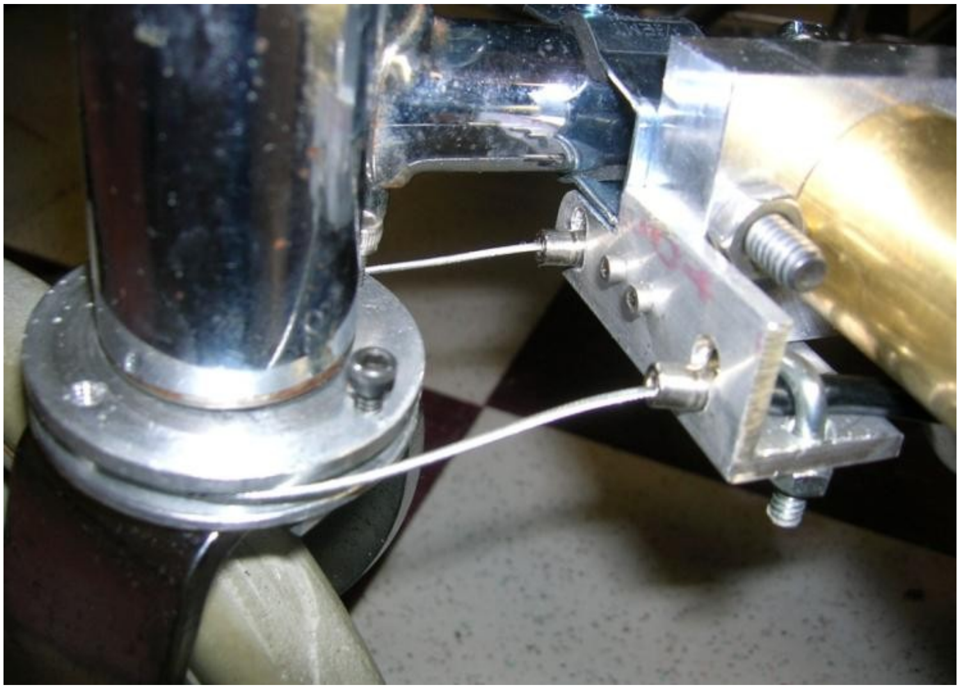


Figure 123: Steering Caster

Figure 124: Handle Assembly

Figure 125: Shifter-Pawl Assembly

Figure 126: Propulsion Mechanism, Interior

Figure 127: Propulsion Mechanism

Appendix F: Raw Evaluation Data (Final Testing)

The following appendix contains the raw data from the final wheelchair assessments in the form of evaluations filled out by the individuals testing the chairs.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	05-06 MQP ~~**Quickie (dual pushrim)**~~	**08-09 Wheelchair MQP**
Forward Propulsion	4	4	3
Backward Propulsion	4	3	2
Turning Right	5	3	1
Turning Left	5	3	3
Forward to Backward Shifting	5	2	2
3 point turning	5	4	
Braking	3	5	5
Parking Brake	3	3	3
Force Required for Operation	5	4	3
Device Usage Comfort	5	4	3
Intuitiveness of Use	5	2	3
Overall Propulsion Mechanism	4	3	4
Overall Turning Mechanism	5	3	1
Overall Braking Mechanism	3	5	5
Totals:			

Additional Comments: for the MQP wheelchair, the handle makes it hard to turn left. Also grinding

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	05-06 MQP ~~**Quickie (dual pushrim)**~~	**08-09 Wheelchair MQP**
Forward Propulsion	5	2	4
Backward Propulsion	5.	2	—
Turning Right	3	3	2
Turning Left	3	3	2
Forward to Backward Shifting	4	2	—
3 point turning	4	4	—
Braking	2	4	4
Parking Brake	2	3	3
Force Required for Operation	4	1	2
Device Usage Comfort	4	2	2
Intuitiveness of Use	4	3	3
Overall Propulsion Mechanism	4	2	2
Overall Turning Mechanism	4	3	2
Overall Braking Mechanism	3	3	3
Totals:			

Additional Comments:

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	05-06 MQP ~~**Quickie (dual pushrim)**~~	**08-09 Wheelchair MQP**
Forward Propulsion	4	3	5
Backward Propulsion	5	4	2
Turning Right	5	3	4
Turning Left	5	3	1
Forward to Backward Shifting	4	2	2
3 point turning	4	4	2
Braking	2	5	4
Parking Brake	3	5	4
Force Required for Operation	4	3	5
Device Usage Comfort	5	3	3
Intuitiveness of Use	5	3	3
Overall Propulsion Mechanism	4	3	5
Overall Turning Mechanism	5	1	1
Overall Braking Mechanism	3	4	3
Totals:			

Additional Comments:

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	05-06 MQP ~~**Quickie (dual pushrim)**~~	**08-09 Wheelchair MQP**
Forward Propulsion	3	3	4
Backward Propulsion	3	5	4
Turning Right	5	3	4
Turning Left	5	3	1
Forward to Backward Shifting	5	3	2
3 point turning	4	4	6
Braking	4	4	3
Parking Brake	N/A	N/A	N/A
Force Required for Operation	4	3	3
Device Usage Comfort	5	2	2
Intuitiveness of Use	5	3	4
Overall Propulsion Mechanism	4	3	5
Overall Turning Mechanism	5	3	1
Overall Braking Mechanism	4	4	3
Totals:			

Additional Comments:

Very noisy

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 2=Fair 3=Good 4=Very good 5=Excellent

Categories	Meyra Chair	05-06 MQP ~~Quickie (dual pushrim)~~	08-09 Wheelchair MQP
Forward Propulsion	3	4	4
Backward Propulsion	3	4	4
Turning Right	4	4	2
Turning Left	4	4	2
Forward to Backward Shifting	3	2	2
3 point turning	4	3	N/A
Braking	1	3	3
Parking Brake	N/A	N/A	N/A
Force Required for Operation	4	1	2
Device Usage Comfort	4	2	2
Intuitiveness of Use	4	3	3
Overall Propulsion Mechanism	4	4	4
Overall Turning Mechanism	4	5	2
Overall Braking Mechanism	2	4	4
Totals:			

Additional Comments:

↑
over turned

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	05-06 MQP ~~**Quickie (dual pushrim)**~~	**08-09 Wheelchair MQP**
Forward Propulsion	4	4	5
Backward Propulsion	4	4	5
Turning Right	4	2	4
Turning Left	4	2	4
Forward to Backward Shifting	4	3	4
3 point turning	4	~~3~~ 4	NA
Braking	3	4	4
Parking Brake	NA	NA	NA
Force Required for Operation	3	2	4
Device Usage Comfort	5	3	5
Intuitiveness of Use	4	4	4
Overall Propulsion Mechanism	4	3	5
Overall Turning Mechanism	4	3	4
Overall Braking Mechanism	4	3	4
Totals:	50		

Additional Comments:

→ the 05-06 chair turning was very sensitive so it was hard to drive straight.

→ The 08-09 chair was almost as easy to steer as the Meyra, but was easier to drive (less force needed to drive)

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor **2=Fair** **3=Good** **4=Very good** **5=Excellent**

Categories	**Meyra Chair**	~~**Quickie (dual pushrim)**~~ 05-06 MQP	**08-09 Wheelchair MQP**
Forward Propulsion	4	5	5
Backward Propulsion	4	3	5
Turning Right	4	4	3
Turning Left	4	4	3
Forward to Backward Shifting	4	1	3
3 point turning	4	2	3
Braking	3	4	4
Parking Brake	3	4	4
Force Required for Operation	3	4	5
Device Usage Comfort	3	3	4
Intuitiveness of Use	4	4	4
Overall Propulsion Mechanism	4	3	5
Overall Turning Mechanism	3	4	3
Overall Braking Mechanism	3	4	3
Totals:			

Additional Comments:

The mqp chair feels a lot more comfortable to use, but turning is hard.

Rate the following one-arm propelled wheelchairs on a scale from 1 to 5.

1= Poor 2=Fair 3=Good 4=Very good 5=Excellent

Categories	Meyra Chair	05-06 MQP ~~Quickie (dual pushrim)~~	08-09 Wheelchair MQP
Forward Propulsion		3	4
Backward Propulsion		2	2
Turning Right		Over turn difficult worked 3	5
Turning Left		3	2
Forward to Backward Shifting		1	2
3 point turning		4	1
Braking		5	3
Parking Brake		N/A	5
Force Required for Operation		5	5
Device Usage Comfort		3	4
Intuitiveness of Use		3	5
Overall Propulsion Mechanism		Sounds annoying 4	3
Overall Turning Mechanism		4	2
Overall Braking Mechanism		3	4
Totals:			

Additional Comments:

Appendix G: Stress Analysis

The following appendix contains a partial stress analysis conducted on key components of the accessory.

The force exerted on the entire drive system can be taken from previous calculations on internal angles and mechanical advantage change over the stroke (Figure 128).

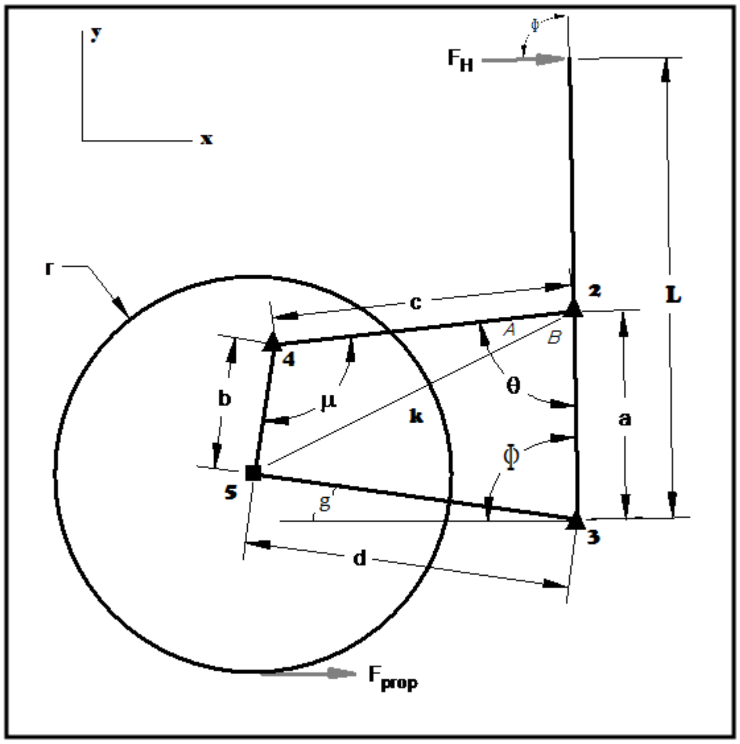


Figure 128: Simple Representation of Wheelchair Accessory

In Section 7.3, the dependence and force transfer were calculated in a simple model of the propulsion accessory. The stress analysis will use the numbers calculated in the worst case scenario. The maximum values were all found to occur when the angle of the input lever to the ground, φ, was equal to 90 degrees, and the length of the variable link, a, was equal to 3.937” (0.1m). Using the equations from the previous section, the angle of the input forces in this configuration, μ, is 76.16°. Finally, the maximum force transferred through link c in this case is approximately 396.6 lb (1764 N).

Shear stresses, tensile stresses, and compressive stresses are all calculated using this equation:

$$\tau \text{ } or \text{ } \sigma = \frac{F}{A}$$

where F is the applied force and A is the cross sectional area of the piece. Bending, which is a combination of tension and compression uses this equation

$$\sigma = \frac{Mc}{I}$$

where *M* is the moment created by force acting on a beam at a defined point, *c* is a distance from the neutral bending plane of the material, and *I* is the moment of inertia of the cross section of the part. Torsion uses a similar equation,

$$\tau = \frac{Tc}{J}$$

where *T* is the torque around the center of mass of the cross section of the part, *c* is a distance away from that center, and *J* is the rotational moment of inertia of that cross section. In these situations, *c* will be the maximum distance from the center, a point on the surface, to approximate maximum stresses.

These equations assume a uniform distribution of stresses, and cannot be used to represent all geometries and loading conditions. With that in mind, much of this analysis is approximate, and gives an idea of scale and appropriateness of safety factors. Failure conditions are given by the upper elastic limit of deformation for aluminum alloy 6061, which is 20.3 ksi (140 MPa) in shear and 34.8 ksi (240 MPa) in tension or compression. The area of interest for this analysis is the housing and drive mechanism, which occupy the link b configuration in Figure 128. The first part to consider is the link attached to the top of the housing where link c is connected (Figure 129). *F* is the applied force from the coupler, or link c.

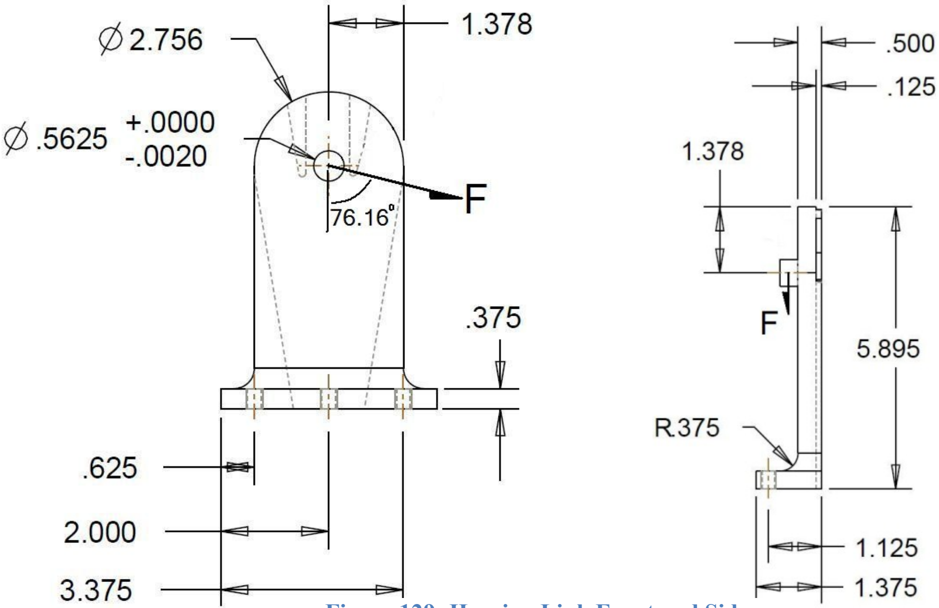


Figure 129: Housing Link Front and Side

Shear stress and bending stress are both present on the post protruding from the surface of the link. This post acts as the pin for the joint between this link and link c. For this problem, it is assumed that the rest of the link will not deform, to isolate the post. The resulting shear stress in the post is approximately 812.2 psi (5.6 MPa) and the maximum stresses due to bending are approximately 11.3 ksi (78.1 MPa), both below their respective maximums with a minimum safety factor of 3.

Because the force acts on the post, the main body of the link will undergo torsion, and bending, as well as compression. For this problem, some simplifying assumptions were made. First, it is assumed that the link is 0.375" wide, ignoring the 0.125" deep grooves on the back surface used to engage the shifting mechanism. These calculations also deal only with the plate like section of the part, and not the foot used to mount to the housing. The stresses have been approximated to:

$$\tau \text{Torsion} = 841.2 \text{ psi } (5.8 \text{ MPa})$$

$$\sigma \text{Bending (with compression)} = 4.12 \text{ ksi } (28.4 \text{ MPa})$$

While these numbers do not represent the true maximum stress due to the compound loading of this part, they are far enough below the yield stress of the material that their combined effect will not cause damage to the system.

The final analysis for this element of the design is the fastening system holding the linkage to the housing. The three holes on the foot are designed for clearance of a 5/16" hardened steel cap head screw, which threads into the housing. The yield strength, and thus the failure criteria, of hardened steel is 100.1 ksi (690 MPa). This problem will be simplified to create a worst-case scenario. In this scenario, only one bolt in one of the side positions remains. Also, the figure will be simplified by assuming that the bolts are in the same plane as the acting force. Finally, it will be assumed that the foot acts as a roller, only supporting forces vertically. This should put the highest possible stress on the remaining bolt. Using these assumptions, the stress in the fastener is calculated to be:

$$\tau \text{Shear} = 1.23 \text{ ksi } (8.5 \text{ MPa})$$

$$\sigma \text{Tension} = 1.84 \text{ ksi } (12.7 \text{ MPa})$$

These numbers are both well below the yield strength of the fastener, and their combined effect is insubstantial.

The next element to which force is transferred is the housing (Figure 130). The housing rocks on the axle, which fits in the 0.17323" diameter hole in the body of the housing. The axle and the housing are separated by a 0.157” thick plastic bushing. The bushing helps reduce the friction between the housing and the axle, allowing the housing to rock freely.

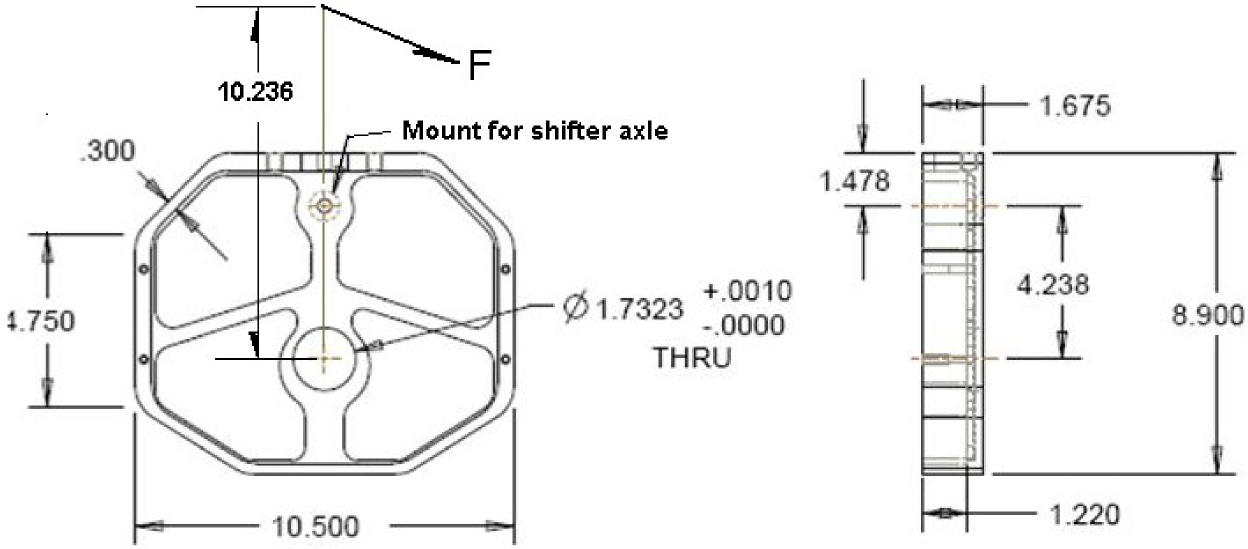


Figure 130: Housing Front and Side

The housing is the largest manufactured piece on the project, and is most likely stronger than necessary, given the use of aluminum alloy 6061-T651. A beyond worst-case scenario for stress can be easily calculated to show this. If the entire input force of 396.6 lb (1764 N) acted on a strip of aluminum that was 10.236” long (the distance from the input on the housing link to the axle) and 0.23” thick (the thinnest section of the housing wall) with an assumed safety factor of 5, and that the force acts perpendicular to the strip at the edge furthest from the axle (in the plane it currently occupies), the strip would only need to be 3.9” wide. The actual part has much more material and geometrical features that would add to its strength under a loading condition more favorable than the one outlined above. This part is clearly over-engineered; however, the available manufacturing processes are limited, and so the part will be milled from aluminum as designed.

Working backwards, the stress on the gear mounted over the clutch can be calculated. By treating the whole system as a rigid body, the moment about the axle can be found, which is

$$M = 328.5 \text{ lb*ft } (445.4 \text{ N*m})$$

This is only slightly lower than the original line analysis. The axle force R1 is equal to the applied force F. F is the force being transferred from the shifter system. For this analysis it is assumed that the shifter and gear interact like a roller, being unable to support forces not normal to their surfaces, and ignoring any friction present in the element of slip between the surfaces. Figure 131 is a stand-in model for what was eventually used as the collar: half of a US Tsubaki DS40A22 Double Single sprocket.

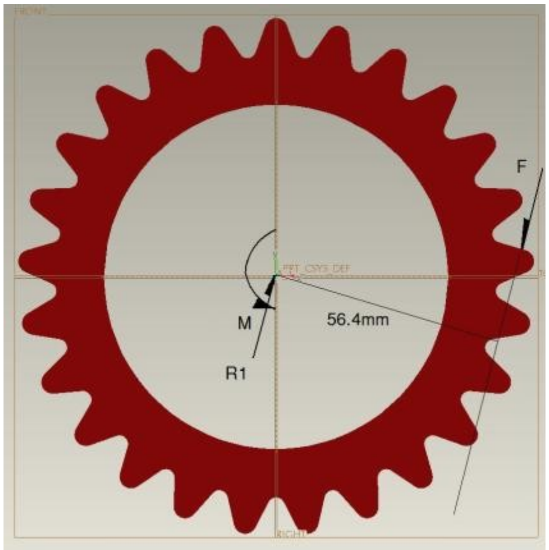


Figure 131: Gear Clutch Collar

The teeth on the sprocket are 0.275" thick and approximately 0.4" wide. The teeth of the sprocket are made from flame hardened steel, which has a yield strength of 100.1 ksi (690 MPa). The shifter is designed to act on the teeth as shown in Figure 131, meaning that F = 1.77 ksi (7897 N). With these forces, if it is assumed that the teeth are 0.254" deep, and the force acts at their midpoint, the stresses present are calculated to be

$$\tau\text{Shear} = 5.21 \text{ ksi } (35.9 \text{ MPa})$$

$$\sigma\text{Bending} = 31.2 \text{ ksi } (215.4 \text{ MPa})$$

While the bending force on the teeth is high, the material strength of the steel still provides a safety factor of 4. Most commercial gears are designed for good mesh and the ability to run at high speeds. This gear is primarily designed to act as a selection mechanism.

The force on the teeth from the analysis above can be transferred to the shifting mechanism. The area of interest here is the engagement system of the shifter, which is the interference of the slots on the back of the housing link with the side of the shifter. This interference creates a distributed load along one side of the shifter (Figure 132).

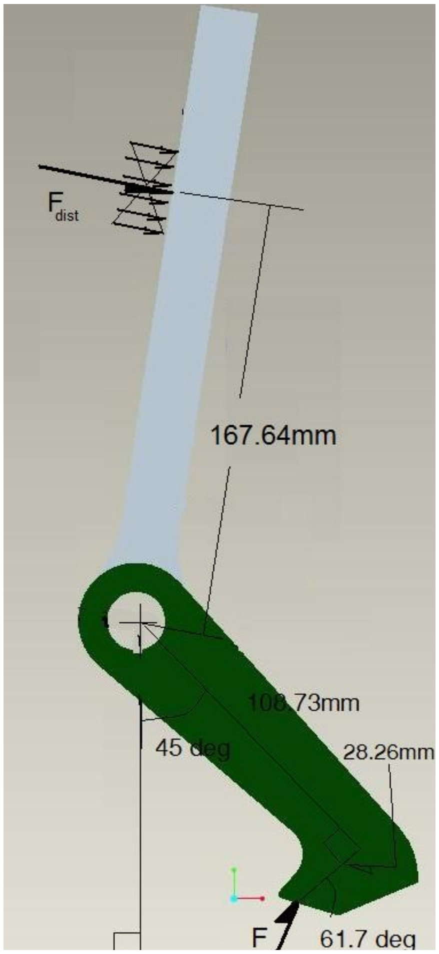


Figure 132: Shifter Loading

The distributed load acts along 1.5” of the shifter that is in contact with one of the islands in the back of the housing link. The equivalent force for the distributed load acts at 6.6” from the shifter axle, which is the moment center for this calculation. When the moment about the shifter axle is calculated, it is determined that the force is equal to 841.7 lbf (3744 N). As stated, the force acts along the 1.5” long island. The island is 0.094” deep. This means that the stress on both parts in this interaction is

$$\tau\text{Shear} = 5.93 \text{ ksi } (40.9 \text{ MPa})$$

This figure assumes that both parts are perfectly flat, and also perfectly aligned. Deflection in the shifter axle could increase this stress substantially. The same forces reach the yield stress of the material when the area is reduced to 0.403 in^2 (0.000026 m^2). This reduction only requires a deflection of 0.6°. As was proven during testing, this slipping due to deflection was a common problem.

The last parts to be considered are the spokes holding the axle to the wheelchair pushrim (Figure 133).

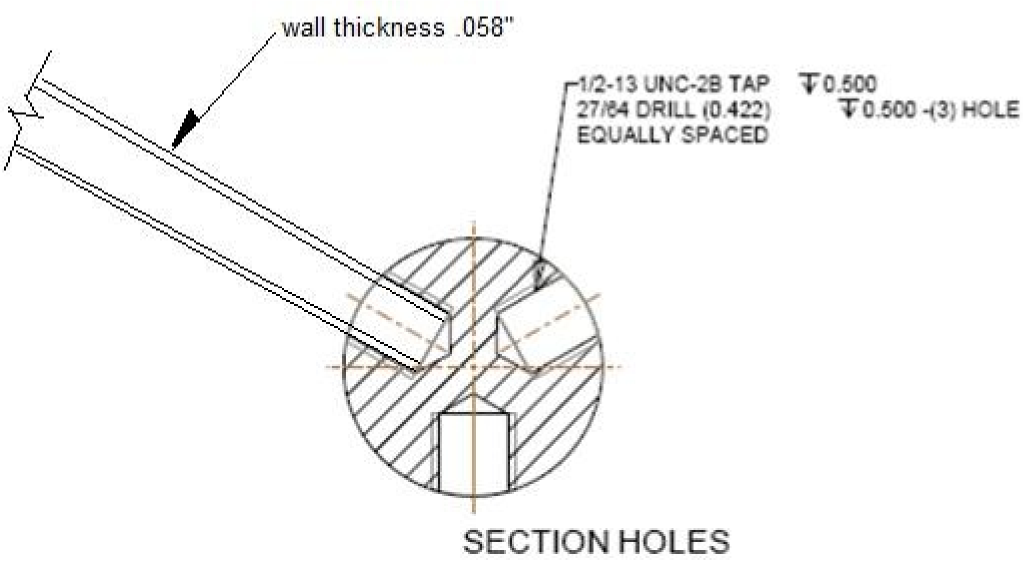


Figure 133: Axle & Spoke Section

These spokes are 1/2" diameter aluminum pipe, with a wall thickness of 0.058". Three identical pipes are screwed into the axle at 120° intervals, equally sharing the moment provided by the axle. The axle has a 1.57" diameter, the surface of which will be the position of the highest load. With the moment around the axle calculated at 328.5 lb*ft (445.4 N*m), each spoke must support 1.67 ksi (7423 N) of force. With the given pipe dimensions, this means that the shear stress is approximately

$$\tau_{\text{Shear}} = 8.96 \text{ ksi } (61.8 \text{ MPa})$$

This calculation does not, however, take into account the bending forces that are also present on the piece from the same rotation. Most importantly, this does not take into account the reduction of diameter presented by threading the pipe. The threads are only 0.0413" (1.05 mm) deep, but increase the shear stress to

$$\tau_{\text{Shear}} = 26.8 \text{ ksi } (185 \text{ MPa})$$

Additionally, the tensile load on the surface of one side of the spoke along the thread is

$$\sigma = (2350.8 \text{ MPa})$$

Using Mohr's circle, the maximum shear and tensile stresses on the same point are represented by these equations:

$$\tau_{Max} = \sqrt{\frac{1}{2}(\sigma_x + \sigma_y)^2 + \tau_{xy}{}^2} \qquad \text{and} \qquad \sigma_{Max} = \frac{1}{2}(\sigma_x + \sigma_y) + \sqrt{\frac{1}{2}(\sigma_x + \sigma_2)^2 + \tau_{xy}{}^2}$$

This particular load condition has only one tensile load, σ_x, reducing σ_y to zero. Using the calculated tensile and shear stress numbers, the maximum tensile and shear stress can be calculated.

$$\tau_{Max} = 172.6 \text{ ksi } (1190 \text{ MPa})$$

$$\sigma_{Max} = 343 \text{ ksi } (2365.3 \text{ MPa})$$

The plane in which these forces act can be calculated using this equation:

$$\tan(2\theta) = \frac{2\tau_{xy}}{(\sigma_x - \sigma_y)}$$

The maximum tensile stresses act on a plane offset 4.5° from the spoke being the y-axis. The maximum shear stresses act on a plane offset 49.5° from the spoke being the y-axis.

The calculated values are above the yield stress of the material in shear and tension without incorporating any secondary stress concentrations. With this type of loading, failure due to bending is very probable, and through later testing, was proven to be the case.

Appendix H: Project Poster

The following appendix contains the poster used in Project Presentation Day on April 23, 2009

One-Arm Drive Manual Wheelchair

Dominic DiGiovanni, Valerie Marrion, and Hamlet Nina
Mechanical Engineering Department
Advisors: Professor Allen Hoffman, Ph.D. & Professor Holly Ault, Ph.D.

Overview

Traditional manual wheelchairs require considerable use and control of both arms for operation, thus adaptations are required for individuals with asymmetrical use of their arms. Building upon previous projects, the goal of this project was to create an accessory, to be installed on a standard wheelchair, which would allow full control of the wheelchair with only one arm/hand while addressing areas lacking in commercial products and previous designs. Such areas include manufacturability, attendant control, user comfort and ergonomics. After preliminary research and examination of numerous possible design concepts, the project team developed a design for a removable, lever-operated accessory which could be adapted to fit a range of the most popular standard wheelchair models. The design was manufactured and installed on a manual wheelchair for testing. Careful attention was paid to minimizing the number of specialized parts and hardware used in the design in order to improve its manufacturability and ease of installation, and to minimize the need for maintenance.

Goal

The primary goal of this project was to develop, build, and test an accessory for manual wheelchairs which would allow the combined functions of propulsion, steering, and braking to be carried out with one hand. This accessory would also have increased emphasis on manufacturability and minimizing specially-machined parts when compared to previous designs.

Evaluation of Prior Designs

In order to prioritize the design issues in current models which the new design would need to address, the team evaluated three currently-available one-arm propulsion wheelchairs. These models were the prototype from the 2005-06 MQP, a Quickie Dual Pushrim model, and a Meyra lever-operated model. Ten able-bodied individuals between the ages of 19-23 and with no prior exposure to any of the chairs were asked to drive each one around a pre-determined course on the first floor of Higgins Labs. After the test, each individual was asked to rate the three chairs on a scale of 1-5 in fourteen different categories, including ease of forward/reverse propulsion and turning, intuitiveness of use, and braking. They were also asked to provide any additional qualitative comments they felt would be useful. This input was instrumental in formulating the design specifications and in guiding the design and manufacturing processes.


Figure 1a: Quickie Dual Pushrim Chair

- *Quickie Dual Pushrim (Figure 1a)*: "fatiguing to use" (both handrims must be grasped simultaneously to drive both wheels), "difficult to turn", "difficult to keep straight"; low scores in device usage comfort & overall turning mechanism operation but highest score in forward-to-reverse switch category


Figure 1b: Meyra Lever-Operated Chair

- *Meyra lever-operated (Figure 1b)*: "best comfort", "easy to learn and use", "braking is a bit difficult", "steering was by far the best"; highest average in every category except forward-to-reverse switch


Figure 1c: 2005-06 MQP Prototype

- *2005-06 MQP Prototype (Figure 1c)*: "unstable and loud", "bulky", "a lot of sharp edges", "hard to propel in a straight line"; lowest average in every category except overall turning mechanism and turning right in reverse


Figure 2: Static Stability Testing of 2008-09 Prototype

Design Specifications

Based on input from preliminary testing and the team's own observations, a list of design specifications was formulated which the final design would need to follow. These specifications spanned a range of categories, including safety, functionality, specific subsystems, and integration onto a manual wheelchair. Some of the most important specifications were:

- Accessory cannot add more than eight pounds to the chair's weight
- Modifications to the chair cannot cause its dimensions (L x W x H) to exceed 51" x 27.5" x 43"
- Accessory cannot impede chair's ability to be folded
- Accessory must allow forward and backward propulsion, with steering in both directions
- Required lever input force cannot exceed 15 pounds; required brake actuation (grip) force cannot exceed 25 pounds
- Mechanisms and wires must be safely enclosed or stored so as not to pose a safety hazard
- Lever must not move during attendant propulsion (i.e. must be disengaged)
- Adjustable mechanical advantage
- Accessory must be adaptable to either side of the wheelchair

Final Design

Several possible design concepts were proposed for each of the three main subsystems (propulsion, steering, and braking). Preliminary concepts for each subsystem were graded against each other using decision matrices. All possible combinations of the top two concepts in each subsystem (8 combinations total) were then compared in a final decision matrix to determine which concepts would integrate smoothly with one another while fulfilling the design criteria. The final design consists of the following subsystems:

- Propulsion: dual gear-pawl assembly in which the desired direction of motion is chosen by moving a shifter to engage one of the two gears press-fit around oppositely-oriented unidirectional clutches; also has neutral position, user input is transmitted to clutches via four-bar linkage (see Figure 3)
- Brakes: mechanical disc brakes mounted on each of the two large wheels, operated via a single brake lever (Figure 4) connected to a cable doubler
- Steering: cable wrapped around two pulleys, one of which is attached to the main lever handle (Figure 4) and transmits the user's input to the second pulley at the caster wheel (Figure 5), causing the caster to turn

To operate the chair, the user first selects the desired direction of motion using the shifter, which fits tightly into one of three grooves on the propulsion housing (see Figure 3). This causes one of the two pawl arms to engage a gear/clutch assembly. The user then pushes a lever, connected to the propulsion housing by a coupler link, forward to propel the chair either forward or backward. Steering is accomplished by pronation/supination motion of the wrist while grasping the handle, which causes tension in one side of the cable running between the pulleys at the handle and caster. The tension forces the caster pulley to rotate the caster. The two pulleys have a 1:1 circumference ratio, meaning there is no over- or under-steer. To brake, the user squeezes the brake lever on the handle. The cable at the lever is attached to a cable doubler, which allows the single handle to operate both brakes.

Manufacturing & Testing

The majority of the pieces of the propulsion system, as well as some pieces of the steering subassembly, were machined from stock aluminum alloy 6061-T651. Toolpaths and the corresponding NC code for these parts were generated using the Esprit and SurfCAM software packages, based off of the ProEngineer part models. The majority of the hand lever and brake subassemblies were made from commercially-available products.

After the entire accessory was manufactured and assembled, the following tests were conducted to compare it to existing designs, ensure its compliance with ANSI/RESNA standards, and confirm that it accomplished the original goals. Such tests included:

- Static stability testing (Figure 2)
- Operating force requirements
- Operating space requirements
- Dimensional testing
- Basic functionality testing
- Able-bodied student comparisons to commercial lever-operated models

The 2008-09 design successfully addressed many of the problems in currently-available models, though it had some new deficiencies as well. Table 1 summarizes these results, as well as observations from able-bodied student testing. In these tests, only the lever-operated designs were compared, as the different types of one-arm propulsion had already been compared in previous trials. The team thus wanted to compare the 08-09 prototype's strengths and weaknesses as a lever-operated design.

Testing Results for 2008-09 MQP Prototype	
Strengths	Deficiencies
Design-Related • Silent propulsion system • Neutral propulsion configuration & trailing caster allow attendant propulsion • Sharp edges & moving parts have been eliminated or safely enclosed • Shifting mechanism moved to safer location • Satisfies dimensional limits with accessory installed • Chair can still be folded with accessory installed	Design-Related • Propulsion system is very heavy, creating bending force on axle which pulls wheel out of alignment & could damage clutch bearings • Brake & steering cables required constant tensioning, were prone to slipping • Smaller pulleys result in smaller moment arm to transmit steering forces, meaning more effort is required to steer
Able-Bodied Student Testing • Highest rating in forward propulsion & overall propulsion • Improvements over 2006 MQP: - More comfortable to use overall - Less force for steering & propulsion - More intuitive to use	Able-Bodied Student Testing • Very hard to steer left • Low scores in 3-point turning and overall turning • Lowest score in backward propulsion

Table 1: Testing Results

Conclusions

- Design successfully addresses noise, removability, safety and attendant propulsion issues
- Many of the aluminum parts could have been made out of lighter high-density plastic
- Steering pulleys are too small to deliver required force to caster
- Heavy reliance on cables (steering, brakes) led to tension, slipping problems
- More space is required on axle for proper brake/rotor mounting

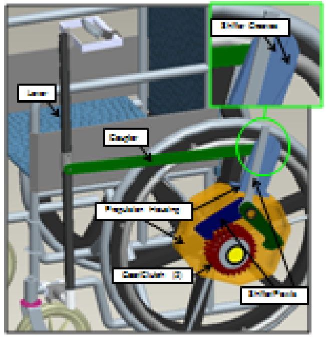


Figure 3: CAD Model of Final Design

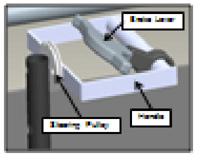


Figure 4: Handle

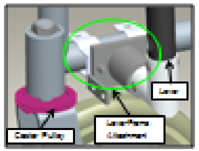


Figure 5: Caster Pulley & Lever Attachment